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Evidence for Temporal Fluctuations in Marine Radiocarbon Reservoir Ages in the Santa Barbara Channel, Southern California

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Differences in the ^{14}C ages of closely associated marine shell and carbonized plant material from stratified archaeological deposits on San Miguel Island, California, suggest Holocene (10,000–present) fluctuations in marine ^{14}C reservoir ages. These fluctuations coincide with $\delta^{18}O$ and $\delta^{13}C$ shifts measured in *Mytilus californianus* shells from the same stratigraphic contexts and general atmospheric/oceanic circulation models for the region. Based on these data we make three primary observations: (1) significant changes appear to have occurred in the radiocarbon reservoir during the Holocene; (2) these fluctuations appear to correlate with regional oceanographic changes; and (3) high resolution ^{14}C dating of marine shells may require different ΔR values for different periods of time.

Keywords: SOUTHERN CALIFORNIA BIGHT, CALIFORNIA CHANNEL ISLANDS, RADIOCARBON DATING, RESERVOIR EFFECT, PALEOCLIMATE, EL NIÑO, UPWELLING.

Introduction

Radiocarbon dating is the primary method of defining chronologies for cultural and environmental changes over the past 40,000 years. In many coastal regions, environmental fluctuations seem to be closely correlated with shifts in human adaptations. Establishing such correlations, however, requires relatively precise dating. Charcoal and marine shell are the principal materials used to obtain radiocarbon assays on coastal archaeological and paleontological deposits. Two fundamental assumptions underlie the radiocarbon technique: (1) the initial ^{14}C content of all samples of the same age is the same; and (2) the radiocarbon content of samples is not altered in the post-depositional environment. There are inherent problems associated with all datable materials depending upon geographical and depositional contexts (Dean, 1978; Arundale, 1981; Schiffer, 1986; Hedges & Van Klinken, 1992). Recognizing sources of variability in the ^{14}C content of all materials and developing reliable methods for correcting disparities are necessary for the comparability of radiocarbon dates between archaeological and paleontological chronologies.

Marine shell is the most abundant and well-preserved datable material in archaeological deposits along the California coast. Indeed, the predominant material used for radiocarbon dating prehistoric midden deposits is marine shell (Breschini, Haversat & Erlandson, 1996). Globally, marine shell can have radiocarbon ages up to 1000 years older than the

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actual (calendar) age of the shell (Taylor, 1987). This is due, in part, to the slow mixing of deep ocean water worldwide, leaving the marine radiocarbon reservoir depleted in ^{14}C relative to the atmosphere (Broecker & Peng, 1982). The apparent ^{14}C age of the water is incorporated into the carbonate of marine mollusc shells during growth. Large-scale variations in global ^{14}C reservoir ages are corrected with a model of oceanic circulation (Stuiver & Pearson, 1986; Stuiver, Pearson & Braziunas, 1986; Stuiver & Braziunas, 1993).

Regional differences (denoted as ΔR) in the radiocarbon age between sea-surface water and average surface water occur due to local anomalies in ocean circulation (i.e. upwelling). ΔR is the difference between a particular region and the average world ocean, which has an average reservoir age of 400 years (MacFadgen & Manning, 1990). ΔR values are determined for a particular geographical region by radiocarbon dating ‘‘prebomb’’ mollusc shells of known age (Berger, Taylor & Libby, 1966; Robinson & Thompson, 1980; Taylor, 1987; Ingram & Southon, 1997). Along the coast of California, upwelling of ^{14}C-depleted deep oceanic water, originating in the North Atlantic over 1000 years earlier, dilutes the concentration of radiocarbon during spring and summer months. Based on the analysis of historical prebomb shell samples, the ΔR value generally used for the entire coast of California is 225 ± 35 years (Berger, Taylor & Libby, 1966; Robinson & Trimble, 1981; Stuiver, Pearson & Braziunas, 1986). Ingram & Southon (1997) have recently refined reservoir age estimates for eastern Pacific waters based on prebomb mollusc shell ^{14}C measurements. These reservoir estimates are more constrained spatially and show an increasing trend in ΔR from southern (220 ± 40) to northern (290 ± 35) California. The ΔR for the Santa Barbara Channel region is 233 ± 60, close to the average for the coast of California (Ingram & Southon, 1997).

The implicit assumption made when using regional corrections (ΔR) is that the radiocarbon reservoir in any given region has remained stable through time. However, oceanic circulation in the Santa Barbara Channel region is complex (Hickey, 1992; Browne, 1994; Engle, 1994) and has apparently fluctuated during the Holocene (Pisias, 1978, 1979; Dunbar, 1983; Glassow *et al.*, 1994; Ingram & Kennett, 1995). These fluctuations in ocean circulation would have had a direct impact on the marine radiocarbon reservoir. In this paper, we report preliminary ^{14}C data which define temporal shifts in ΔR between 9250 and 3200 BP in the Santa Barbara Channel region. The marine ΔR variations are determined with ^{14}C measurements of marine shell and charcoal pairs from finely stratified archaeological deposits at Daisy Cave (SMI-261) and Cave of the Chimneys, located on San Miguel Island (Figure 1). In addition, stable O and C isotopic measurements of historical and archaeological shells, from the same stratigraphic contexts, are used to support the radiocarbon results. The methods used in this study should be of use in other regions where temporal shifts in the radiocarbon reservoir undoubtedly occurred.

Oceanography of the Santa Barbara Channel

Regional ocean circulation has been recognized to influence the ^{14}C content, particularly in areas where intense upwelling occurs. Contemporary oceanographical circulation in the Santa Barbara Channel region is complex and a number of small and large-scale phenomena can potentially have an impact on the radiocarbon reservoir (Winant & Bratkovich, 1981). In general, the Santa Barbara Channel is influenced by two major current systems (Figure 2): (1) the southward flow of the cold, low salinity California current; and (2) the relatively warm, saline northward-flowing California counter-current (Hickey, 1992; Browne, 1994). The ^{14}C-depleted California current and associated southern California Eddy are the dominant influence along the southern California Bight, including the Santa Barbara Channel region (Wickham, 1975). However, the California counter-current transports ^{14}C-rich equatorial water along the southern California coast. As it moves north it interleaves with the California current and the California Eddy, eventually bifurcating. One branch travels north between the Santa Barbara mainland and the northern Channel Islands and the other runs south of the islands. In the Santa Barbara Channel, the counter-current dominates during the summer and early fall and sometimes surfaces during the winter months. This northward flow slows during the spring.

The localized upwelling of Pacific deep water along the California coast during the spring and summer months is driven by temperature differences between air masses over land and water (Dorman & Palmer, 1981; Bakun, 1973, 1990). Strong southerly winds are generated during these months as air masses over western North America heat up relative to air masses over the Pacific. Near-shore waters are transported offshore and replaced by cold, nutrient-rich, Pacific deep water. Upwelling close to the coast can decrease water temperatures in portions of the California current below 8°C (Bernal & McGowan, 1981; Brink, 1983; Huyer, 1983; O’Brien, 1983; Mooers & Robinson, 1984).

Fluctuations in upwelling intensity along the southern California Bight are generally the result of (1) fluctuations in summer insolation (Bakun, 1990; van Geen *et al.*, 1992; van Geen & Husby, 1996), or (2) El Niño/Southern Oscillation (ENSOs) events (McGowan, 1984; Rassmusson, 1984; Ramage, 1986). Increases in summer insolation result in warmer air masses over western North America, increased southerly winds and more intense upwelling along the coast. Decreases in summer insolation are associated with decreases in the intensity of upwelling. ENSOs are

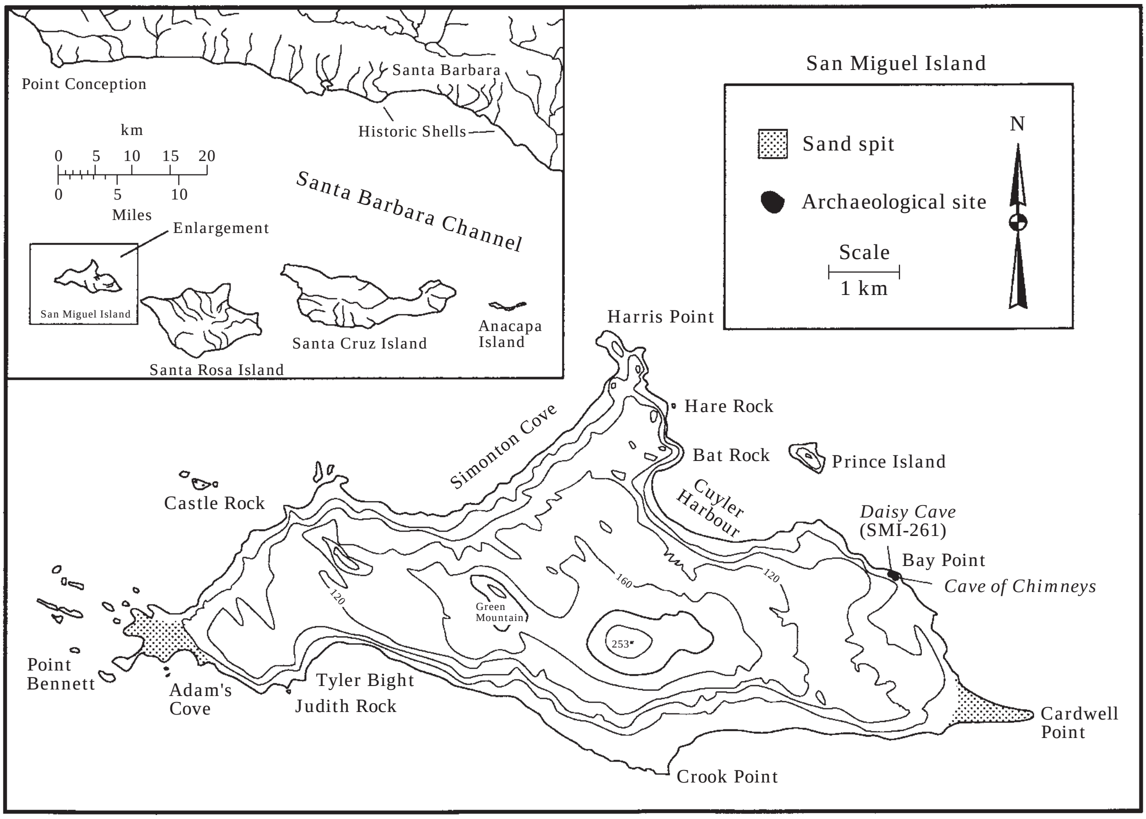

Figure 1. Map of San Miguel Island. Archaeological shell and charcoal samples were collected from SMI-261 (Daisy Cave) and Cave of the Chimneys, located on the north-eastern shore of San Miguel Island. Inset: Map of the Santa Barbara Channel and northern Channel Islands. Historical *Mytilus californianus* shells were collected live from the Santa Barbara coast in 1936.

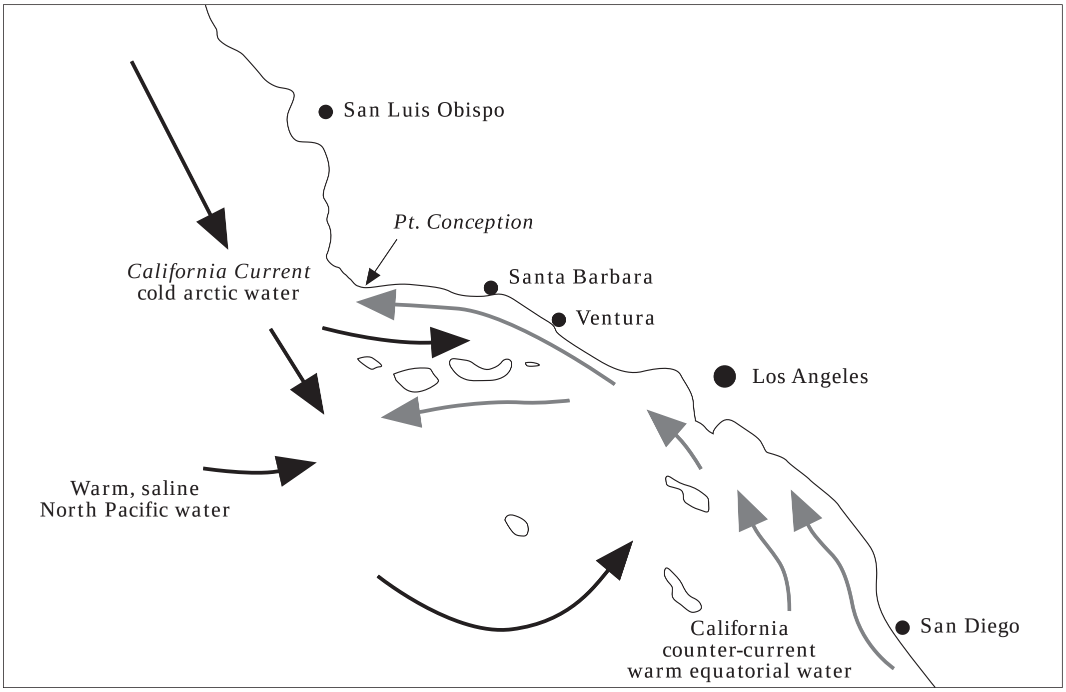

Figure 2. Map of California coast indicating the primary offshore current systems (after Browne, 1994).

driven by oceanic and atmospheric anomalies in the equatorial Pacific causing an eastward movement of warm water that displaces cold water and reduces upwelling along the coast of California. During the El Niño of 1982–1983 sea-surface temperatures along the southern and central coast of California were elevated throughout the annual cycle. During this event, upwelling of cool nutrient rich water was reduced, causing low marine productivity.

Reconstructing the history of oceanic circulation patterns, paleotemperatures, climate, and human responses along the southern California coast has been a major focus of scholars. Given its geographical location, the Santa Barbara Channel region is sensitive to short and long-term climatic change (Pisias, 1978, 1979; Dunbar, 1983; Koerper *et al*., 1985; Arnold & Tissot, 1993; Glassow *et al*., 1994). These changes in ocean circulation must be considered and accounted for when correcting radiocarbon dates on marine shell for this region. In order to assess changes in ΔR over the past several thousand years in the Santa Barbara Channel region, we have collected closely associated charcoal-shell pairs from two archaeological sites on San Miguel Island. Radiocarbon differences between charcoal (reflecting atmospheric ^{14}C) and shell (reflecting oceanic ^{14}C) should allow the assessment of changes in the ocean ^{14}C reservoir over the past 10,000 years.

Methods

Archaeological and historical samples

Shell and charcoal samples were collected from SMI-261 (Daisy Cave) and Cave of the Chimneys, two finely stratified shell midden deposits on the north-east coast of San Miguel Island (Figure 1). The archaeological deposits at Daisy Cave and Cave of the Chimneys provide extremely well-preserved shell and charcoal samples spanning much of the Early and Middle Holocene (Erlandson, 1991, 1994; Erlandson *et al*., 1996). Compared with archaeological sites on the mainland coast, these midden deposits have not been disturbed by burrowing animals. Both deposits were excavated in naturally occurring cultural strata. Shell and charcoal samples were taken in close stratigraphic proximity. A variety of molluscan species were radiocarbon dated, including red abalone (*Haliotis rufescens*), black abalone (*Haliotis cracherodii*), California mussel (*Mytilus californianus*), and black turbans (*Tegula funebralis*). Small charred twigs were preferentially selected to avoid the ‘‘old wood’’ problem (Blong & Gillespie, 1978; Schiffer, 1986), but in some cases the use of large pieces of charcoal could not be avoided.

Historical *Mytilus californianus* shells were provided by the Santa Barbara Museum of Natural History. These shells were collected live from the mainland coast of Santa Barbara in 1936 (Figure 1). Two of these shells were radiocarbon dated for comparative purposes and stable isotopic measurements were done through the growth of the shell. Radiocarbon measurements of these historic shells were averaged with others for the region to derive the historic ΔR value (233 ± 60) for comparative purposes (Ingram & Southon, 1997).

Radiocarbon Analyses

Organic remains (twigs and charcoal) were selected for radiocarbon dating at the Center for Accelerator Mass Spectrometry (CAMS) at the Lawrence Livermore National Laboratory (Davis *et al*., 1990). Prior to analysis, organic carbon samples (1–2 mg) were rinsed sequentially in weak acid (1N hydrochloric acid) and base (1N sodium hydroxide), ending with a weak acid rinse to remove CO_2 absorbed during the alkaline bath. This procedure removes any adhering organic acids and secondary carbonate. The samples were then rinsed in deionized water three times, and oven-dried. Organic carbon samples were combusted in quartz tubes with cupric oxide wire at 900 °C for 3 h to generate carbon dioxide (CO_2). Carbonate samples (8–10 mg) processed at the Lawrence Livermore National Laboratory were evacuated in a 10 ml vacutainer, then reacted with 0.5 ml phosphoric acid to release CO_2. In both cases the evolved carbon dioxide was reduced to graphite using a Cobalt catalyst powder and H_2 gas (Vogel *et al*., 1987).

Beta Analytic dates are based on conventional (LSC) radiocarbon dating. At Beta Analytic, the external surfaces of the shell samples were etched with dilute HCL to remove portions of the shell most susceptible to contamination. The shell samples submitted were unusually well preserved, however, with little or no evidence for weathering or contamination. After pretreatment the remaining shell from each sample was dissolved in a second acid wash to produce CO_2. The charcoal samples were crushed and dispersed in deionized water and submitted to successive HCL-NAOH-HCL washes to eliminate carbonates, remove mechanical contaminants and secondary organic acids and neutralize the solution. According to correspondence from Beta Analytic, benzine synthesis and counting proceeded normally for all samples.

All radiocarbon dates are $^{13}C/^{12}C$ adjusted according to Stuiver & Polach (1977) to correct for mass-dependent fractionation. ΔR determinations were calculated by converting the measured wood ^{14}C ages from each stratigraphic level into equivalent marine model ages (figure 15; Stuiver & Braziunas, 1993). The corrected ^{14}C age of the wood was then deducted from the radiocarbon age of shell for the same level to yield ΔR.

Oxygen and carbon isotopic analysis

Studies of modern marine molluscs from known environments indicate that O and C isotopic analysis is an effective method for reconstructing: (1) sea-surface temperature (Epstein, *et al.*, 1951, 1953; Shackleton, 1969, 1973; Killingley, 1981; Glassow *et al.*, 1994); (2) changes in water salinity (Kennett & Voorhies, 1995, 1996); and (3) fluctuations in upwelling (Killingley & Berger, 1979; Wefer & Killingley, 1980; Glassow *et al.*, 1994). The ratio of ^{18}O to ^{16}O is highly sensitive to changes in water temperature and salinity and is preserved in calcareous fossils such as mollusc shells (Wefer & Berger, 1991). Fluctuations in δ^{13}C are thought to reflect changes in upwelling and overall marine productivity (Killingley & Berger, 1979). Analysis of incremental samples taken along the direction of shell growth enables the reconstruction of O and C isotopic ratios and hence annual fluctuations in water temperature, salinity and upwelling intensity through the life of a mollusc.

Well-preserved archaeological *Mytilus californianus* shells were selected from the same stratigraphical levels as the shell and charcoal pairs. The methods for cleaning and sampling California mussel shell (*M. californianus*) incrementally is detailed in Killingley & Berger (1979) and Glassow *et al.* (1994). Briefly, all shells were cleaned and rinsed with deionized water to remove visible organic material, including the periostracum covering the historical samples. The outer surfaces of the shells were etched using a dilute solution of HCl (0.5 M) to remove any diagenetically altered carbonate (Bailey, Deith & Shackleton, 1983). Shells were sectioned longitudinally to expose the boundary between the exterior prismatic layer (calcite) and the interior, aragonitic nacreous layer (Glassow *et al.*, 1994). Calcite samples were extracted from the exterior prismatic layer of the shell in 2 mm increments along the shell's growth axis using a 0.5 mm drill. Powdered calcite samples (~0.3 mg) were heated at 375°C, under vacuum, for 1 h to remove organic compounds. After cooling to room temperature, the samples were reacted with orthophosphoric acid at 90°C (using a Fairbanks auto-sample device). The O and C isotopic ratios of the evolved CO_2 were measured using mass spectrometry (Finnegan/MAT251-Mass Spectrometer).

All measurements are expressed in δ notation as a deviation from an internationally accepted standard, PeeDee Belemnite (PDB), a carbonate fossil from South Carolina (Herz, 1990). The precision of the O and C isotopic ratios is 0.1‰. More negative δ values indicate higher proportions of the lighter ^{16}O and ^{12}C isotopes compared to the heavier ^{18}O and ^{13}C isotopes.

Results and Discussion

Radiocarbon ages for shell and charcoal samples from Daisy Cave and Cave of the Chimneys are listed in Table 1, along with calculated ΔR values. These data suggest that ΔR values in the Santa Barbara Channel region were not constant between 9470 and 3460 BP. Shifts in ΔR of up to 650 years occur between 9470 and 8910 BP, fluctuating from −360 (9470 BP) to 290 (9070 BP) and back to −10 (8910 BP). This perturbation is followed by an increase in ΔR to 290 (8440 BP). ΔR values show less variation between 8440 and 4310 BP, averaging 210 ± 80 and fluctuating ~230 years between 310 and 80 years. On average, ΔR values between 8440 and 4310 BP are slightly less than the average ΔR (225 ± 35) value currently used for the Santa Barbara Channel Region and smaller than the calculated ΔR based on two historic shells collected from the coast of California in 1936 (233 ± 60). ΔR values at 3560 and 3460 BP are significantly smaller (−50 and −30) than the current value used for the region (225 ± 35).

Maximum, minimum and average δ^{18}O measurements of *Mytilus californianus* shells from the same stratigraphical levels as the shell and charcoal samples appear in Table 2. ΔR values for each stratum are plotted with δ^{18}O measurements in Figure 3. Between 9470 and 9070 BP δ^{18}O fluctuated 0.981‰ from 1.199 (9470 BP) to 0.218‰ (9070 BP). At 8910 BP average δ^{18}O values shift back to a more positive position (1.067‰). This perturbation correlates with a negative shift in ΔR. With the exception of a positive jump at 3460 BP (1.134‰), there was a gradual negative shift in δ^{18}O of 0.835‰ from 1.099 to 0.264‰ between 8440 and 3460 BP.

Maximum, minimum and average δ^{13}C measurements are plotted relative to ΔR values in Figure 4. Between 9470 and 8910 BP there was a sharp increase in δ^{13}C from −0.013 to 1.024‰. This increase in δ^{13}C occurs as ΔR values fluctuate from −360 to 290 years and back to −10 years. Starting at 8910 BP the average δ^{13}C decreases from 1.024 to 0.434‰ and then remains relatively stable until 3460 BP, averaging ~0.267‰. This parallels a period of relative stability in ΔR values.

Paleoceanographic implications

The radiocarbon ages of shell and charcoal from the same strata at Daisy Cave and Cave of the Chimneys fluctuate significantly between 9470 and 3460 BP. This variation may be due to changes in the marine radiocarbon reservoir (ΔR) that occurred in the Santa Barbara Channel during this interval. Assuming that the shell and charcoal samples are contemporary and the charcoal dates are accurate, we make five primary observations: (1) large-scale fluctuations occurred in the radiocarbon reservoir (~650 years) between 9470 and 8910 BP; (2) between 8910 and 4310 BP, ΔR values average 210 years and remain relatively stable; (3) at 3560 and 3460 BP, ΔR values decrease significantly (−50 and −30); (4) ΔR values between 8910 and 4310 BP were on average (210) slightly less than the ΔR value currently used for the Santa Barbara Channel region (225 ± 30); and (5) ΔR values at 3560 and 3460 BP are significantly less than the current ΔR value used in the region. These observations

Table 1. Shell and charcoal dates from SMI-261 (Daisy Cave) and Cave of the Chimneys

Location	Sample number	Material	^{14}C age	Equivalent marine model age	ΔR
Col. E-6, Str. A3	CAMS-9095	Charred twig	3110 ± 60	3460 ± 60	—
Col. E-6, Str. A3	Beta-15619	Red abalone	3430 ± 90	3430 ± 90	− 30
Col. E-6, Str. A1	CAMS-8864	Charred twig	3220 ± 70	3560 ± 80	—
Col. E-6, Str. A1	Beta-49997	Blk. abalone	3510 ± 80	3510 ± 80	− 50
Chim. B: 15-20	CAMS-14364	Charcoal	3930 ± 60	4310 ± 60	—
Chim. B: 15-20	CAMS-12454	Shell	4430 ± 60	4430 ± 60	120
Chim. B: 35-40	CAMS-14367	Charcoal	3940 ± 60	4310 ± 60	—
Chim. B: 35-40	CAMS-12455	Shell	4560 ± 60	4560 ± 60	250
Col. E-6, Str. C	CAMS-8862	Charred twig	6000 ± 70	6420 ± 70	—
Col. E-6, Str. C	Beta-52359	CA mussel	6500 ± 80	6500 ± 80	80
Col. E-6, Str. E1	CAMS-8866	Charred twig	7810 ± 60	8150 ± 60	—
Col. E-6, Str. E1	Beta-15621	Blk. abalone	8460 ± 100	8460 ± 100	310
Col. E-6, Str. E4	CAMS-8865	Charred twig	8040 ± 60	8440 ± 60	—
Col. E-6, Str. E4	Beta-15622	Blk. abalone	8730 ± 120	8730 ± 120	290
Col. E-6, Str. F1	CAMS-8867	Charred twig	8600 ± 60	8910 ± 60	—
Col. E-6, Str. F1	Beta-15623	CA mussel	8900 ± 120	8900 ± 60	− 10
Col. E-6, Str. F3	CAMS-8863	Charred twig	8810 ± 80	9070 ± 80	—
Col. E-6, Str. F3	Beta-49948	CA mussel	9360 ± 90	9360 ± 90	290
Cave A, IIc	CAMS-14366	Charred twig	9180 ± 60	9470 ± 60	—
Cave A, IIc	CAMS-12456	CA mussel	9110 ± 90	9110 ± 90	− 360

All samples are from Daisy Cave except for Chim B: 15–20 and Chim B: 35–40. Beta Analytic dates are based on conventional (LSC) radiocarbon dating. CAMS dates are based on accelerator mass spectrometry. All radiocarbon dates ^{13}C/^{12}C adjusted according to Stuiver & Polach (1977). The measured charcoal ^{14}C ages were converted to equivalent marine model ages using the method of Stuiver & Braziunas (1993, Figure 15) and then deducted from the ^{14}C age of shell from the same stratigraphic level to yield ΔR.

Table 2. Maximum, minimum and average δ^{18}O and δ^{13}C measurements of historic Mytilus californianus *shells and archaeological shells from Daisy Cave (SMI-261) and Cave of the Chimneys*

Sample number	Site	Unit	Level	δ^{18}O	Max.	Min.	δ^{13}C	Max.	Min.
MC11	SMI-261	D5	A3	0.264	0.814	− 0.267	0.434	0.989	− 0.141
JE23	SMI-261	D5	A1	1.134	1.734	0.001	0.048	0.837	− 0.655
JE30	Chim	B	35–40 cm	0.429	1.077	− 0.330	0.342	0.872	− 0.346
JE20	SMI-261	D6	C	0.838	1.206	0.208	0.078	0.396	− 0.104
MC10	SMI-261	D6	E1	0.935	1.451	0.351	0.424	0.935	− 0.385
JE21	SMI-261	D6	F1	1.099	1.496	0.730	1.024	1.713	0.202
JE11	SMI-261	E6	F2	1.067	1.556	0.055	0.718	1.299	− 0.084
JE10	SMI-261	E6	F3	0.218	0.638	− 0.250	0.261	1.158	− 0.293
JE31	SMI-261	CA	IIc	1.199	1.608	0.675	− 0.013	0.279	− 0.510

should be considered preliminary until they have been reproduced and higher temporal resolution is obtained.

Considerable variation in the radiocarbon reservoir (ΔR), δ^{18}O and δ^{13}C values between 9470 and 8910 BP suggest either; (1) significant fluctuations in the strength of coastal upwelling, or (2) rapid changes in the source of Santa Barbara Channel waters. Based on a radiocarbon chronology of varved sediments in Poland, Goslar *et al.* (1995) have suggested that the published ^{14}C calibration curves may require adjustment around 8800–9000 ^{14}C BP. Alteration of calculated global reservoir ages would affect the amplitude of calculated ΔR, but fluctuations in δ^{18}O and δ^{13}C suggest that changes in oceanographic circulation in the Santa Barbara Channel did occur. Sancetta *et al.* (1992) argue, based on lithology, diatoms and pollen in a core located 120 km off the coast of southern Oregon, that patterns of summer upwelling were well developed by 9000 BP, but there were years when winds

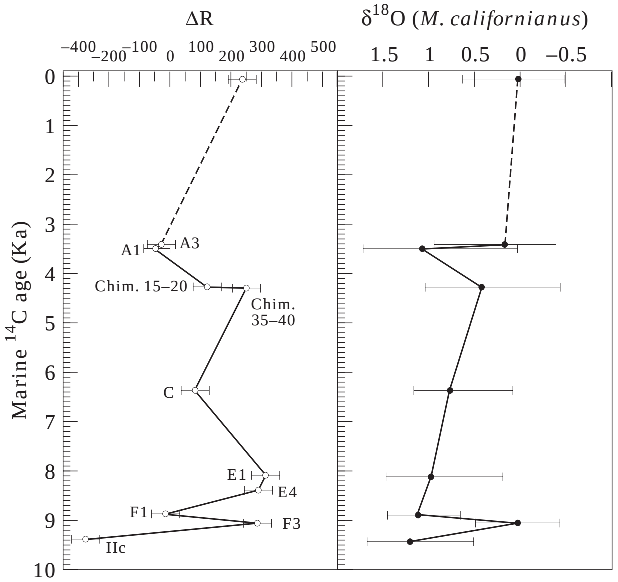

Figure 3. ΔR values derived from shell and charcoal pairs from Daisy Cave (SMI-261) and Cave of the Chimneys plotted against δ^{18}O values of *Mytilus californianus* shells from the same stratigraphic levels.

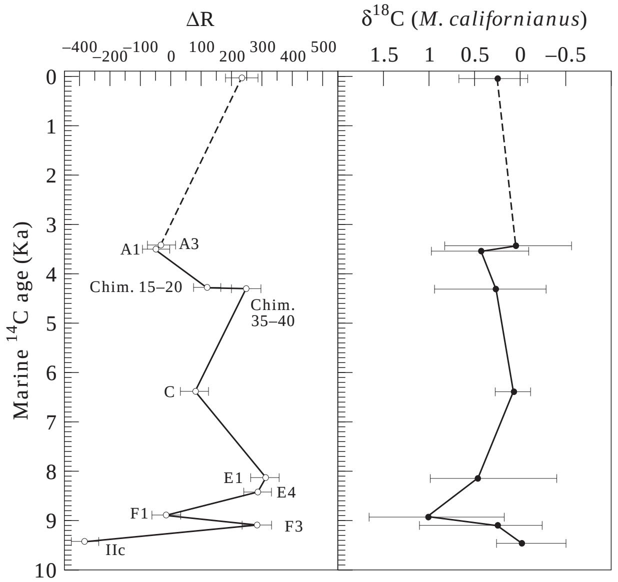

Figure 4. ΔR values derived from shell and charcoal pairs from Daisy Cave (SMI-261) and Cave of the Chimneys plotted against δ^{13}C values of *Mytilus californianus* shells from the same stratigraphic levels.

were too weak to support summer upwelling. Our data are consistent with these findings, but there is some evidence for persistent coastal upwelling during the early Holocene off the California coast (Anderson, Hemphill-Haley & Gardner, 1987). Alternatively, large-scale fluctuations in ΔR during this interval may have resulted from changes in the source water entering the Santa Barbara Channel region. Ingram & Kennett, J. (1995) suggest that ^{14}C age differences in planktonic-benthic foraminiferan pairs from a core in the Santa Barbara region reflect changes in the age and thus the source of intermediate waters entering the Santa Barbara Basin.

The near stability of ΔR values between 8440 and 4310 BP, on average slightly below contemporary levels, suggests that oceanic circulation was similar to today, and seasonal upwelling persisted through this interval. δ^{13}C measurements of *M. californianus* shells from the same stratigraphical levels are consistent with this stability and the characterization of Anderson, Hemphill-Haley & Gardner (1987), who argued that upwelling along the California coast has remained strongly seasonal since the late Pleistocene. Smaller variations during this interval are undoubtedly related to changes in upwelling, possibly in response to the influence of El Niño/Southern Oscillation or other short-term changes in coastal upwelling. Other short-term fluctuations in the radiocarbon reservoir caused by these influences undoubtedly occurred, but the temporal resolution of our study does not allow us to comment on their relative influence.

The decrease in ΔR values between 8440 and 3460 BP is consistent with general atmospheric circulation models predicting greater summer insolation in the northern hemisphere during the early Holocene than during the late Holocene (Heusser, Heusser & Peteet, 1985; COHMAP, 1988). Van Geen *et al.* (1992) argue that the decrease in summer insolation through the Holocene translates to decreases in coastal upwelling during this interval. Evidence for this is a decrease in the ratio of Cd/Ca in planktonic foraminifera in a core, spanning the last 4000 years, taken inside San Francisco Bay. Declining ΔR values between 8440 and 3460 BP are consistent with this characterization. The negative shift in δ^{18}O of $\sim$1.2‰ through the Holocene is also consistent with this model and evidence for cooler sea-surface temperatures during the middle Holocene (Glassow *et al.*, 1994). Prior to 6000 BP much of the shift in δ^{18}O is related to changes in the O isotopic composition of the world ocean related to sea-level rise (Fairbanks, 1989). However, the negative shift in δ^{18}O continues after the isotopic composition of the world ocean stabilizes (Figure 3).

Implications for correcting reservoir ages in prehistoric marine shell

Archaeologists continue to ask more complicated questions about prehistoric human behaviour, particularly how and why it changed through time. These questions require accurate radiocarbon dates so that archaeological patterns can be compared within and between time periods. Over the past 20 years, the reliability of marine shell for radiocarbon dating archaeological deposits has increased considerably. Dating historical shell from known contexts has been an extremely successful method for determining and refining regional differences in ΔR (Berger, Taylor & Libby, 1966; Robinson & Thompson, 1981; Ingram & Southon, 1997). For some regions at least, ΔR values derived from historical shell may closely reflect ΔR values through the Holocene (Southon, Nelson & Vogel, 1990).

In the Santa Barbara Channel, where oceanic circulation is complex and sensitive to short- and long-term change, we argue that correcting fluctuations in the radiocarbon reservoir is not straightforward. Radiocarbon dating of paired shell and charcoal samples from Daisy Cave and Cave of the Chimneys suggests that ΔR values fluctuated through the Holocene Epoch. Between 9470 and 8910 BP, ΔR values are highly variable, as are δ^{18}O and δ^{13}C measurements of *M. californianus* shells from the same stratigraphical levels. Based on this observation we argue that the ΔR value currently used for the Santa Barbara region is unreliable for correcting marine shell dates that occur during this interval. If marine shell dates fall within this interval we suggest using δ^{18}O and δ^{13}C measurements of stratigraphically associated shells to characterize the marine environment at the time of deposition. Based on the stability of ΔR values between 8440 and 4310 BP, the current ΔR correction used for the Santa Barbara Channel region may be adequate (225 ± 30). However, this value appears to be too large for correcting dates between 3560 and 3460 BP.

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