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COASTAL UPWELLING AND RADIOCARBON—EVIDENCE FOR TEMPORAL FLUCTUATIONS IN OCEAN RESERVOIR EFFECT OFF PORTUGAL DURING THE HOLOCENE

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ABSTRACT. This paper focuses on the use of the radiocarbon content of marine shells collected along the Portuguese coast as a proxy for the intensity of coastal upwelling off of Portugal. Differences in the ^{14}C ages of closely associated marine mollusk shells and terrestrial material (charcoal or bones) from several Portuguese archaeological contexts seem to be significant throughout the Holocene. ΔR values range from 940 ± 50 to –160 ± 40 ^{14}C yr. Five of these values are significantly higher than the modern value (250 ± 25 ^{14}C yr), while the remaining values are lower. The modern value was calculated by measuring the ^{14}C content of live-collected, pre-bomb marine mollusk shells. This value is in accordance with an active upwelling of strong intensity that currently occurs off of Portugal. Some primary observations based on data presented here can be made: i) during the Holocene important changes have occurred in the ocean reservoir effect off the Portuguese coast; ii) these fluctuations may be correlated with regional oceanographic changes, namely with changes in the strength of coastal upwelling; and iii) these changes suggest some sort of variability of the climatic factors forcing coastal upwelling off of Portugal.

INTRODUCTION

Along the western coasts of Europe, active upwelling is at present practically restricted to the Atlantic coast of the Iberian Peninsula, particularly from Cape Finisterre to Cape São Vicente (Wooster et al. 1976) and along the south coast of Portugal (Fiúza 1982, 1983). The western coast extends along the 9°W meridian between 37°N and 43°30′N, and the southern coast (Algarve) is oriented along 37°N between 7°20′W and 9°W (see Figure 1). The regime of winds strongly correlates with latitudinal migration of the subtropical front and with the dynamics of the Azores anticyclone cells. Hence, the atmospheric circulation associated with the Azores high corresponds to westerly winds off the Atlantic Iberian coast in the winter and to considerably stronger northerly and northwesterly winds in the summer. These northerly summer winds induce Ekman transport offshore along the western coast, i.e. they are clearly upwelling from June to September. The surface water circulation of the southern coast must be considered in relation to the Northeastern Atlantic circulation. Due to the dynamic effect of Cape São Vicente, the upwelled water in the western coast moves southeastward and eastward, creating a quasi-permanent upwelling area around the Cape as a prolongation of the western coastal upwelling system (Fiúza 1982, 1983; Fiúza et al. 1982; Ferreira 1984). When prevailing winds in the Gulf of Cádiz are from the west, the upwelled waters travel east along the southern coast, and a minor upwelling area is found to the east of Cape Santa Maria, Faro (Vargas et al. 2003).

Several upwelling proxies, such as sea surface temperatures (SST) and salinities (Fiúza 1982, 1983; Fiúza et al. 1982; Relvas and Barton 2000; Sánchez and Relvas 2003; Peliz et al. 2002) or diatom accumulation rates, planktonic foraminifera, and O and C isotopes (Abrantes 2000; Abrantes et al. 2001), have been used to study this phenomenon. Among them, SST data permit calculation of thermal anomalies of the waters along the coast relative to the central North Atlantic, where isotherms present a consistently zonal distribution (Fiúza 1982, 1983; Fiúza et al. 1982). In addition, the remotely sensed surface thermographies show that shortly after the beginning of a northerly wind cycle, upwelling begins south of all capes on the west Iberian coast and is strongly influenced by the

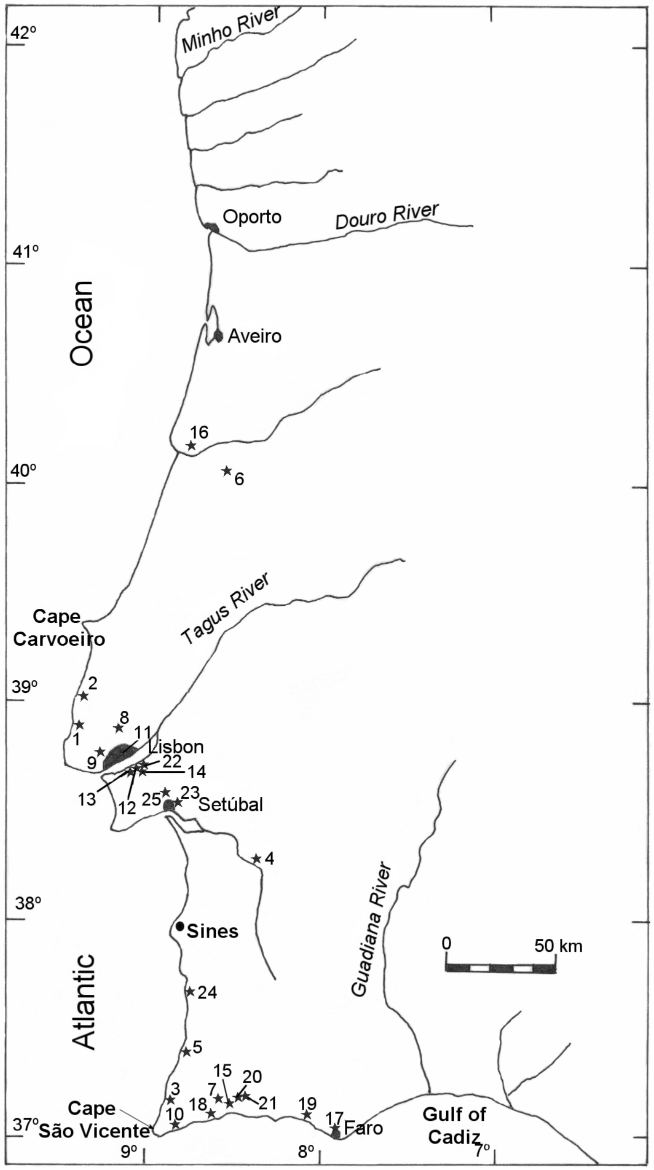

Figure 1 Locations of the sampled archaeological sites identified in Table 1

bathymetry of the shelf-upper slope region. Other factors such as land runoff and local aerological circulations determine the complex upwelling pattern off the Portuguese coast—for instance, in summer, a strong thermal gradient exists between the coastal region of Sines (38°N) and the continental region at the same latitude, which gives rise to very strong sea breezes. In general terms, it can be stated that upwelling is more pronounced to the south of Cape Carvoeiro (39°20′N), with a maximum intensity in the Sines coastal region (Ferreira 1984).

As upwelled waters are depleted in radiocarbon relative to sea surface water, the ^{14}C content of marine shells that inhabit coastal regions can be used as an upwelling proxy, since the ocean reservoir is deficient in ^{14}C compared with the atmosphere. Stuiver et al. (1986) modeled the response of the world oceans to atmospheric ^{14}C variations. From this modeling, 2 calibration curves for marine samples have been derived—one related to the deep ocean and the other to the sea surface water (mixed layer). Regional differences in ^{14}C content between the sea surface water of a specific region and the average surface water are due to several causes and anomalies, namely the upwelling of deep water. Thus, a parameter, denoted as ΔR, can be 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. Usually, ΔR values are determined for a particular geographical region by ^{14}C dating of marine mollusk shells of historic (known) age, collected alive before 1950, i.e. of "pre-bomb" age (Stuiver et al. 1986). Although reservoir ages are time-dependent, ΔR is not unless some change of oceanographic conditions restricted to the considered regional ocean has occurred. Since rates of regional upwelling can vary in the course of time and the intensity of the ^{14}C depletion in the mixed layer depends upon the wind-driven coastal upwelling, it is likely that values of ΔR can also vary throughout time (Stuiver and Braziunas 1993:155). A ΔR value higher than the modern value (i.e. the one determined using marine mollusk shells of historic known age) will probably represent a period of higher-than-modern upwelling rates, and, conversely, periods with lower-than-modern ΔR values may represent periods of weaker coastal upwelling. Thus, 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).

From previous research concerning the coastal upwelling off of Portugal and its variability during the Holocene (Soares 1993), a mean value (250 ± 25 ^{14}C yr) for ΔR was calculated using shells from marine mollusks collected alive along the Portuguese coast between 1886 and 1937. This mean value is in accordance with the occurrence of an active upwelling of strong intensity as exists today and is valid for the whole Portuguese coast. In compliance with the definition, ΔR was assumed to be constant (Stuiver et al. 1986). Nevertheless, the research carried out at that time indicated that before 1300 BP, a coastal environment probably existed that was weakly influenced by the upwelling of deep water. After 1100 BP, the reservoir age of Portuguese coastal waters seems to have increased to the modern value of ΔR in accordance with the occurrence of an active coastal upwelling of strong intensity. These data suggest that between 1300 and 1100 BP, a change in certain climatic parameters along the Portuguese coast might have occurred, causing a significant intensification of coastal upwelling off of Portugal (Soares 1993:484).

We have continued the previous research by ^{14}C dating more pairs of closely associated samples of marine shells and charred wood or bones collected from the same stratigraphic level at various excavated Portuguese archaeological sites representing different periods in the Holocene. Our main purpose is not only to clarify the eventual variability of coastal upwelling off of Portugal but also to identify shifts in oceanic circulation, probably coupled with climatic change.

SAMPLING

Pairs of closely associated archaeological samples (marine shells/charcoal, wood, or bones) from each depositional context were collected from a range of Portuguese archaeological sites. It is assumed that the deposition of both types of samples was simultaneous or, in other words, that the time of death of organisms from both reservoirs was the same.

We tried to eliminate problematical associations by closely consulting the excavators of each sampled site. In order to obtain accurate results, we selected samples from i) single or stratified deposits whose archaeology indicated they had always remained undisturbed and ii) deposits of domestic refuse thought to have accumulated rapidly. For Epipaleolithic or Mesolithic shell middens, we took shell and charcoal samples in close stratigraphic proximity.

In some cases, we measured several different shell species or different materials of terrestrial origin (charcoal and bones) from the same archaeological context. Using different shell species, we tried to test not only if their respective ^{14}C dating results were influenced by dietary or habitat preferences of the analyzed mollusks but also to identify eventual outliers. For charcoal samples, it was not possible to undertake any prior anthracological analyses, and in order to overcome the problem of the "old wood effect," which can lead to low or negative ΔR values, associated bones were dated whenever possible. Also whenever possible, other contexts from the same archaeological site were ^{14}C dated and the results compared with the data used to calculate ΔR in order to verify their reliability.

This methodology was thought to be the most promising to obtain accurate values of ΔR. A detailed discussion of these matters can be found in Soares (2005), including a description of the sampled archaeological sites, as well as all the data obtained from our research concerning the variability of coastal upwelling off of Portugal and the regional reservoir ages. Sampling locations are shown in Figure 1.

EXPERIMENTAL

Samples were first cleaned by manually removing foreign material. Charcoal and wood samples were further decontaminated by acid/alkali/acid digestion. For bone samples, gelatin was extracted 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 of the shells was discarded by controlled acid leaching (0.5M HCl at 25 °C). For some samples, where size allowed, controlled acid hydrolysis was used to separate approximately equal volumes of CO_2 representative of the intermediate fraction and the inner fraction of the shells' carbonate structure.

We measured the ^{14}C content by means of the liquid scintillation technique (Soares 1989). Stable isotope enrichment values ($\delta^{13}C$) were determined for the CO_2 gas produced at the initial stage of benzene synthesis.

^{14}C ages or the radiometric enrichment $D^{14}C$ were calculated in accordance with the definitions recommended by Stuiver and Polach (1977).

RESULTS AND DISCUSSION

Measurements of the ^{14}C contents of the terrestrial/marine pairs and the resulting ΔR values are listed in Table 1. Following Stuiver and Braziunas (1993: Figure 15), ΔR values were calculated by converting the terrestrial biosphere sample ^{14}C age from each archaeological context 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.

As already mentioned, we dated 2 or more samples of the same origin (e.g. samples of marine shells, each one comprising only 1 species) from the same stratigraphic level and context. A weighted mean was then calculated using $D^{14}C$ values, and a statistical criterion was established to determine if the value for a given sample fell within the limits established by the mathematical expression $A_s - A_m \leq 2\sqrt{\sigma_s^2 + \sigma_m^2}$, where A_s is the median value for the given sample, σ_s^2 its associated variance, A_m the group weighted mean, and σ_m^2 its associated variance. If the value falls outside the prescribed limits, it is rejected and a new weighted mean is calculated.

Table 1 ^{14}C measurements of pairs of samples (marine shells/charcoal or bones) from the same archaeological context.

Lab nr	Shell sample description	$\delta^{13}C$ (‰)	$D^{14}C$ (‰)	^{14}C age (yr BP)	Lab nr	Terrestrial sample description	$\delta^{13}C$ (‰)	$D^{14}C$ (‰)	^{14}C age (yr BP)
1 – MAGOITO (38°55′N; 9°26′W)									
ICEN-80	*Mytilus edulis*	2.34	–711.0 ± 2.5						
ICEN-81	*Patella* sp.	2.75	–704.3 ± 4.3						
ICEN-82	*Cerastoderma edule*	1.33	–708.9 ± 3.6						
		Mean	–709.2 ± 2.1	9920 ± 60	ICEN-52	Charcoal	–24.56	–693.3 ± 2.4	9490 ± 60
				ΔR = 160 ± 60 yr					
2 – S. JULIÃO I (38°57′N; 9°23°W)									
ICEN-108[a]	*Cerastoderma edule*	0.38	–648.5 ± 2.1						
ICEN-109[b]	*C. edule*	5.70	–655.0 ± 2.9						
ICEN-152[a]	*C. edule*	–0.18	–649.7 ± 2.5						
ICEN-153[b]	*C. edule*	–1.75	–645.7 ± 2.0						
ICEN-154[c]	*Ostrea* sp.	–1.53	–601.4 ± 4.4						
		Mean	–648.7 ± 1.6	8400 ± 40	ICEN-179	Charcoal	–24.74	–636.2 ± 4.4	8120 ± 100
				ΔR = –70 ± 40 yr					
2 – S. JULIÃO II (38°57′N; 9°23′W)									
ICEN-83[a]	*Cerastoderma edule*	–1.33	–677.3 ± 2.5						
ICEN-84[b]	*C. edule*	–0.33	–676.2 ± 2.1	9060 ± 50	ICEN-76	Charcoal	–24.72	–621.7 ± 4.4	7810 ± 90
				ΔR = 940 ± 50 yr					
ICEN-106[a]	*Cerastoderma edule*	–2.51	–633.2 ± 2.4						
ICEN-107[b]	*C. edule*	–1.23	–636.6 ± 2.2	8130 ± 50	ICEN-73	Charcoal	–23.42	–612.4 ± 4.1	7610 ± 80
				ΔR = 170 ± 50 yr					
3 – CASTELEJO (37°05′N; 8°58′W)									
ICEN-214	*Thais haemastoma*	1.89	–636.9 ± 5.0						
ICEN-219[a]	*Patella* sp.	–0.42	–634.1 ± 2.1						
ICEN-220[b]	*Patella* sp.	0.39	–638.1 ± 2.0						
		Mean	–637.9 ± 1.9	8160 ± 40	ICEN-211	Charcoal	–23.98	–629.3 ± 2.6	7970 ± 60
				ΔR = –110 ± 40 yr					
ICEN-216	*Thais haemastoma*	1.65	–636.8 ± 3.3						
ICEN-217[a]	*Mytilus edulis*	–0.03	–641.8 ± 2.5						
ICEN-218[b]	*M. edulis*	1.79	–639.7 ± 2.8						

Table 1 ^{14}C measurements of pairs of samples (marine shells/charcoal or bones) from the same archaeological context. *(Continued)*

Lab nr	Shell sample description	$\delta^{13}C$ (‰)	$D^{14}C$ (‰)	^{14}C age (yr BP)	Lab nr	Terrestrial sample description	$\delta^{13}C$ (‰)	$D^{14}C$ (‰)	^{14}C age (yr BP)
ICEN-221[a]	*Patella* sp.	2.11	–645.3 ± 2.6						
ICEN-222[b]	*Patella* sp.	0.32	–639.4 ± 2.0						
ICEN-212[c]	*Balanus* sp.	1.28	–627.1 ± 4.0						
		Mean	–639.0 ± 1.5	8180 ± 40	ICEN-213	Charcoal	–23.59	–625.9 ± 1.8	7900 ± 40
				ΔR = –20 ± 40 yr					
4 – VALE DE ROMEIRAS (38°23′N; 8°32′W)									
ICEN-145[a]	*C. edule* + *C. glaucum*	–2.40	–613.7 ± 4.7						
ICEN-146[b]	*C. edule* + *C. glaucum*	–4.32	–599.3 ± 2.9	7350 ± 60	ICEN-144	Animal bones	–17.40	–588.2 ± 5.6	7130 ± 110
				ΔR = –170 ± 60 yr					
5 – FIAIS (37°34′ N; 8°40′W)									
ICEN-104[a,c]	*Ostrea* sp.	–1.60	–574.2 ± 2.8						
ICEN-105[b,c]	*Ostrea* sp.	–1.73	–572.4 ± 3.0						
ICEN-103	*C. edule* + *Patella* sp.	–1.07	–597.3 ± 3.8	7310 ± 75	ICEN-110	Animal bones	–21.10	–574.8 ± 11.8	6870 ± 220
				ΔR = 70 ± 75 yr					
6 – BURACA GRANDE (39°59′N; 8°33′W)									
Sac-1459	Several species	–1.75	–576.7 ± 7.1	6910 ± 140	ICEN-1461	Charcoal	–28.49	–570.7 ± 11.1	6790 ± 210
				ΔR = –250 ± 140 yr					
7 – ALCALAR – Monument 7 (37°12′N; 8°35′W)									
Sac-1607[a]	*Venerupis decussatus*	–1.94	–546.0 ± 3.0						
Sac-1608[b]	*V. decussatus*	–2.07	–559.3 ± 3.4						
Sac-1593[a]	*V. decussatus*	–2.34	–553.2 ± 3.0						
Sac-1594[b]	*V. decussatus*	–2.99	–551.8 ± 3.3						
Sac-1601	*V. decussatus*	–2.19	–558.6 ± 3.9						
Sac-1602	*V. decussatus*	–6.83	–555.8 ± 3.3						
		Mean	–555.6 ± 1.9	6520 ± 40	Sac-1794	Charcoal	–29.72	–504.2 ± 6.0	5640 ± 100
				ΔR = 410 ± 40 yr					
8 – OLELAS (38°50′ N; 9°17′W)									
ICEN-880	*Pecten maximus*	0.54	–442.1 ± 7.4	4690 ± 110	ICEN-879	Bones	–21.14	–421.9 ± 3.2	4400 ± 45
				ΔR = –70 ± 110 yr					
9 – LECEIA (38°44′N; 9°17′W)									
ICEN-95	*Venus* sp.	1.34	–419.8 ± 4.0						

Table 1 ^{14}C measurements of pairs of samples (marine shells/charcoal or bones) from the same archaeological context. *(Continued)*

Lab nr	Shell sample description	δ^{13}C (‰)	D^{14}C (‰)	^{14}C age (yr BP)	Lab nr	Terrestrial sample description	δ^{13}C (‰)	D^{14}C (‰)	^{14}C age (yr BP)
ICEN-101[a]	*Patella* sp.	2.98	–421.7 ± 3.6		ICEN-92	Charcoal	–24.56	–400.9 ± 5.7	
ICEN-102[b]	*Patella* sp.	1.68	–418.4 ± 4.0		ICEN-89	Animal bones	–19.91	–407.4 ± 5.3	
		Mean	–419.1 ± 2.8	4360 ± 40			*Mean*	–404.4 ± 3.9	4160 ± 55
				ΔR = –160 ± 40 yr					
10 – PEDRA ESCORREGADIA (37°04′N; 8°55′W)									
ICEN-847	*Patella* sp.	1.08	–454.7 ± 3.5						
ICEN-848[c]	*Thais haemastoma*	1.28	–441.4 ± 3.4						
ICEN-845[a]	*Pollicipes* sp.	–1.20	–453.2 ± 3.8		ICEN-844	Human bones	–19.42	–396.9 ± 5.0	
ICEN-846[b]	*Pollicipes* sp.	–1.02	–455.1 ± 3.8		ICEN-1028	Human bones	–19.68	–376.8 ± 7.9	
		Mean	–454.9 ± 2.6	4870 ± 40			*Mean*	–391.2 ± 4.2	3990 ± 60
				ΔR = 550 ± 40 yr					
11 – TAPADA DA AJUDA (38°44′N; 9°1′W)									
ICEN-96	*Trochocochlea lineata*	2.98	–349.1 ± 3.1						
ICEN-97	*Mytilus edulis*	0.04	–342.2 ± 3.9						
ICEN-98[a]	*Patella* sp.	0.23	–347.3 ± 3.6		ICEN-100	Animal bones	–19.80	–311.9 ± 3.6	
ICEN-99[b]	*Patella* sp.	–1.42	–340.0 ± 3.4		ICEN-184	Charcoal	–25.38	–311.5 ± 8.6	
		Mean	–344.3 ± 2.0	3390 ± 25			*Mean*	–311.8 ± 3.3	3000 ± 40
				ΔR = 40 ± 25 yr					
12 – QUINTA DO PERCEVEJO (38°41′N; 9°10′W)									
ICEN-1082[a]	*Venerupis decussatus*	–0.14	–343.9 ± 4.3						
ICEN-1083[b]	*V. decussatus*	–0.17	–342.3 ± 3.8	3370 ± 45	ICEN-1084	Charcoal	–26.02	–306.8 ± 5.1	2940 ± 60
				ΔR = 100 ± 45 yr					
13 – QUINTA DO MARCELO (38°41′N; 9°10′W)									
ICEN-946[a]	*Patella* sp.	1.18	–340.5 ± 4.6						
ICEN-947[b]	*Patella* sp.	1.15	–343.1 ± 4.9						
ICEN-944[a]	*Trochocochlea lineata*	0.36	–344.4 ± 4.1						
ICEN-945[b]	*T. lineata*	1.27	–336.0 ± 3.9						
		Mean	–338.8 ± 3.1	3320 ± 40	ICEN-943	Animal bones	–20.85	–292.7 ± 10.3	2780 ± 120
				ΔR = 210 ± 40 yr					
ICEN-919[a]	*Patella* sp.	0.67	–321.5 ± 4.4						

Table 1 ^{14}C measurements of pairs of samples (marine shells/charcoal or bones) from the same archaeological context. *(Continued)*

Lab nr	Shell sample description	$\delta^{13}C$ (‰)	$D^{14}C$ (‰)	^{14}C age (yr BP)	Lab nr	Terrestrial sample description	$\delta^{13}C$ (‰)	$D^{14}C$ (‰)	^{14}C age (yr BP)
ICEN-920[b]	*Patella* sp.	1.27	–329.6 ± 3.2	3210 ± 40	ICEN-924	Animal bones	–19.50	–285.3 ± 5.9	2700 ± 70
				ΔR = 170 ± 40 yr					
ICEN-921[a]	*Patella* sp.	0.91	–322.7 ± 3.8						
ICEN-922[b]	*Patella* sp.	0.77	–325.8 ± 4.3	3170 ± 50	ICEN-923	Animal bones	–20.57	–272.8 ± 9.1	2560 ± 100
				ΔR = 210 ± 50 yr					
14 – Quinta do Almaraz (38°41′N; 9°09′W)									
ICEN-915[a]	*Cerastoderma edule*	0.68	–313.3 ± 4.5						
ICEN-916[b]	*C. edule*	0.82	–309.1 ± 4.0						
ICEN-917[a]	*Venerupis decussatus*	0.09	–320.9 ± 3.9						
ICEN-918[b]	*V. decussatus*	0.29	–322.7 ± 5.1						
		Mean	–314.3 ± 3.1	3030 ± 35	ICEN-927	Animal bones	–20.03	–273.9 ± 5.2	2570 ± 60
				ΔR = 40 ± 35 yr					
ICEN-913[a]	*V. decussatus*	0.25	–310.5 ± 4.3						
ICEN-914[b]	*V. decussatus*	0.15	–313.5 ± 4.0	3020 ± 45	ICEN-926	Animal bones	–20.40	–282.2 ± 4.6	2660 ± 50
				ΔR = 0 ± 45 yr					
ICEN-911[a]	*Mytilus edulis*	–0.30	–290.7 ± 4.2						
ICEN-912[b]	*M. edulis*	0.47	–296.4 ± 4.0	2820 ± 45	ICEN-925	Animal bones	–20.38	–258.5 ± 4.3	2400 ± 45
				ΔR = 110 ± 45 yr					
Sac-1364[a]	*V. decussatus*	–0.41	–424.6 ± 3.2		Sac-1363[c]	Animal bones	–21.97	–531.2 ± 2.8	
Sac-1365[b]	*V. decussatus*	–1.02	–306.5 ± 3.7	2940 ± 40	Sac-1656	Animal bones	–20.80	–286.4 ± 4.1	2710 ± 45
				ΔR = –110 ± 40 yr					
Sac-1367	*Mytilus edulis*	–0.23	–315.3 ± 4.2						
Sac-1366	*Cerastoderma edule*	–0.49	–312.4 ± 4.0						
Sac-1368	*Venerupis decussatus*	–0.30	–317.4 ± 3.9						
		Mean	–315.1 ± 3.3	3040 ± 25	Sac-1362	Animal bones	–20.48	–268.7 ± 4.8	2510 ± 50
				ΔR = 110 ± 25 yr					
Sac-1626[a]	*V. decussatus*	–0.07	–425.4 ± 3.1		Sac-1636	Charcoal	–25.10	–278.8 ± 11.2	
Sac-1627[b]	*V. decussatus*	1.92	–318.2 ± 4.2	3080 ± 50	Sac-1655	Animal bones	–19.22	–291.9 ± 5.7	
							Mean	–289.2 ± 5.1	2740 ± 60
				ΔR = 0 ± 50 yr					
15 – ROCHA BRANCA (37°11′N; 8°26′W)									
ICEN-851[a]	*Mytilus edulis*	–2.69	–310.8 ± 3.8						

Table 1 ^{14}C measurements of pairs of samples (marine shells/charcoal or bones) from the same archaeological context. *(Continued)*

Lab nr	Shell sample description	$\delta^{13}C$ (‰)	$D^{14}C$ (‰)	^{14}C age (yr BP)	Lab nr	Terrestrial sample description	$\delta^{13}C$ (‰)	$D^{14}C$ (‰)	^{14}C age (yr BP)
ICEN-852[b]	*Mytilus edulis*	–1.59	–312.5 ± 3.7	3010 ± 45	ICEN-853	Charcoal	–24.84	–273.5 ± 3.8	2570 ± 45
				ΔR = 20 ± 45 yr					
ICEN-231[b]	*Ostrea* sp.	–0.14	–280.8 ± 4.0	2650 ± 45	ICEN-201	Charcoal	–24.58	–262.6 ± 4.3	2450 ± 45
				ΔR = –150 ± 45 yr					
ICEN-856[a]	*Trochocochlea lineata*	0.06	–303.8 ± 4.0						
ICEN-857[b]	*T. lineata*	–0.25	–301.6 ± 4.3	2880 ± 50	ICEN-855	Animal bones	–20.49	–257.4 ± 4.0	2390 ± 45
				ΔR = 170 ± 50 yr					
16 – SANTA OLAIA (40°10′N; 8°43′W)									
ICEN-778	*Cerastoderma edule*	1.35	–300.2 ± 3.9	2870 ± 45	ICEN-777	Charcoal	–25.04	–249.2 ± 18.1	2300 ± 200
				ΔR = 200 ± 45 yr					
17 – POLÍCIA JUDICIÁRIA, FARO (37°00′N; 7°56′W)									
ICEN-157	*Venerupis decussatus*	4.67	–280.5 ± 4.5	2640 ± 50	ICEN-156	Animal bones	–17.49	–242.8 ± 3.8	2230 ± 40
				ΔR = 70 ± 50 yr					
18 – VILA VELHA DE ALVOR (37°08′N; 8°36′W)									
ICEN-233[a]	*Ostrea* sp.	2.38	–241.7 ± 4.6						
ICEN-234[b, c]	*Ostrea* sp.	1.53	–239.1 ± 4.8						
ICEN-235[c]	*Venerupis decussatus*	1.91	–164.6 ± 7.5		ICEN-226	Charcoal	–21.18	–212.4 ± 30.4	
ICEN-236[c]	*Cerastoderma edule*	0.60	–130.7 ± 7.5		ICEN-227	Animal bones	–21.06	–231.3 ± 6.4	
ICEN-232	*Trochocochlea lineata*	1.07	–265.4 ± 6.8	2480 ± 70			*Mean*	–230.5 ± 12.8	2100 ± 140
				ΔR = 50 ± 70 yr					
19 – LOULÉ VELHO (37°04′N; 8°04′W)									
Sac-1578[a]	*Cerastoderma edule*	0.26	–253.2 ± 3.7						
Sac-1579[b]	*C. edule*	4.56	–265.4 ± 4.8	2480 ± 50	Sac-1576	Charcoal	–25	–223.1 ± 6.9	2030 ± 70
				ΔR = 90 ± 50 yr					
Sac-1807	*C. edule*	1.02	–232.6 ± 4.5	2130 ± 45	Sac-1808	Animal bones	–18.70	–196.2 ± 4.4	1750 ± 45
				ΔR = 30 ± 45 yr					
20 – CISTERN-WELL OF SILVES (37°11′N; 8°26′W)									
ICEN-549[a]	*Venerupis decussatus*	–1.39	–169.4 ± 4.5						
ICEN-550[b]	*V. decussatus*	0.01	–182.9 ± 4.0	1620 ± 40	ICEN-551	Charcoal	–24.48	–146.9 ± 4.1	1280 ± 40
				ΔR = –40 ± 40 yr					

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Table 1 ^{14}C measurements of pairs of samples (marine shells/charcoal or bones) from the same archaeological context. *(Continued)*

Lab nr	Shell sample description	$\delta^{13}C$ (‰)	$D^{14}C$ (‰)	^{14}C age (yr BP)	Lab nr	Terrestrial sample description	$\delta^{13}C$ (‰)	$D^{14}C$ (‰)	^{14}C age (yr BP)
ICEN-228[a]	*Ostrea* sp.	1.52	–112.3 ± 5.2						
ICEN-229[b,c]	*Ostrea* sp.	–1.23	–109.6 ± 5.4						
ICEN-225	*Cerastoderma edule*	–0.75	–208.8 ± 6.9	1880 ± 70	ICEN-202	Charcoal	–25.01	–132.2 ± 4.9	1140 ± 45
				ΔR = 360 ± 70 yr					
21 – RUA DA ARROCHELA, SILVES (37°11′N; 8°26′W)									
Sac-1441[a]	*V. decussatus*	–0.68	–169.5 ± 3.7						
Sac-1442[b]	*V. decussatus*	–0.21	–168.0 ± 3.9						
Sac-1421[a]	*C. edule*	0.65	–156.5 ± 4.5						
Sac-1422[b]	*C. edule*	0.67	–171.8 ± 4.1						
		Mean	–169.8 ± 2.8	1490 ± 30	Sac-1443	Charcoal	–23.68	–123.6 ± 4.5	1060 ± 40
				ΔR = 50 ± 40 yr					
22 – JUDIARIA, ALMADA (38°41′N; 9°09′W)									
Sac-1415[a]	*Cerastoderma edule*	–0.15	–156.1 ± 4.1						
Sac-1416[b]	*C. edule*	–0.94	–167.4 ± 4.3	1470 ± 40	Sac-1420	Animal bones	–20.98	–122.0 ± 4.5	1050 ± 40
				ΔR = 40 ± 40 yr					
Sac-1417[a]	*C. edule*	–0.24	–164.6 ± 4.2						
Sac-1418[b]	*C. edule*	–3.18	–151.2 ± 5.7	1320 ± 50	Sac-1419	Animal bones	–20.14	–121.8 ± 4.8	1040 ± 45
				ΔR = –100 ± 50 yr					
Sac-1394[b]	*C. edule*	–0.78	–169.8 ± 4.2	1490 ± 40	Sac-1395	Animal bones	–21.56	–118.7 ± 4.5	1020 ± 40
				ΔR = 90 ± 40 yr					
Sac-1377[a]	*C. edule*	–0.79	–146.1 ± 4.6						
Sac-1378[b]	*C. edule*	0	–153.9 ± 4.6	1340 ± 45	Sac-1376	Animal bones	–21.22	–97.0 ± 4.7	820 ± 40
				ΔR = 140 ± 45					
Sac-1383[a]	*C. edule*	0.14	–136.3 ± 5.1						
Sac-1384[b]	*C. edule*	–0.15	–146.4 ± 4.6	1270 ± 45	Sac-1382	Animal bones	–21.14	–96.4 ± 4.4	810 ± 40
				ΔR = 80 ± 45 yr					
Sac-1371[a]	*Patella* sp.	0.10	–128.6 ± 4.6						
Sac-1372[b]	*Patella* sp.	–0.51	–116.1 ± 4.6	990 ± 40	Sac-1370	Animal bones	–21.20	–76.6 ± 4.8	640 ± 40
				ΔR = –40 ± 40 yr					
23 – TRAVESSA DA PORTUGUESA, SETÚBAL (38°31′N; 8°53′W)									
ICEN-700[a]	*Mytilus* sp.	–1.06	–135.4 ± 4.2						

Table 1 ^{14}C measurements of pairs of samples (marine shells/charcoal or bones) from the same archaeological context. *(Continued)*

Lab nr	Shell sample description	$\delta^{13}C$ (‰)	$D^{14}C$ (‰)	^{14}C age (yr BP)	Lab nr	Terrestrial sample description	$\delta^{13}C$ (‰)	$D^{14}C$ (‰)	^{14}C age (yr BP)
ICEN-701[b]	*Mytilus* sp.	1.01	–164.4 ± 4.3						
ICEN-702	*C. edule*	0.87	–157.6 ± 4.5						
		Mean	–161.2 ± 3.1	1410 ± 30	ICEN-698	Wood (grapevine)	–27.29	–109.6 ± 4.4	930 ± 40
				ΔR = 110 ± 30 yr					
ICEN-704[c]	*Glycymeris glycymeris*	2.36	–198.2 ± 4.3						
ICEN-703	*C. edule + C. glaucum*	0.92	–145.7 ± 4.4	1270 ± 40	ICEN-699	Wood (grapevine)	–25.45	–102.9 ± 4.7	870 ± 40
				ΔR = 40 ± 40 yr					
24 – MALHÃO									
ICEN-163	*Balanus* sp.	3.78	–167.2 ± 7.6						
ICEN-164[a]	*Charonia* sp.	3.60	–171.4 ± 4.1						
ICEN-165[b]	*Charonia* sp.	1.00	–155.9 ± 4.7						
ICEN-167[a]	*Mytilus edulis*	2.40	–164.4 ± 5.1		ICEN-130	Charcoal	–23.83	–117.0 ± 25.2	
ICEN-168[b]	*Mytilus edulis*	3.61	–169.2 ± 3.0		ICEN-161	Charcoal	–22.84	–102.2 ± 8.7	
		Mean	–165.5 ± 2.4	1450 ± 30			*Mean*	–103.7 ± 9.5	880 ± 85
				ΔR = 210 ± 30 yr					
25 – CASTELO DE PALMELA (38°34′N; 8°54′W)									
Sac-1444	*Mytilus + Cerastoderma + Trochocochlea*	–1.49	–205.8 ± 6.5	1850 ± 70	Sac-1445	Animal bones	–25.02	–102.9 ± 10.1	870 ± 90
				ΔR = 620 ± 70 yr					

[a]Intermediate fraction (not considered in the calculation of the mean).
[b]Inner fraction.
[c]Rejected in the calculation of the mean.

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The mathematical constraint imposed upon the results allows us to verify (see Table 1) that the ^{14}C content of different contemporary shell species (at least those from mollusks usually consumed by people) were not influenced by the dietary or habitat preferences of the respective organisms (see e.g. the values for Tapada da Ajuda or Quinta do Almaraz at 2510 ± 50 BP). Nevertheless, the values determined using samples of *Ostrea* are generally very different from those obtained using samples of other shell species (see results from S. Julião I, Fiais, Vila Velha de Alvor, and the cistern-well of Silves), and, in some cases, the age determined for the *Ostrea* sample is more recent than the age of the associated terrestrial material (e.g. from S. Julião I or from the cistern-well of Silves). Thus, these facts may be related to the dietary preference of *Ostrea*, but the incorporation of materials (carbonates) of different ages into the shell during its diagenesis cannot be ruled out.

Only the value of $D^{14}C$ determined for the inner fraction of marine shell samples (when 2 fractions are obtained and analyzed) is taken into consideration for ΔR calculation. The $D^{14}C$ value for the intermediate fraction is merely an index of reliability for the inner fraction $D^{14}C$ as are the inner and the intermediate fraction $\delta^{13}C$ values. For uncontaminated marine samples, $\delta^{13}C$ must be higher than –3‰ (Keith and Anderson 1963).

In Table 2, the ΔR values are presented for each archaeological context listed in decreasing chronological order. The context age was determined by using samples of terrestrial biosphere origin. These ages are presented as conventional ^{14}C dates and also as calendar dates using the program CALIB Rev 5.0.1 (Stuiver and Reimer 1993; Reimer et al. 2004).

Table 2 Reservoir effect values for the Portuguese coast.

Archaeological site	^{14}C age (BP)	cal BC/cal AD[a] (2 σ)	cal BP[a] (2 σ)	ΔR (^{14}C yr)
Magoito	9490 ± 60	cal BC 9130–8630	10,580–11,080	160 ± 60
S. Julião I	8120 ± 100	cal BC 7450–6710	8660–9400	–70 ± 40
Castelejo	7970 ± 60	cal BC 7050–6690	8640–9000	–110 ± 40
Castelejo	7900 ± 40	cal BC 7030–6640	8590–8980	–20 ± 40
S. Julião II	7810 ± 90	cal BC 7030–6470	8420–8980	940 ± 50
S. Julião II	7610 ± 80	cal BC 6630–6260	8210–8580	170 ± 50
Vale Romeiras	7130 ± 110	cal BC 6230–5780	7720–8180	–170 ± 60[b]
Fiais	6870 ± 220	cal BC 6220–5380	7330–8160	70 ± 75
Buraca Grande	6790 ± 210	cal BC 6070–5320	7270–8020	–250 ± 140[b]
Alcalar	5640 ± 100	cal BC 4720–4270	6220–6660	410 ± 40
Olelas	4400 ± 45	cal BC 3320–2910	4860–5270	–70 ± 110[b]
Leceia	4160 ± 55	cal BC 2890–2580	4530–4840	–160 ± 40
Pedra Escorregadia	3990 ± 60	cal BC 2840–2300	4250–4780	550 ± 40
Tapada da Ajuda	3000 ± 40	cal BC 1390–1120	3070–3340	40 ± 25
Quinta do Percevejo	2940 ± 60	cal BC 1370–980	2930–3320	100 ± 45
Marcelo	2780 ± 120	cal BC 1370–670	2620–3320	210 ± 40
Quinta do Almaraz	2740 ± 60	cal BC 1020–800	2750–2960	0 ± 50
Quinta do Almaraz	2710 ± 45	cal BC 970–800	2750–2920	–110 ± 40[b]
Marcelo	2700 ± 70	cal BC 1020–770	2720–2970	170 ± 40
Quinta do Almaraz	2660 ± 50	cal BC 920–770	2720–2870	0 ± 45
Rocha Branca	2570 ± 45	cal BC 820–540	2490–2770	20 ± 45
Quinta do Almaraz	2570 ± 60	cal BC 840–420	2370–2790	40 ± 35
Marcelo	2560 ± 100	cal BC 900–410	2360–2840	210 ± 50
Quinta do Almaraz	2510 ± 50	cal BC 800–420	2370–2740	110 ± 25
Rocha Branca	2450 ± 45	cal BC 760–410	2360–2700	–150 ± 45[b]

Table 2 Reservoir effect values for the Portuguese coast. *(Continued)*

Archaeological site	^{14}C age (BP)	cal BC/cal AD[a] (2 σ)	cal BP[a] (2 σ)	ΔR (^{14}C yr)
Quinta do Almaraz	2400 ± 45	cal BC 750–390	2340–2700	110 ± 45
Rocha Branca	2390 ± 45	cal BC 750–390	2340–2700	170 ± 50
Santa Olaia	2300 ± 200	cal BC 830–cal AD 120	1830–2780	200 ± 45
Judiciária (Faro)	2230 ± 40	cal BC 390–200	2150–2340	70 ± 50
Vila Velha de Alvor	2100 ± 140	cal BC 410–cal AD 240	1710–2360	50 ± 70
Loulé Velho	2030 ± 70	cal BC 340–cal AD 130	1820–2290	90 ± 50
Loulé Velho	1750 ± 45	cal AD 140–400	1550–1810	30 ± 45
Poço-Cisterna	1280 ± 40	cal AD 660–860	1090–1290	–40 ± 40
Poço-Cisterna	1140 ± 45	cal AD 780–990	960–1170	360 ± 70
Arrochela	1060 ± 40	cal AD 890–1030	920–1060	50 ± 40
Judiaria	1050 ± 40	cal AD 890–1030	920–1060	40 ± 40
Judiaria	1040 ± 45	cal AD 890–1150	800–1060	–100 ± 50[b]
Judiaria	1020 ± 40	cal AD 900–1150	800–1050	90 ± 40
Trav. Portuguesa	930 ± 40	cal AD 1020–1210	740–930	110 ± 30
Malhão	880 ± 85	cal AD 1020–1280	670–940	210 ± 30
Trav. Portuguesa	870 ± 40	cal AD 1040–1260	700–910	40 ± 40
Castelo de Palmela	870 ± 90	cal AD 1000–1280	670–950	620 ± 70
Judiaria	820 ± 40	cal AD 1060–1280	670–890	140 ± 45
Judiaria	810 ± 40	cal AD 1160–1280	670–790	80 ± 45
Judiaria	640 ± 40	cal AD 1280–1400	550–670	–40 ± 40
Portuguese coast	Modern	AD (1880–1940)		250 ± 25

[a]Calendar dates are given by the intervals, the limits of which, rounded off to the nearest multiple of 10, correspond to the lower and upper limits of extreme intervals of the calibrated ^{14}C dates.

[b]ΔR values of reduced reliability due to the fact that the marine samples were made up of shells collected in an estuarine system with a strong content of brackish water (Vale Romeiras) or of a mixture of shell species where the existence of individuals of different ages cannot be discarded (Buraca Grande); concerning Olelas and Quinta do Almaraz (ΔR= –110 ± 40), the contemporaneity between the samples from different reservoirs is not secure; and, finally, the marine sample from Rocha Branca (ΔR = –150 ± 45) was made up of *Ostrea*, which usually gives an anomalous result.

ΔR values range from 940 ± 50 to –160 ± 40 ^{14}C yr, if data of reduced reliability are excluded. A very similar situation occurs at the northern coast of California, where results range from 870 ± 90 to –170 ± 90 ^{14}C yr (Ingram 1998). This considerable variation suggests a significant fluctuation in the strength of the Portuguese coastal upwelling, which may be the result of fluctuations in latitudinal migration of the subtropical front or of the North Atlantic Oscillation (the strength of northerly and northwesterly winds depends on these factors) or of the summer insolation (increase in summer insolation results in stronger sea breezes that enhance the northerly component of the wind).

If the ΔR data determined for the Portuguese coast are plotted against time (Figure 2), 5 peaks can be observed, namely at 7810 ± 90, 5640 ± 100, 3990 ± 60, 1140 ± 45, and 870 ± 90 BP (8.42–8.98, 6.22–6.66, 4.25–4.79, 0.96–1.17, and 0.67–0.95 cal kyr BP, respectively). These ΔR values are significantly higher than the modern value (250 ± 25 yr), while the remaining ones are lower. There are 3 hypotheses that may explain those peaks: i) they are outliers; ii) they reflect a very strong upwelling; or iii) they are correlated with Bond events (those high values may be due to the huge amounts of ^{14}C-depleted fresh water from ice sheets—"many thousands of years of stored precipitation," following Teller et al. [2002]—that were injected in the North Atlantic at high latitudes). Further detailed research is needed to validate any of these hypotheses.

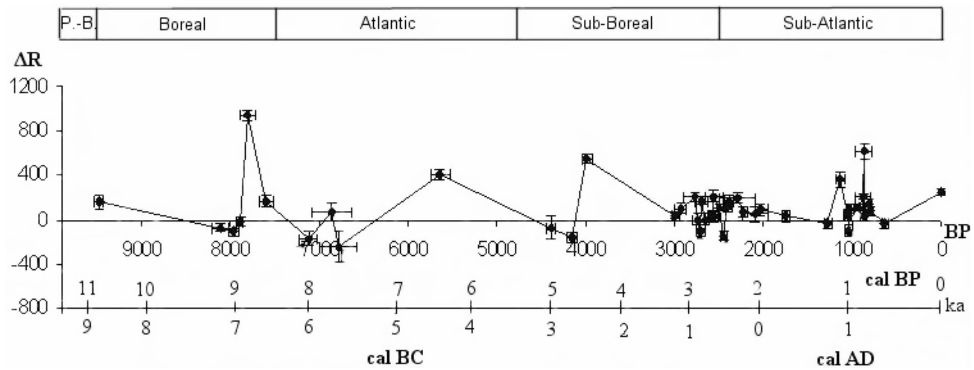

Figure 2 The variability in ocean reservoir effect off the Portuguese coast during the Holocene. ΔR (±1 σ) values are plotted versus terrestrial ^{14}C ages (±1 σ).

The other ΔR values are certainly related to the strength of the coastal upwelling prevailing at the corresponding time. However, as we mention above, the "old wood effect" problem may apply for some of our dated charcoal samples, which may explain the low or negative ΔR values. Nevertheless, 2 associated terrestrial samples (see Table 1) from Leceia (1 of charcoal, 1 of bones) were ^{14}C dated, and the results are not statistically different; the ΔR value is negative (ΔR = –160 ± 40 ^{14}C yr). From Olelas, Quinta do Almaraz (at 2710 ± 45 BP), and Judiaria (at 1040 ± 45 BP and 640 ± 40 BP), only 1 sample of bones from each site (as representative of the terrestrial biosphere in the pair) was dated and the calculated ΔR values are also negative. Two associated samples of terrestrial material (bones and charcoal) from Tapada da Ajuda, Quinta do Almaraz (2740 ± 60 BP), and Vila Velha do Alvor were also dated. The results were statistically similar for each pair, and the calculated ΔR values were positive, although low. All this suggests that the old wood effect problem was probably not very important for the ^{14}C dating of the sampled Portuguese archaeological contexts, and low or negative ΔR values correspond with a weak, or even nonexistent, coastal upwelling off the Portuguese coast.

Looking at the values in Table 2 (and Figure 2) some other inferences can be drawn:

1. During the Preboreal, an upwelling regime may have occurred along the Portuguese coast (see ΔR value for Magoito).
2. During the Boreal cold climate, a weak or nonexistent coastal upwelling can be assigned to the Portuguese coast (negative ΔR values).
3. Four values for ΔR were obtained in the Atlantic period. Nevertheless, 2 of them are less reliable (see Table 1) since in one case (Vale Romeiras) the marine samples came from shells collected in an estuarine system with a strong content of brackish water, and in the other case (Buraca Grande) from a mixture of shell species where the existence of individuals of different ages cannot be discounted. The remaining 2 values (from S. Julião II and Fiais) suggest an existing coastal upwelling, perhaps weaker than the modern one.
4. Between the beginning of the Subboreal and 4000 BP, only 1 ΔR value was obtained. The negative value suggests that a weak or nonexistent coastal upwelling prevailed during this period.
5. Between 4000 and 3000 BP, no ΔR values were determined for the Portuguese coast, if we exclude the value for Pedra Escorregadia, i.e. one of the peaks referred to above. Nevertheless, pollen diagrams from peat deposits located in the Setúbal-Sines region (SW Portugal) for this time interval indicate favorable conditions for a more sclerophyllous vegetation type than previously existed and for a hiatus in peat accumulation, suggesting a drier and warmer climate

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(Mateus 1992; Mateus and Queiroz 1993). These climatic conditions would favor an enhanced coastal upwelling with corresponding high ΔR values. Thus, the referred ΔR peak (550 ± 40 ^{14}C yr at 3990 ± 60 BP) may be correlated with this supposed enhanced coastal upwelling.

6. From 3000 to ~600 BP, more than 30 ΔR values were determined. These values suggest a weaker upwelling than exists today—the calculated weighted mean for ΔR being 95 ± 15 ^{14}C yr.
7. The modern value of ΔR (250 ± 25 ^{14}C yr) was determined using shells from marine mollusks collected alive along the Portuguese coast between 1886 and 1937 (Soares 1993), i.e. just after the Little Ice Age. Recent research suggests that the Portuguese coastal upwelling regime has weakened since the 1940s (Lemos and Pires 2004).

All these data suggest that during the Holocene, a more dynamic upwelling regime prevailed off the Portuguese coast than had been previously thought and, consequently, the Holocene climate over the Iberian Peninsula may exhibit a significant variability, which agrees with recent studies for the North Atlantic area (Bond et al. 1997, 2001; Broecker 2000; deMenocal 2000; McDermott et al. 2001).

CONCLUSIONS

Reservoir ages can provide information concerning the intensity of coastal upwelling and mixing processes in regions of the ocean strongly influenced by this phenomenon. A record of past reservoir ages is preserved in the ^{14}C ages of contemporary marine and terrestrial material. ^{14}C dating of more than 100 samples of marine shells and associated charcoal or bone from Portuguese archaeological sites with ages spanning the Holocene show that the ΔR values range from 940 ± 50 to –160 ± 40 ^{14}C yr, suggesting significant fluctuations in the strength of Portuguese coastal upwelling. Most of these values are lower than the modern value (250 ± 25 ^{14}C yr). Periods of low ΔR may indicate periods during which rates of upwelling were lower than at present. Although some of these periods are poorly sampled, as are those from the beginning of the Holocene until the end of the Atlantic, the few ΔR results suggest an upwelling of weak intensity or, at the least, one that was less strong than it is today. The time frame from 3000 to ~600 BP—a well-sampled period including more than 30 ΔR values with a weighted mean of 95 ± 15 ^{14}C yr—seems also to be a period of upwelling lower than at present. Conversely, between 4000 and 3000 BP, we obtained only 1 ΔR value that is higher than the modern one, suggesting a period of higher coastal upwelling along the Portuguese coast. All these data suggest that the Portuguese coastal upwelling exhibits a significant variability during the Holocene, which may be coupled with climate variability over the Iberian Peninsula.

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