

## RESERVOIR AGES IN EASTERN PACIFIC COASTAL AND ESTUARINE WATERS

*B. LYNN INGRAM*

Department of Geography, University of California, Berkeley, California 94720 USA

and

*JOHN R. SOUTHON*

Center for Accelerator Mass Spectrometry, L-397, Lawrence Livermore National Laboratory  
Livermore, California 94551 USA

**ABSTRACT.** We have refined marine reservoir age estimates for eastern Pacific coastal waters with radiocarbon measurements of mollusk shells collected prior to 1950. We have also investigated interspecific variability in  $^{14}\text{C}$  ages for historic and ancient shells from San Francisco Bay.

### INTRODUCTION

Globally, ocean surface waters are depleted in radiocarbon content relative to the atmosphere by an amount equivalent to 400  $^{14}\text{C}$  yr. Regionally the oceans deviate from this value, reflecting variations in upwelling (Stuiver, Pearson and Braziunas 1986), freshwater inflow in coastal regions (Spiker 1980), and interhemispheric variations in atmospheric  $^{14}\text{C}$  content (Stuiver and Braziunas 1993). Knowledge of the value of the regional deviation from the ocean reservoir age (or  $\Delta R$ ) is necessary to accurately calibrate  $^{14}\text{C}$  ages of marine materials. Since the 1950s, determination of  $\Delta R$  values by surface water  $^{14}\text{C}$  measurements has been precluded due to the artificially high  $^{14}\text{C}$  activity in surface waters from nuclear testing. Thus,  $\Delta R$  values in coastal waters must be determined indirectly from  $^{14}\text{C}$  measurements of carbonate shells or other marine materials of known age collected prior to 1950.

Previous  $^{14}\text{C}$  measurements of known-age mollusk shells indicate an average  $\Delta R$  for coastal California of  $225 \pm 15$  yr, for seven analyses (Berger, Taylor and Libby 1966; Robinson and Trimble 1981), corresponding to a significant  $^{14}\text{C}$  depletion. This is attributed to upwelling of "old" Pacific Intermediate Water, driven by a divergence in surface ocean flow patterns created by winds blowing southward along the California coast (Dorman and Palmer 1980; Robinson 1980). Other studies suggest that the  $\Delta R$  values along the California coast are variable, with values as great as 500 yr (Bouey and Basgall 1991). The  $\Delta R$  value has been shown to decrease from  $185 \pm 20$  yr off Mexico (8 analyses), to  $5 \pm 50$  yr in Central American and Equadorean waters (9 analyses), and to increase again to  $190 \pm 40$  yr off Peru and northern Chile (3 analyses; Taylor and Berger 1967).

Due to the small number of samples, and large spatial and possibly temporal variability in upwelling in these coastal areas, more analyses are clearly necessary. So is characterization of the effects of other processes such as freshwater inflow, carbon recycling, and variable growth habits of marine organisms. In this study, we measured the  $^{14}\text{C}$  ages of historically collected mollusk shells from coastal California, Mexico, Central America and Chile to better constrain the modern  $\Delta R$  values in these regions. In addition,  $^{14}\text{C}$  ages of historically collected mollusks, as well as fossil mollusks separated from sediments cored in San Francisco Bay, were used to assess interspecific differences in reservoir ages in modern and ancient estuarine environments.

### METHODS

Modern (pre-bomb) mollusk specimens used in this study were provided by the Museum of Paleontology at the University of California, Berkeley, and the Natural History Museum in Santa Barbara.

Species used in the study are native oysters, clams and mussels (*Ostrea lurida*, *Macoma balthica*, *Mytilus californianus* and *Mytilus edulis*). In most cases, it is uncertain whether these specimens were collected live or not. These species were chosen because they commonly occur in archaeological coastal deposits (shellmounds) and geological sediments along coastal California (Fig. 1). They may also provide information about the causes of interspecific  $^{14}\text{C}$  age differences.

In addition to historically collected material, we separated these same mollusk species from estuarine sediments cored in San Francisco Bay. Mollusks from the same stratigraphic level in the core were  $^{14}\text{C}$ -dated to determine differences in apparent ages between species that might be useful in assessing various processes leading to interspecies differences. This information is also useful in illustrating the range in  $^{14}\text{C}$  ages obtainable from the same stratigraphic level in geological sediments using different carbonate shell material.



Fig. 1. California sampling locations for this study: SB = Stinson Beach; SFB = San Francisco Bay; ES = Elkhorn Slough; PP = Point Pinos; CB = Carmel Bay; PB = Pelican Bay; SBB = Santa Barbara Basin; SP = San Pedro; NBa = Newport Bay; NBe = Newport Beach; DM = Del Mar; MBe = Mission Beach; MBa = Mission Bay.

### Radiocarbon Analysis

Radiocarbon analyses were performed at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory (Davis *et al.* 1990). Shell samples (*ca.* 8 mg of carbonate) were etched with 0.5N hydrochloric acid and rinsed with deionized water. Carbonate samples were placed in a 10-ml vacutainer (disposable blood sample vial), which was evacuated through the rubber stopper using a hypodermic needle. After evacuation to below 20 mtorr, 0.5 ml of phosphoric acid was added to the vacutainer with a syringe, and the sample was hydrolyzed for 30–60 min at 90°C to generate  $\text{CO}_2$ . This was reduced to graphite using hydrogen with a cobalt catalyst (Vogel, Nelson and Southon 1987).  $^{14}\text{C}/^{13}\text{C}$  ratios were measured by AMS, and  $^{14}\text{C}$  ages were determined following the conventions of Stuiver and Polach (1977) and Donahue, Linick and Jull (1990).

TABLE 1.  $^{14}\text{C}$  Ages on Known Age Mollusks

CAMS no.	Sample	Museum no.	Date	Location* (lat./long.)	$\delta^{13}\text{C}\dagger$ (‰)	$\text{D}^{14}\text{C}$ (‰)	$\Delta^{14}\text{C}$ (‰)	$^{14}\text{C}$ age	Model age	$\Delta\text{R}$
<i>San Francisco Bay Estuary</i>										
15700	Mytilus 4	R-1776	1943	Pt. Richmond, San Pablo Bay 38°N, 122.5°W	-2	-107.3 ± 5.9	-101.5 ± 6.2	910 ± 50	477	435 ± 53
15701	Ostrea 1	R-1776	1943	Pt. Richmond, San Pablo Bay 38°N, 122.5°W	0	-89.4 ± 6.7	-83.6 ± 7.0	705 ± 60	477	275 ± 59
15702	Macoma 15	R-1776	1943	Pt. Richmond, San Pablo Bay 38°N, 122.5°W	0	-98.8 ± 9.0	840 ± 80	477 ± 80	477	359 ± 80
8139	Mytilus	--	1939	San Francisco Bay 37.7°N, 122.2°W	-2	-111.5 ± 10.7	-105.2 ± 10.9	950 ± 100	474	476 ± 97
8140	Mytilus 18	--	1939	San Francisco Bay 37.7°N, 122.2°W	-2	-84.9 ± 7.4	-78.5 ± 7.7	710 ± 60	474	238 ± 65
8141	Mytilus 19	--	1939	San Francisco Bay 37.7°N, 122.2°W	-2	-94.4 ± 7.4	-88.1 ± 7.7	800 ± 70	474	322 ± 66
8873	Mytilus 20	--	1939	San Francisco Bay 37.7°N, 122.2°W	-2	-117.0 ± 7.8	-117.0 ± 8.1	1000 ± 70	474	526 ± 71
18486	Macoma 3	R-1670	1899	San Francisco Bay 37.7°N, 122.2°W	-0.79	-88.2 ± 5.3	-82.0 ± 5.7	740 ± 50	467	275 ± 47
<b>Mean</b>							<b>-92.8 ± 42</b>			<b>365 ± 35</b>
<i>Northern California Coast</i>										
16293	Macoma 6	R-1652	1936	Stinson Beach, Marin Co. 37.9°N, 122.7°W	2	-155.4 ± 4.1	-148.7 ± 4.6	1360 ± 40	472	885 ± 39
16295	Mytilus 15	1652	1936	Stinson Beach, Marin Co. 37.9°N, 122.7°W	0	-88.8 ± 5.5	-82.1 ± 5.9	750 ± 50	472	275 ± 48
16296	Ostrea 3	1652	1936	Stinson Beach, Marin Co., CA 37.9°N, 122.7°W	2	-93.3 ± 5.5	-86.6 ± 5.9	790 ± 50	472	315 ± 49
16294	Macoma 12	R-1755	1930	Elkhorn Slough, Monterey Bay, 36.8°N, 121.8°W	2	-102.7 ± 5.4	-97.3 ± 5.8	870 ± 50	467	403 ± 48
18494	Mytilus 12	1775	1939	Point Pinos, Pacific Grove 36.7°N, 121.9°W	-0.2	-85.4 ± 5.9	-79.1 ± 6.2	720 ± 50	474	243 ± 52
18497	Mytilus 16	1774	1939	Carmel Bay, Monterey 36.6°N, 121.9°W	0.17	-82.3 ± 6.0	-75.9 ± 6.3	690 ± 50	474	216 ± 53
<b>Mean (Macoma 6 omitted)</b>							<b>-84.2 ± 3.7</b>			<b>290 ± 35</b>
<i>Santa Barbara Channel</i>										
‡	Mytilus	43190	1936	Santa Barbara 34.6°N, 119.7°W	0.29	-94.6 ± 3.3	-87.9 ± 3.9	800 ± 30	478	320 ± 29
‡	Mytilus	431902	1936	Santa Barbara 34.6°N, 119.7°W	0.13	-87.2 ± 6.3	-80.5 ± 6.6	730 ± 60	478	255 ± 55
16297	Mytilus 9	E-1064	1949	Pelican Bay, Santa Cruz Is. 34.1°N, 119.7°W	0	-72.7 ± 4.8	-62.6 ± 5.2	610 ± 40	482	124 ± 42
<b>Mean</b>							<b>-77.0 ± 7.5</b>			<b>233 ± 60</b>
<i>Southern California Coast</i>										
18503	Ostrea 8	D-7921	1895	San Pedro, Los Angeles 33.7°N, 118.2°W	2.79	-87.0 ± 6.3	-80.4 ± 6.6	730 ± 55	469	263 ± 55
18501	Ostrea 6	E-6358	1948	Newport Bay, Orange Co. 33.6°N, 117.9°W	2	-101.4 ± 5.9	-91.2 ± 6.2	860 ± 50	481	378 ± 53

TABLE 1. (Continued)

CAMS no.	Sample	Museum no.	Date	Location* (lat./long.)	$\delta^{13}\text{C}\dagger$ (‰)	$\text{D}^{14}\text{C}$ (‰)	$\Delta^{14}\text{C}$ (‰)	$^{14}\text{C}$ age	Model age	$\Delta\text{R}$
18502	Ostrea 7	E-6162	1948	Newport Bay, Orange Co. 33.6°N, 117.9°W	1.64	-998.0 ± 0.8	--	49,990 ± 3200	--	--
18500	Ostrea 5	A-3991	1890	Newport Beach, Orange Co 33.6°N, 117.9°W	2.66	-131.0 ± 6.7	123.8 ± 7.0	1130 ± 60	471	657 ± 62
18495	Mytilus 13	A-3991	1890	Newport Beach, Orange Co 33.6°N, 117.9°W	0.27	-82.4 ± 5.9	-75.2 ± 6.2	690 ± 50	471	220 ± 52
16298	Macoma 14	A-3991	1890	Newport Beach, Orange Co 33.6°N, 117.9°W	2	-139.5 ± 4.8	-132.3 ± 5.2	1210 ± 45	471	736 ± 45
18496	Mytilus 14	E-6138	1948	Del Mar, San Diego 32.9°N, 117.3°W	-0.25	-76.7 ± 4.9	-57.4 ± 5.3	560 ± 40	481	82 ± 42
18487	Macoma 10	B-829	1939	Mission Bay, San Diego 32.8°N, 117.2°W	1.64	-76.7 ± 4.9	-70.4 ± 5.3	640 ± 40	474	167 ± 43
18493	Mytilus 8	E-6168	1948	Mission Bay, San Diego 32.8°N, 117.2°W	-0.38	-81.2 ± 5.2	-70.9 ± 5.6	680 ± 45	481	199 ± 45
18488	Macoma 13	R-1655	1938	Mission Beach, San Diego 32.8°N, 117.2°W	2.64	-417.0 ± 3.8	--	4330 ± 50	--	--
18498	Ostrea 2	1655	1938	Mission Beach, San Diego 32.8°N, 117.3°W	2.71	-149.0 ± 5.6	-142.6 ± 5.9	1300 ± 50	473	823 ± 53
<b>Mean (Macoma 13, 14 &amp; Ostrea 2, 5, 7 omitted)</b>							<b>-74.3 ± 4.6</b>			<b>220 ± 40</b>
<i>Gulf of California</i>										
18489	Macoma 16	B-839	1940	Miramar Beach, Guaymas, Mexico 28°N, 111°W	1.82	-101.7 ± 5.9	-95.5 ± 6.2	860 ± 50	475	387 ± 53
18499	Ostrea 4	A-3646	1940	Carmen Is., Baja, Mexico 26°N, 110°W	2.86	-107.3 ± 6.2	-101.0 ± 6.5	910 ± 60	475	436 ± 56
<b>Mean</b>							<b>-98.3 ± 4.5</b>			<b>410 ± 40</b>
<i>Central America</i>										
18491	Macoma 18	S-78	1932	San Jose de Guate, Guatemala 14.0°N, 90.9°W	1.83	-80.8 ± 6.0	-75.6 ± 6.3	680 ± 50	469	208 ± 52
18492	Mytilus 3	R-1659	1938	Gulf of Fonseca, Honduras 13.2°N, 87.6°W	-0.41	-75.8 ± 6.3	-69.4 ± 6.6	630 ± 50	473	160 ± 55
18490	Macoma 17	A-4010	1939	Corinto, Nicaragua 12.5°N, 87.2°W	1.62	-88.5 ± 5.9	-82.2 ± 6.2	740 ± 50	472	272 ± 52
<b>Mean</b>							<b>-75.7 ± 3.7</b>			<b>215 ± 30</b>
<i>Central Chile</i>										
17919 17992	Mytilus 2	R-1763	1939	Valparaiso, Chile 33.1°S, 71.8°W	1.98	-62.4 ± 6.1	-56.0 ± 6.4	520 ± 50	474	43 ± 52
<i>Southern Chile</i>										
17918	Mytilus 1	R-1766	1939	Puerto Natales, Chile 51.7°S, 72.5°W	-2.32	-80.8 ± 4.7	-74.4 ± 5.1	680 ± 40	474	203 ± 41

\*All locations are in California unless otherwise noted

† $\delta^{13}\text{C}$  values shown as single digits are estimated

‡Mean of several determinations

## RESULTS AND DISCUSSION

Radiocarbon ages for modern shell samples are listed in Table 1, together with  $^{14}\text{C}$  depletions ( $\Delta^{14}\text{C}$ ) and  $\Delta\text{R}$  values. Data from this work, and from previous studies compiled by Stuiver, Pearson and Braziunas (1986) are shown in Figure 2. Ages of fossil mollusk shells from San Francisco Bay sediment cores are listed in Table 2 (see also Fig. 3). The  $\Delta^{14}\text{C}$  values for the modern shells were corrected for the  $^{14}\text{C}$  decay that occurred between the growth year (collection year) and 1950, and for the input to the oceans of  $^{14}\text{C}$ -depleted fossil-fuel carbon. We have used  $^{14}\text{C}$  data from banded corals (Druffel and Suess 1983), and the calculations of Stuiver, Pearson and Braziunas (1986), to correct for this fossil-fuel influence.  $\Delta\text{R}$  values were calculated by comparing global marine surface ages from an ocean model (Stuiver and Braziunas 1993) with the measured  $^{14}\text{C}$  ages. We have calculated regional means from our  $\Delta\text{R}$  data, but these should be used cautiously, since there may be inherent variability in  $\Delta\text{R}$  in some of the areas studied (see below). In addition, because it was not certain which of the samples were collected live, those samples with unusually high  $\Delta\text{R}$  values were assumed to have been reworked, and thus were not used in calculating the mean  $\Delta\text{R}$  values.

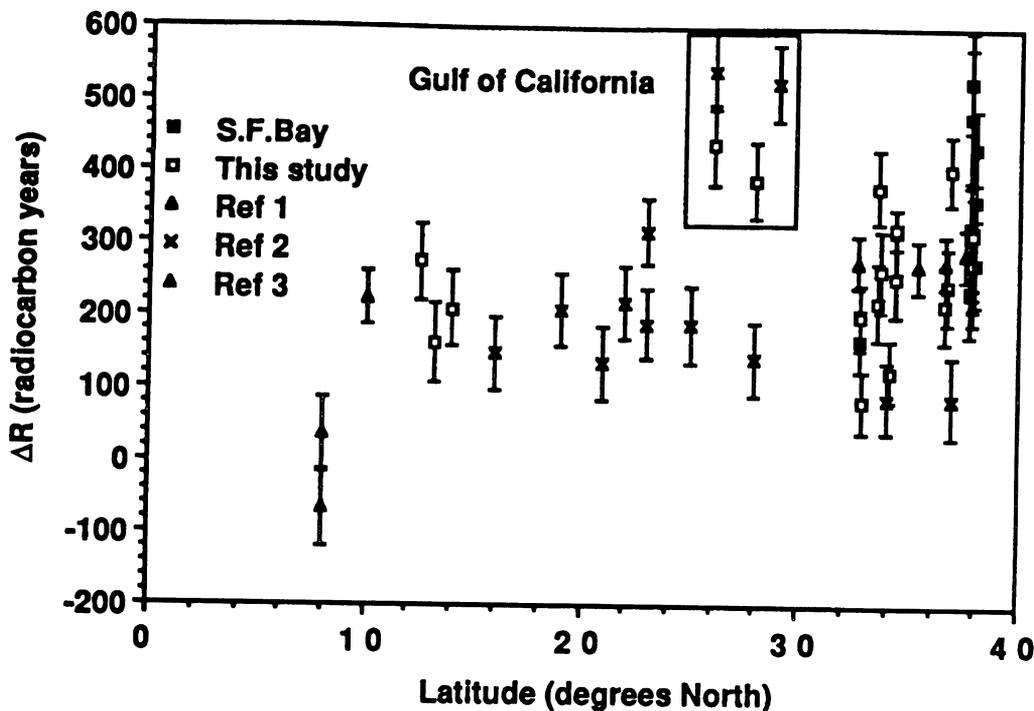


Fig. 2.  $\Delta\text{R}$  results from this investigation compared with those from three previous studies. San Francisco Bay data are plotted separately, since these waters are strongly influenced by river input. Ref 1: Robinson and Trimble (1980); Ref 2: Berger, Taylor and Libby (1966); Ref 3: Taylor and Berger (1967).

### Modern Shells and Eastern Pacific Reservoir Ages

The coastal samples from Northern California show large reservoir ages (low  $\Delta^{14}\text{C}$ ), due to intense upwelling in this region. The estuarine  $\Delta^{14}\text{C}$  values from San Francisco Bay are generally lower than those of the coastal samples. There is a large input of freshwater to the estuary from the Sacramento–San Joaquin River system, producing salinities as low as 10–20‰ in Bay waters, and our results suggest that pre-bomb

freshwater entering the Bay was significantly depleted in  $^{14}\text{C}$ . Recent measurements of  $^{14}\text{C}$  in Sacramento River water show  $\Delta^{14}\text{C}$  values 70‰ below those of the post-bomb atmosphere, and ground-water  $^{14}\text{C}$  activities near the Sacramento River are *ca.* 65 pMC (L. Davisson, LLNL, personal communication).

TABLE 2.  $^{14}\text{C}$  Ages for Mollusks from San Francisco Bay Sediment Cores

Depth (cm)	$^{14}\text{C}$ age		
	<i>Macoma</i>	<i>Mytilus</i>	<i>Ostrea</i>
<i>CP-1</i>			
173	1910 ± 220	--	960 ± 120
<i>CP-2</i>			
453	4680 ± 80	--	4540 ± 70
<i>CP-3</i>			
9	2540 ± 70	--	3210 ± 60
65	3650 ± 60	--	4160 ± 60
86	3610 ± 70	--	4280 ± 60
133	3680 ± 70	--	5040 ± 60
143	4110 ± 60	--	4520 ± 60
161	4200 ± 70	--	4860 ± 60
<i>OP-1</i>			
5	750 ± 60	1650 ± 60	
29	1110 ± 60	1700 ± 70	1090 ± 70
57	1410 ± 60	1890 ± 70	900 ± 70
65	730 ± 70	1830 ± 100	
402	3310 ± 70	3760 ± 70	
523	5070 ± 60	4850 ± 90	
<i>OP-2</i>			
257	1310 ± 60	1110 ± 70	
740	6270 ± 60	6200 ± 70	

The data in Figure 2 suggest an increase in  $\Delta R$  for coastal California waters of 50–100 yr at *ca.* 33–34°N latitude. This is plausible on oceanographic grounds, because the coastline trends sharply eastward below Pt. Conception at the western end of the Santa Barbara Basin (see Fig. 1). For much of the year, the California Current continues on a more southerly course, and the Southern California Bight to the southeast is occupied by a northward-flowing countercurrent. Coastal waters to the south are less subject to upwelling, and are less influenced by the southward advection of water from the strong upwelling regions further north (Dorman and Palmer 1980).

A feature of the southern California data was the high proportion of outliers. Six of the 11 samples gave results consistent with those of Berger, Taylor and Libby (1966), but two samples (*Macoma*-13 and *Ostrea*-7) were clearly reworked, and three others gave  $\Delta R$  values of *ca.* 700 yr. We have tentatively assumed that these are also reworked and have excluded them from calculation of the regional mean  $\Delta R$ . The five outliers are from, or adjacent to, estuaries (Newport Bay and Mission Bay) and could possibly result from reworking during flood events, if some of this material were redeposited on nearby oceanfront beaches. Erosion from uplifted beach bluff deposits is another possible mechanism for producing reworked material.

The presence of these samples in the museum collections may be an indicator that reworked specimens are relatively common in some California beach deposits. If this is true, it suggests that the probability of error in dating natural shell deposits is high, unless multiple samples are dated to reveal the presence of reworked material. Midden samples, which were collected live, would not be subject to this difficulty. If estuarine reworking is involved, choosing only open-ocean species may reduce the likelihood of error. Note, however, that reworking is not the only possible explanation for high mollusk reservoir ages. Dye (1994) has shown that  $^{14}\text{C}$  ages for limpet, cowrie and gastropod species found on Pleistocene limestone substrates in Hawaii are significantly older than those for specimens found on lava, and the likely effect on shell ages of dissolved geologic carbonate in river water has long been recognized (Berger, Taylor and Libby 1966).

The high  $\Delta R$  values from the Gulf of California samples are consistent with previous data (Berger, Taylor and Libby 1966) and with expectations for this known region of strong upwelling (Schrader *et al.* 1980). The Central American data agree with previous results (Berger, Taylor and Libby 1966; Taylor and Berger 1967), which show  $\Delta R$  relatively constant with latitude, down to  $10^\circ\text{N}$  (Fig. 2). Below that latitude, coastal waters as far south as the Galapagos are strongly influenced by equatorial water masses that are better equilibrated with the atmosphere than the waters of the California Current system further north. A sample from far southern Chile shows a larger  $\Delta R$  than a specimen from Valparaiso, suggesting a stronger influence of  $^{14}\text{C}$ -depleted Southern Ocean water on the former. This is consistent with a previous study in the Beagle Channel, Tierra del Fuego (Albero, Angiolini and Piana 1986), which also showed large reservoir ages.

### San Francisco Bay Mollusks

The results from in and around San Francisco Bay show that the natural variability in  $^{14}\text{C}$  ages is much greater than the analytical uncertainty associated with the measurements. Three species of mollusk collected from Stinson Beach, just outside the Bay, reveal that the  $^{14}\text{C}$  age of carbonate collected at the same time in the same environment may not necessarily have the same age. Ages of coexisting mollusks collected in 1936 differ by several hundred years, with a *Macoma* shell (reworked?) having the oldest age. Perhaps more significantly, modern mussels (*Mytilus californianus*), collected in 1939 from the central part of the Bay, show a spread of almost 300 yr. The mean  $\Delta R$  of 375 yr in Table 1 thus represents a modern average value for San Francisco Bay, but wide variations about this mean are present.

Fossil mollusk shells from San Francisco Bay sediment cores show large differences in  $^{14}\text{C}$  activity between mollusk types from the same stratigraphic level. For example, in core CP-3, taken in the south-central part of San Francisco Bay, *Ostrea lurida* is consistently older than *Macoma balthica*, by an average of 900  $^{14}\text{C}$  yr (Table 2; Fig. 3), but a single *Ostrea* sample from core CP-1 is younger than the *Macoma* shell. In core OP-1, *Mytilus edulis* is consistently older than *Macoma* by 450–1100 yr (six samples), whereas in OP-2 *Mytilus* is younger than *Macoma* by 70–220 yr (two samples). This variability in the species age offsets between cores (while age offsets are generally systematic within individual cores) suggests that several factors may contribute to the  $^{14}\text{C}$  age differences we observe.

One possible influence is the life habitat of the mollusk species. Clams, which are infauna, burrow into the sediment, to a depth of 5–15 cm. In contrast, oysters and mussels are epifaunal, living close to the sediment-water interface. Thus, oyster and mussel fossils from the same stratigraphic level would be expected to have an older age than coexisting clams. In most (but not all) cases, the data in Table 2 do show *Macoma* having the youngest ages. However, in core CP-3 (Fig. 3), for example,

the age differences of 400–1400 yr correspond to depth differences of 30–110 cm, an order of magnitude deeper than clams actually live.

Another factor may be the effect of different feeding modes. Oysters and mussels obtain carbon directly from the water from phytoplankton. *Macoma* also feeds on surface deposits, deriving carbon not only from phytoplankton and phytobenthos, but from other sources such as river-borne organic detritus, decaying vascular plants transported from marshes, and microbes in the sediment (Nichols and Pamatmat 1988). Tanaka, Monaghan and Rye (1986) have shown that 23–85% of the carbon incorporated into shell carbonate of mollusks is metabolic. No studies to date have evaluated the relative sources of carbon to mollusks in San Francisco Bay. However, a feeding preference for river-borne vascular plant debris or other terrestrial organic matter, which could have a young  $^{14}\text{C}$  age relative to the coastal ocean, might give a younger age for some mollusk shells.

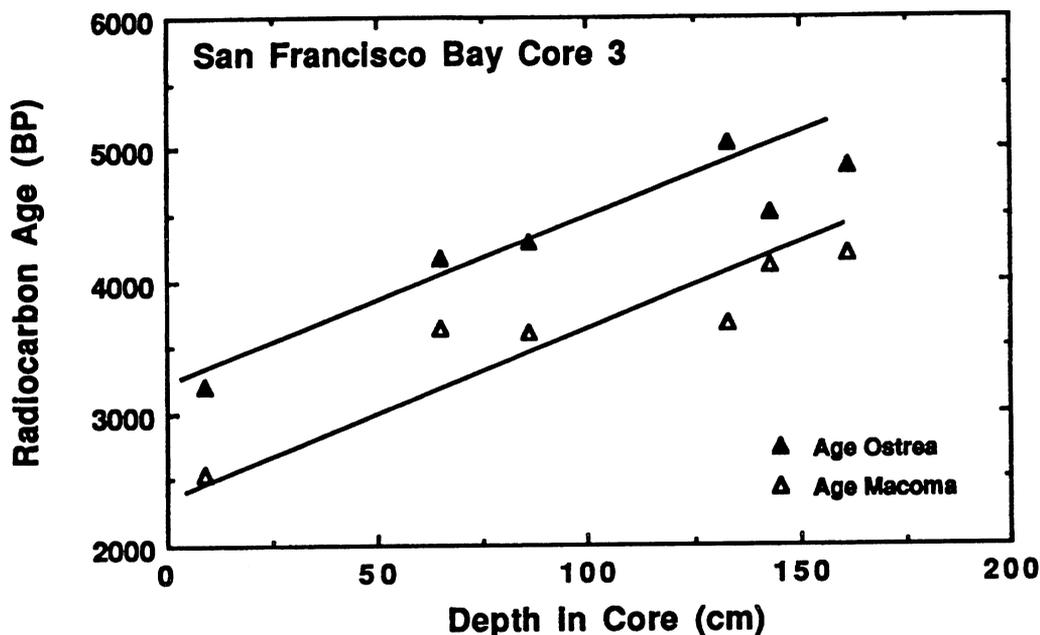


Fig. 3.  $^{14}\text{C}$  ages for oysters (*Ostrea lurida*) and clams (*Macoma balthica*) from sediment core CP-3 from south San Francisco Bay

A third possible explanation for age variations is seasonal differences in growth. Post-bomb measurements by Robinson (1980) showed seasonal swings of up to 130‰ in the  $\Delta^{14}\text{C}$  of California coastal surface waters. Allowing for the reduced atmosphere-surface-deepwater  $^{14}\text{C}$  gradient in pre-bomb times, seasonal variations of up to 30‰ seem plausible. Upwelling off California occurs during the late spring to early summer. Studies of the growth rates of *Macoma* in San Francisco Bay indicate that the clam grows much of its shell during the spring and fall (Nichols and Thompson 1982; Thompson and Nichols 1988), implying that it may have an older apparent age than a mollusk species that grew primarily in winter. However, because no comparable studies have been done with oysters or mussels in San Francisco Bay, the apparent age of *Macoma* relative to these other mollusks cannot be assessed. Note that this mechanism does not just apply in San Francisco Bay: seasonality of mollusk growth rates in a variable upwelling environment could contribute to the variability of coastal reservoir ages as well.

## CONCLUSION

We have refined reservoir ages and  $\Delta R$  values of eastern Pacific coastal waters with  $^{14}\text{C}$  measurements on mollusk shells collected prior to 1950. Our results are generally in agreement with data from previous studies, and are consistent with known patterns of ocean circulation. The highest  $\Delta R$  values are found in the Gulf of California, and  $\Delta R$  increases toward the northern California coast: both are areas of strong upwelling. Data from two estuaries and nearby beaches in southern California included several outliers. The spurious  $^{14}\text{C}$  ages may have resulted from processes such as reworking of mollusk shells during, e.g., storms or flood events. Thus, particular care may be required in using shell for dating California geological coastal deposits. Other dating problems may arise because reservoir ages from areas of seasonal upwelling, or from boundaries between different ocean circulation regimes, may vary significantly on seasonal, interannual, or longer time scales.

Evidence of serious problems in the dating of mollusks from estuaries is given by the San Francisco Bay results. Known-age *Mytilus edulis* from a single location in the Bay showed an age spread of almost 300 yr; and *Mytilus*, *Macoma* and *Ostrea* shells separated from the same level in sediment cores gave highly discrepant results, with age offsets as high as 1400 yr. Possible mechanisms for these variations include differences in habitat and feeding patterns, and the effects of seasonal changes in growth rates coupled with temporal upwelling and freshwater inflow variations. The variability in the results from different sediment cores within the Bay suggests that the causes are complex.

## ACKNOWLEDGMENTS

Part of this work was performed under the auspices of the Department of Energy at the Lawrence Livermore National Laboratory under contract W-7405-Eng-48. B.L.I. was supported in part by an appointment to the Global Change Distinguished Postdoctoral Fellowship program, sponsored by the U.S. Department of Energy, Office of Health and Environmental Research, and administered by the Oak Ridge Institute for Science and Education. We thank Doug Kennett and Zoe Knesl for assistance with sample collection.

## REFERENCES

- Albero, M. C., Angiolini, F. E. and Piana, E. L. 1986 Discordant ages related to reservoir effect of archaeological remains from the Tunel site, Beagle Channel, Argentine Republic. *In* Stuiver, M. and Kra, R. S., eds., Proceedings of the 12th International  $^{14}\text{C}$  Conference. *Radiocarbon* 28(2A): 748–753.
- Berger, R., Taylor, R. E. and Libby, W. 1966 Radiocarbon content of marine shells from the California and Mexican west coast. *Science* 153: 864–866.
- Bouey, P. D. and Basgall, M. E. 1991 Archaeological patterns along the south-central coast, Point Piedras Blancas, San Luis Obispo County, California. California Department of Transportation 05-SLO-1: 39–48.
- Davis, J. C., Proctor, I. D., Southon, J. R., Caffee, M. W., Heikkinen, D. W., Roberts, M. L., Moore, T. L., Turteltaub, K. W., Nelson, D. E., Loyd, D. H. and Vogel, J. S. 1990 LLNL/UC AMS facility and research program. *In* Proceedings of the 5th International Conference on Accelerator Mass Spectrometry. *Nuclear Instruments and Methods* B52(3,4): 269–272.
- Donahue, D. J., Linick, T. W. and Jull, A. J. T. 1990 Isotope-ratio and background corrections for accelerator mass spectrometry radiocarbon measurements. *Radiocarbon* 32(2): 135–142.
- Dorman, C. E. and Palmer, D. P. 1980 Southern California summer coastal upwelling. *In* Richards, F. A., ed., *Coastal Upwelling*. Washington, D.C., American Geophysical Union: 44–56.
- Druffel, E. R. M. and Suess, H. A. 1983 On the radiocarbon record in banded corals: Exchange parameters and net transport of  $\text{CO}_2$  between atmosphere and surface ocean. *Journal of Geophysical Research* 88: 1271–1280.
- Dye, T. 1994 Apparent ages of marine shells: Implications for archaeological dating in Hawai'i. *Radiocarbon* 36(1): 51–57.
- Nichols, F. G. and Pamatmat, M. M. 1988 The ecology of the soft-bottom benthos of San Francisco Bay: A community profile. *U.S. Fish and Wildlife Service Biology Report* 85(7.19): 73 p.

- Nichols, F. H. and Thompson, J. K. 1982 Seasonal growth in the bivalve *Macoma balthica* near the southern limit of its range. *Estuaries* 5: 110–120.
- Robinson, S. W. 1980 Natural and man-made radiocarbon as a tracer for coastal upwelling processes. In Richards, F. A., ed., *Coastal Upwelling*. Washington, D.C., American Geophysical Union: 298–302.
- Robinson, S. W. and Trimble, D. 1981 US Geological Survey Menlo Park, California, radiocarbon measurements II. *Radiocarbon* 23(2): 305–321.
- Schrader, H., Kelts, K., Curray, J., Moore, D., Aguayo, E., Aubrey, M. P., Einsele, G., Fornari, D., Gieskes, J., Kastner, M., Lyle, M., Matoba, Y., Molina-Cruz, A., Niemitz, J., Rueda, J., Saunders, A., Simoneit, B. and Vaquier, V. 1980 Laminated diatomaceous sediments from the Guaymas basin slope (central Gulf of California): 250,000 year climate record. *Science* 207: 1207–1209.
- Spiker, E. C. 1980 The behavior of  $^{14}\text{C}$  and  $^{13}\text{C}$  in estuarine water: Effects of *in situ*  $\text{CO}_2$  production and atmospheric exchange. *Radiocarbon* 22(3): 647–654.
- Stuiver, M. and Braziunas, T. F. 1993 Modeling atmospheric  $^{14}\text{C}$  influences and  $^{14}\text{C}$  ages of marine samples to 10,000 BC. *Radiocarbon* 35(1): 137–189.
- Stuiver, M., Pearson, G. W. and Braziunas, T. 1986 Radiocarbon age calibration of marine samples back to 9000 cal yr BP. *Radiocarbon* 28(2B): 980–1021.
- Stuiver, M. and Polach, H. A. 1977 Discussion: Reporting of  $^{14}\text{C}$  data. *Radiocarbon* 19(3): 355–363.
- Tanaka, N., Monaghan, M. C. and Ry, D. M. 1986 Contribution of metabolic carbon to mollusc and barnacle shell carbonate. *Nature* 320: 520–523.
- Taylor, R. E. and Berger, R. 1967 Radiocarbon content of marine shells from the Pacific coasts of Central and South America. *Science* 158: 1180–1182.
- Thompson, J. K. and Nichols, F. H. 1988 Food availability controls seasonal cycle of growth in *Macoma balthica* (L.) in San Francisco Bay, California. *Journal of Experimental Biology and Ecology* 116: 43–61.
- Vogel, J. S., Nelson, D. E. and Southon, J. R. 1987  $^{14}\text{C}$  background levels in an accelerator mass spectrometry system. *Radiocarbon* 29(3): 323–333.