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Stable isotope compositions of fossil mollusks from southern California: Evidence for a cool last interglacial ocean

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ABSTRACT

Stable isotope compositions have been determined for modern mullusks and fossil mollusks collected from uplifted marine terraces at three localities in southern California. By using a paleoclimatic model that decouples the temperature and ice-volume signals in ocean water, ocean-water temperatures off southern California are estimated to have been -3.8 °C at ~85 ka, -3.0 °C at ~107 ka, and -2.2 °C at ~125 ka relative to present temperature. These results indicate rather cool conditions during the peak of the last interglacial stage at 125 ka and conflict with results from terrace faunal studies that suggest water temperatures were warm or warmer than at present.

INTRODUCTION

The temperature of the ocean during the peak of the last interglacial stage at ~125 ka (oxygen-isotope substage 5e) has been estimated by using biotic census counts and stable isotope analyses in foraminifera from deep-sea cores (CLIMAP Project Members, 1984) and stable isotope analyses of mollusks and corals from uplifted coral-reef terraces (Shackleton and Matthews, 1977; Fairbanks and Matthews, 1978; Aharon et al., 1980; Aharon, 1983; Matthews, 1985). A general conclusion from these studies is that the temperature of the last interglacial ocean at ~125 ka was similar to the temperature of the present ocean. However, studies of deep-sea cores and terrace fossils in areas such as the Caribbean–Gulf of Mexico area, the southeastern Pacific Ocean, and around New Guinea indicate cooler-than-present temperatures for the last interglacial ocean (CLIMAP Project Members, 1984; Aharon et al., 1980). Data are sparse from the northeastern Pacific Ocean basin because sedimentation rates are high. With one exception off the coast of Oregon (Heusser and Shackleton, 1979), none of the many cores from this area intersect the boundary between the last interglacial stage and the beginning of the Wisconsin Glaciation (e.g., Gorsline and Prensky, 1975; Kahn et al., 1981). The marine paleoclimate of the ocean off the west coast of North America during the last interglacial stage has been inferred from the geographic ranges of fossils from tectonically uplifted marine terraces (Grant and Gale, 1931; Woodring et al., 1946; Valentine, 1955, 1961; Emerson, 1956; Valentine and Meade, 1961; Addicott, 1966; Zinsmeister, 1974; Valentine, 1976; Kern, 1977; Kennedy, 1978; Emerson et al., 1981; Kennedy et al., 1982; Kennedy and Wehmiller, 1986). Such interpretations have often been complicated by fossil assemblages that have a mixture of both warm and cool faunas. Most of these complications have disappeared with better age control (Kennedy, 1982), but several well-mapped and confidently dated 125-ka terraces do indeed have both warm and cool faunal elements. Examples include the Palos Verdes Sand Cabrillo Beach terrace in San Pedro (Woodring et al., 1946; Valentine and Meade, 1961; Muhs and Rosholt, 1984); the second terrace on San Nicolas Island (Vedder and Norris, 1963; Valentine and Veeh, 1969); the Nestor terrace in San Diego (Ku and Kern, 1974; Kern, 1977); and the second terrace at Turtle Bay, Baja California (Emerson et al., 1981).

Oxygen-isotope studies of Quaternary marine mollusks have been used only occasionally for paleoclimatic studies in California, despite the widespread abundance of fossils in marine terraces (Valentine and Meade, 1961; Dodd, 1966; Killingley, 1983). Marine-terrace fossils are, however, attractive for stable isotope studies because (1) terrace fossils are abundant in California, (2) marine terraces can now be dated by several methods, and (3) unlike deep-sea cores, the ice-volume signal in stable isotope data can be decoupled from the paleoclimatic signal by using well-established sea-level curves (Aharon et al., 1980; Aharon, 1983). We sampled fossil bivalve mollusks from marine terraces on San Clemente Island, San Nicolas Island, and at Point Loma in San Diego, California (Fig. 1), as

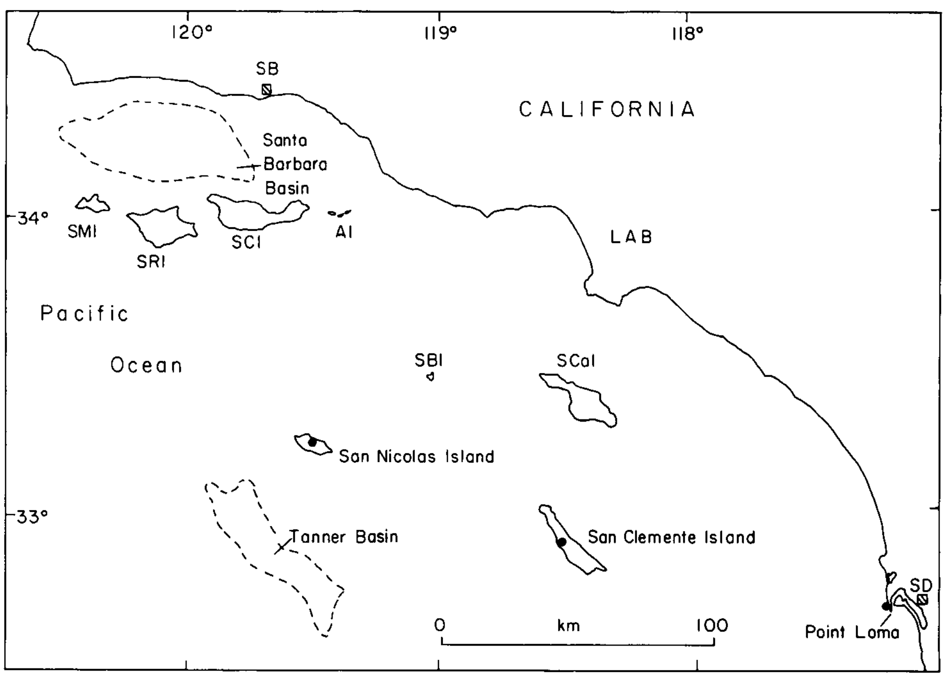

Figure 1. Map showing localities studied. LAB = Los Angeles basin; SB = Santa Barbara; SD = San Diego; SMI = San Miguel Island; SRI = Santa Rosa Island; SCI = Santa Cruz Island; AI = Anacapa Islands; SCal = Santa Catalina Island. Large dots indicate sample localities.

well as modern shells from nearby marine habitats. At all three localities there are 125-ka terraces (deep-sea substage 5e) that have been dated by uranium-series methods on coral (Valentine and Veeh, 1969; Ku and Kern, 1974; Muhs and Szabo, 1982). The lower, younger terraces on San Clemente Island and San Nicholas Island have amino-acid age estimates of about 85 ka (deep-sea substage 5a) and 107 ka (deep-sea substage 5c), respectively (Muhs, 1983, 1985). Our goal was to determine ocean paleotemperatures from the oxygen-isotope composition of the fossils.

METHODS

The small bivalve *Epilucina californica* was analyzed in this study because it is the only fossil that is found in abundance at all three localities. All samples were first examined under a binocular microscope for evidence of algal borings, and the contaminated areas were removed. Previous studies of marine mollusks clearly show that oxygen-isotope values vary in relation to seasonal temperature changes when individual layers are analyzed (Killingley and Berger, 1979; Killingley, 1981, 1983; Jones et al., 1986). Therefore, radial sections cut parallel to the direction of growth or the entire individual was analyzed so that an integrated thermal history would be represented. All samples were ground to a fine powder and were 99%–100% aragonite as determined by X-ray diffraction analysis. Isotopic compositions were determined by using the H_3PO_4 method of McCrea (1950) and are reported in δ notation in units of per mil relative to PDB. By using this method, a $\delta^{13}C$ value of -5.00‰ and a $\delta^{18}O$ value of +7.20‰ were measured for NBS-19. No significant isotopic differences were detected between untreated splits of samples and those that were either treated with sodium hypochlorite or heated to remove organic material. Duplicate analyses indicate a 1σ reproducibility of ±0.04 for both carbon and oxygen.

ISOTOPIC COMPOSITION OF MODERN MOLLUSKS

The $\delta^{18}O$ values of the modern specimens indicate that biological fractionation effects in *Epilucina* are minimal and that this species is a reliable indicator of temperature (Table 1). Modern mean annual sea-surface (10-m depth) temperatures are about 16 °C at both San Diego and San Clemente Island (Lynn, 1966), and modern *Epilucina* specimens from these two localities have $\delta^{18}O$ values that are not significantly different from one another. In contrast, the sea-surface temperature near San Nicolas Island is ~15 °C, and the $\delta^{18}O$ values of shells from that locality are significantly higher than values in shells from San Diego (at the 95% confidence level) and San Clemente Island (at the 99% confidence level). On the assumption that a 1 °C temperature difference is equivalent to a $\delta^{18}O$ difference of about 0.23‰ (Epstein et al., 1953), the difference in water temperature between San Nicolas Island and the other two localities is about 1.3 °C on the basis of oxygen-isotope data, which agrees well with the measured temperature difference.

ISOTOPIC COMPOSITION OF FOSSIL MOLLUSKS

Analyses of fossil *Epilucina* indicate that there are significant differences between the stable isotope compositions of fossils having different ages (Table 1). On San Nicolas Island, samples from the ~107-ka terrace have $\delta^{18}O$ values significantly higher (at the 98% confidence level) than those from the 125-ka terrace; a similar difference is seen between the single sample from the 85-ka terrace on San Clemente Island and samples from the corresponding 125-ka terrace. These data support the observation of Kern (1977), Kennedy (1978), and Kennedy et al. (1982) that faunas from 85–107-ka terraces in California indicate cooler water conditions than those at ~125 ka. Thus, oxygen-isotope data may be useful in relative-age differentiation and correlation of late Pleistocene marine-terrace deposits in California.

The $\delta^{18}O$ values of the 125-ka fossils are significantly higher than those of the modern specimens (Table 1). T-tests indicate that these differences are significant at confidence levels of 95% (San Diego), 99% (San Clemente Island), and 99.9% (San Nicolas Island). Because shoreline and radiometric data from tectonically stable coastlines indicate that sea level at ~125 ka was 2–10 m higher than at present (Veeh, 1966; Ku et al., 1974), oceanic waters at that time should have had a slightly lower $\delta^{18}O$ value than those of the modern ocean due to the ice-volume effect, even if there were no oceanic temperature differences. Thus, our data indicate that, relative to present conditions, temperatures off the California coast during the peak of the last interglacial stage were significantly cooler.

PALEOTEMPERATURE ESTIMATES

Paleotemperatures can be generated from the oxygen-isotope data for the 85 ka, 107 ka, and 125 ka highstands of sea, after accounting for the ice-volume effects, by following the method of Aharon et al. (1980). In brief, the first step is to assume that all of the observed differences between fossil and present $\delta^{18}O$ values are due to ice-volume effects, and an ancient sea level is calculated (Table 1). In making this calculation, we have assumed a 0.11‰ change in $\delta^{18}O$

Table 1. STABLE ISOTOPE DATA, MODERN SEA SURFACE TEMPERATURES, SEA LEVELS, AND AGES FOR SOUTHERN CALIFORNIA MARINE TERRACES

Locality	Present temp.* (°C)	Terrace	Ages† (ka)	Present† elevation (m)	Estimated sea level§ (m)	No. of individuals**	$\delta^{13}C$ (PDB)	$\delta^{18}O$ (PDB)	$\delta^{18}O$ sea level†† (m)	$\delta^{18}O$ residual†† (‰)	ΔT§§ (°C)
San Clemente Island	~16.0	Modern	0	0	0	6 (11)	1.96 ±0.39	0.26 ±0.17	--	--	--
		1st	~85	5	-13	1 (2)	-2.14	-1.27	-92	0.87	-3.8
		2nd	127 ±7	32	+6	4 (8)	2.14 ±0.15	0.69 ±0.12	-39	0.50	-2.2
San Nicolas Island	~15.0	Modern	0	0	0	7 (20)	2.45 ±0.35	0.61 ±0.12	--	--	--
		1st	~107	11	-10	6 (14)	1.61 ±0.28	1.42 ±0.15	-74	0.70	-3.0
		2nd	120 ±20	31	+6	4 (8)	1.65 ±0.43	1.05 ±0.14	-40	0.51	-2.2
San Diego (Point Loma)	~16.0	Modern	0	0	0	3 (8)	1.29 ±0.64	0.34 ±0.16	--	--	--
		Nestor	121 ±10	25	+6	3 (9)	2.09 ±0.25	0.82 ±0.14	-44	0.55	-2.4

*Taken from mean annual sea surface temperature data in Lynn (1966).

†Age estimates and present elevations of shoreline angles from Vedder and Norris (1963), Valentine and Veeh (1969), Ku and Kern (1974), Kern (1977), Muhs and Szabo (1982), and Muhs (1985); age of first terrace on San Clemente Island is best estimate based on amino acid data in Muhs (1983).

§Sea level at time of terrace formation taken from Veeh (1966), Ku et al. (1974), and Dodge et al. (1983).

**Number of individual valves; number in parenthesis is number of analyses (more than one radial slab was taken from some individual valves). Errors are 1σ from mean of individuals.

††$\delta^{18}O$ sea level (m) = [$\delta^{18}O_{fossil}$ (‰) - $\delta^{18}O_{modern}$ (‰)] ÷ 0.11 (‰) x 10 (m).
$\delta^{18}O$ residual (‰) = [$\delta^{18}O$ sea level (m) - Estimated sea level (m)] ÷ 10 (m) x 0.11 (‰).

§§Isotope temperature difference from present values, $\Delta T = \delta^{18}O$ residual/0.23.

between modern and fossil shells for each 10-m change in sea level (Shackleton and Opdyke, 1973; Fairbanks and Matthews, 1978; Aharon et al., 1980; Dodge et al., 1983). This calculated sea level is then compared to the sea level determined independently from terrace elevation data (Mesolella et al., 1969; Bloom et al., 1974; Dodge et al., 1983; Chappell, 1983), and a "residual" $\delta^{18}O$ value is determined. This latter value represents the difference in the $\delta^{18}O$ values between fossil and modern specimens that is due to temperature.

Our calculations indicate that ocean surface temperatures off California were cooler at 85 and 107 ka than at present (Table 1). The temperature estimate at 85 ka is tentative because we had only one individual of this age for analysis from San Clemente Island. Even though the 85 and 107 ka highstands are sometimes considered to be "interglacial," our data suggest that they were accompanied by rather cool water temperatures on the California coast. Studies of stable isotope compositions of foraminifera derived from a core taken from nearby Tanner Basin (Fig. 1) indicate that the difference in temperature between the last glacial maximum and the Holocene thermal maximum was about 5 °C (Kahn et al., 1981). Thus, our data indicate that the amount of cooling (relative to the present) at 85 and 107 ka along the California coast was more than half the amount of cooling during the glacial maximum. In contrast, stable isotope data from reef terraces in New Guinea and Barbados indicate that at both 85 and 107 ka, there was virtually no change in tropical surface-water temperatures compared to the present (Aharon et al., 1980; Aharon, 1983; Matthews, 1985).

Calculations of temperature changes from 125 ka to the present are in agreement at all three of our localities and indicate that water temperatures off southern California were 2.2–2.4 °C cooler during the peak of the last interglacial stage than at present (Table 1). These results are contrary to those from most other areas studied by CLIMAP Project Members (1984), which indicated that the temperature of the last interglacial ocean was virtually the same as that of the present ocean. The results are also contrary to conclusions of faunal studies, which generally indicate that coastal California water temperatures were as warm or warmer at ~125 ka than at present (Valentine, 1961; Kern, 1977; Kennedy et al., 1982; Kennedy and Wehmiller, 1986). It should be noted, however, that the CLIMAP study showed that some parts of the global ocean, such as areas in the western equatorial Atlantic–Caribbean–Gulf of Mexico area and the southeastern Pacific off western South America, were significantly cooler at ~125 ka than at present. In addition, other studies in southern California indicate that the last interglacial period at 125 ka was not uniformly warmer than at present. We have already mentioned that several 125 ka terraces in southern California have mixtures of warm and cool faunal elements, although the warm elements are usually dominant. A previous stable isotope study of mollusks from the Nestor terrace on Point Loma, California, indicated that mean annual surface-water temperatures at 125 ka were 0.8–3.6 °C cooler than at present (~16.0 °C) (Valentine and Meade, 1961). There is also evidence that there has been considerable temperature variability off southern California within the Holocene. Studies of radiolarian faunas from a varved sediment core in the Santa Barbara Basin (Fig. 1) indicate that mean February sea-surface temperatures during the Holocene may have varied from about 11 to 25 °C (Pisias, 1978). In a Tanner Basin (Fig. 1) core, Holocene mean annual surface-water paleotemperatures as much as 4.5 °C lower than at present have been estimated (Kahn et al., 1981). These studies all suggest that generalizations about "warm" interglacial water temperatures and "cool" glacial or interstadial water temperatures off the California coast are no doubt oversimplified.

PALEOCEANOGRAPHY

Cooler-than-present temperatures off the California coast during the peak of the last interglacial stage at ~125 ka could have resulted from two different mechanisms related to the California Current. The California Current is accompanied by upwelling of cooler bottom waters at many places along the southern California coast. An increase in the strength of northerly winds increases both the strength of the current and the amount of upwelling (Pisias, 1978). Studies of modern mollusks have shown that individual growth layers quite faithfully record lower $\delta^{13}C$ values during the southern California spring upwelling season (Killingley and Berger, 1979). Our data indicate that increased upwelling at 107 and 125 ka may have been a factor on San Nicolas Island, as $\delta^{13}C$ values in shells from the 107 and 125 ka terraces are significantly lower than those in the modern shells, at the 98% confidence level (Table 1). For San Diego and San Clemente Island, however, t-tests showed no significant differences between the $\delta^{13}C$ values of modern and 85 or 125 ka shells, which does not support the existence of stronger upwelling in the past.

A second mechanism that may have resulted in cooler temperatures during the peak of the last interglacial stage is a greater contribution of high-latitude source waters to the California Current at that time than at present. The modern California Current is a continuation of the Aleutian or Subarctic Current, which in turn forms by mixing of the Kuroshio and Oyashio currents (Sverdrup et al., 1942). Little mixing of the southward-flowing California Current with the North Pacific Current to the west takes place, as evidenced by the relatively cool temperatures of the California Current and $\delta^{18}O$ surface-water values, which are similar to those of Pacific Ocean surface waters at much higher latitudes (Broecker, 1986). If, during the peak of the last interglacial period, the Oyashio Current contributed more cold water to the Subarctic Current than it does at present, the result would be a cooler California Current that may or may not have been accompanied by increased upwelling, depending on local wind strengths. In this model, cooler-than-present ocean temperatures should be recorded in 125-ka marine fossils all along the Pacific coast of North America affected by the California Current. However, foraminiferal data from a single core off the coast of southern Oregon and marine-terrace faunas from a locality in central Oregon indicate that water temperatures at 125 ka were slightly warmer than at present (CLIMAP Project Members, 1984; Kennedy, 1978; Kennedy et al., 1982). To test this model more rigorously, however, oxygen-isotope compositions of mollusks are needed from well-dated 125 ka marine terraces and their modern equivalents along the Pacific coast of North America from about lat 50° to 25°N.

The cooler-than-present water temperatures off southern California at ~85 and ~107 ka are in agreement with faunal data of Kern (1977), Kennedy (1978), Kennedy et al. (1982), and Kennedy and Wehmiller (1986), but they cannot be explained by increased upwelling, at least on San Clemente Island. Clearly, data from mollusks of these ages are needed from more localities, but cooler waters at these times may be explained by cooler Pacific Ocean deep water during the time interval from ~115 to ~10 ka (Shackleton and Chappell, 1985).

CONCLUSIONS

Stable isotope studies of modern and fossil mollusks indicate that during the last interglacial stage, water temperatures off the southern California coast were cooler than at present. These temperature reductions are estimated to be -3.8 °C at ~85 ka, -3.0 °C at ~107 ka, and -2.2 °C at ~125 ka. The cooler-than-present waters at ~85 and ~107 ka are in agreement with faunal data and may be explained by deep-water cooling in the Pacific Ocean in the time interval from ~115 to ~10 ka. However, neither this mechanism nor upwelling explain the cooler-than-present waters at ~125 ka indicated by the stable isotope data. Faunas from 125-ka terraces in southern California have both warm and cool species at several localities, although warm-water forms seem to be dominant.

More studies are needed before we can adequately explain the anomalous data that suggest cool-water conditions existed off the California coast during the peak of the last interglacial stage at 125 ka. Our results do indicate, however, that oceanic paleotemperatures in this region are not a simple case of warm interglacial vs. cool glacial or interstadial periods and that the mechanisms of climatic change in this area are probably more complex than previously supposed.

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