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The last interglacial period on the Pacific Coast of North America: Timing and paleoclimate

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ABSTRACT

New, high-precision U-series ages of solitary corals (*Balanophyllia elegans*) coupled with molluscan faunal data from marine terraces on the Pacific Coast of North America yield information about the timing and warmth of the last interglacial sea-level highstand. *Balanophyllia elegans* takes up U in isotopic equilibrium with seawater during growth and shortly after death. Corals from the second terrace on San Clemente Island (offshore southern California), the third terrace on Punta Banda (on the Pacific Coast of northern Baja California), and the Discovery Point Formation on Isla de Guadalupe (in the Pacific Ocean offshore Baja California) date to the peak of the last interglacial period and have U-series ages ranging from ca. 123 to 114 ka. The first terrace on Punta Banda has corals with ages ranging from ca. 83 to 80 ka, which corresponds to a sea-level highstand formed in the late last interglacial period. U-series analyses of corals from the Cayucos terrace (central California) and the Nestor terrace at Point Loma (southern California) show that these fossils have evidence of open-system history, similar to what has been reported by other workers for the same localities. Nevertheless, a model of continuous, secondary U and Th uptake shows that two ages of corals are likely present at these localities, representing the ca. 105 and ca. 120 ka sea-level highstands reported elsewhere.

U-series ages of last interglacial corals from the Pacific Coast overlap with, but are on average younger than the ages of corals from Barbados, the Bahamas, and Hawaii. This age difference is explained by the nature of the geomorphic response to sea-level change: fringing or barrier reefs on low-latitude coastlines have an accretionary growth style that keeps pace with rising sea level, whether on a tectonically rising or stable coastline. In contrast, midlatitude, high-energy coastlines are sites of platform cutting during the early part of a sea-level high stand and terrace scouring and concomitant sediment and fossil deposition as sea level starts to recede. The youngest ages of corals from the Pacific Coast suggest that sea level was still relatively high at ca. 116 ka, which is not in agreement with other estimates of relatively large global ice volume at that time.

Reliably dated, ca. 120 ka marine-terrace deposits on the Pacific Coast have fossil mollusks that indicate water temperatures as warm or warmer than at present. In contrast, ca. 80 ka marine deposits reported here and elsewhere have fossil mollusks indicating cooler-than-modern water temperatures. The presence of both ca. 105 ka and ca. 120 ka corals on the Nestor and Cayucos terraces explains a previously enigmatic mixture of warm-water and cool-water mollusks. At ca. 105 ka, a relatively high sea level with cool waters may have “captured” the terrace formed during the 120 ka sea-level highstand, in areas of low uplift rate.

The inference of cooler-than-modern waters off the Pacific Coast of North America at ca. 80 ka and ca. 105 ka, based on ma-

rine-terrace faunas, does not agree with estimates of sea-surface temperatures derived from alkenone studies in the Santa Barbara Basin. However, cooler water temperatures at these times are in agreement with paleotemperature estimates from planktonic foraminiferal data for the Santa Barbara Basin. All records, from central California to Baja California, whether from marine terraces or offshore cores, indicate at least seasonably warmer-than-modern waters during the peak of the last interglacial period at ca. 120 ka.

Keywords: corals, marine terraces, Mollusca, Pacific Coast, paleoclimate, sea level, uranium-series method, zoogeography.

INTRODUCTION

The precise timing, duration, and paleoclimatic conditions of the peak of the last interglacial period (substage 5e of the marine oxygen isotope record) have been actively debated. Understanding the timing of this warm period is important because it may give crucial information on the likely duration of the present interglacial period (Broecker, 1998; Kukla, 2000). The sea-level record is an important means by which both the duration and warmth of the last interglacial period can be estimated. The Quaternary geologic record of sea-level highstands takes the form of emergent reefs and marine terraces, on either tectonically stable or rising coasts. Corals present in these deposits can be accurately and precisely dated by using U-series methods via thermal-ionization mass spectrometry (TIMS). On coastlines that are neither rising nor subsiding, marine deposits or growth-position

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reef corals will be left as emergent records only during times when sea level was higher—and therefore global ice volume was lower—than at present. Records from Hawaii (Szabo et al., 1994; Muhs et al., 2002), the Bahamas (Chen et al., 1991; Muhs et al., 1994a), and Australia (Zhu et al., 1993; Collins et al., 1993; Stirling et al., 1995, 1998) indicate that the last interglacial sea-level highstand could have begun well before the Northern Hemisphere, high-latitude summer insolation peak at ca. 128 ka and was still high as late as 116 ka, when high-latitude summer insolation in the Northern Hemisphere was at its lowest values of the past 200 k.y. This timing of the last interglacial sea-level highstand conflicts with inferences from the deep-sea oxygen isotope record of a considerable volume of global ice at ca. 116 ka (Mix, 1992; Shackleton, 1987; Martinson et al., 1987).

On the slowly uplifting coastline of California and northern Baja California (Fig. 1), marine terraces are prominent landforms (Woodring et al., 1946; Bradley and Griggs, 1976; Kern, 1977; Muhs, 1983; Rockwell et al., 1989, 1992; Lajoie et al., 1991; Kennedy et al., 1992; Kern and Rockwell, 1992; Muhs et al., 1990, 1994b). Marine terraces are emergent, erosional platforms veneered with thin, sometimes fossiliferous, marine sand and gravel. U-series dating of solitary corals from these deposits by alpha spectrometry shows that, to a first approximation, marine terraces on the coast of California correlate with the same high stands of sea level recorded by uplifted reefs on tropical coastlines such as New Guinea, Barbados, and Haiti (Ku and Kern, 1974; Rockwell et al., 1989; Stein et al., 1991; Muhs et al., 1994b).

Erosional landforms such as marine terraces may not form at precisely the same time during a sea-level highstand as constructional coral reefs. What are referred to as “keep-up” reefs of tropical waters are those dominated by shallow-water corals such as *Acropora* (Neumann and MacIntyre, 1985). Such reefs, found on Barbados, Haiti, and parts of the Bahamas, can keep pace with rapidly rising sea level. Thus, on an emergent coast, these reefs record the early rise of sea level as well as its peak (Fig. 2). On a high-energy, erosional coastline such as that along much of California and northern Baja California, the early part of an interglacial sea-level highstand (e.g., during stage 2 or early stage 3 of Fig. 2) may be dominated by terrace cutting. Fossils left on the platform, therefore, may be those from organisms living in nearshore waters considerably later (e.g., from late stage 3 or stage 4 of Fig. 2), perhaps just before sea-level re-

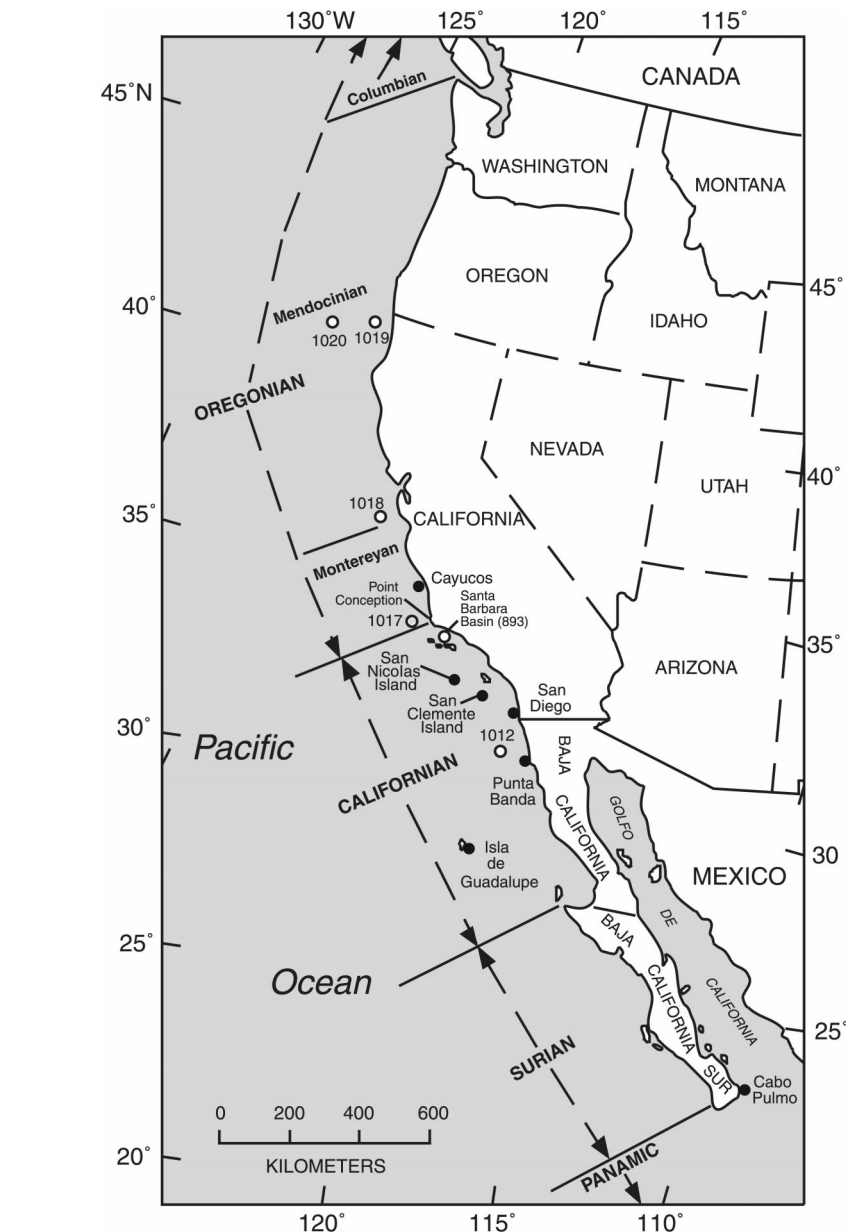


Figure 1. Map showing part of the Pacific Coast of North America and marine-terrace localities studied (solid circles), and ODP (Ocean Drilling Program) localities (open circles with site numbers) referred to in the text. Also shown are the approximate boundaries of molluscan faunal provinces (from Valentine, 1966).

gression. During stage 5 (as shown in Fig. 2), terrace emergence takes place. If this model is correct, California marine-terrace fossils could record the final stages of an interglacial sea-level highstand.

The most comprehensive study of last interglacial sea-surface temperatures is the effort by the CLIMAP group (CLIMAP Project Members, 1984) using foraminifera from deep-sea cores. They concluded that last interglacial ocean temperatures were similar to, or slightly warmer than, present conditions.

However, although this study was global in its extent, few cores were then available from the eastern Pacific Ocean. In the past few years, there have been several new cores raised from localities off the California coast (Fig. 1). We compared paleotemperature estimates from these cores with published molluscan faunas from our marine-terrace localities, using updated zoogeographic information.

In addition to the ca. 120 ka interglacial sea-level highstand, later sea stands at ca. 105 ka and ca. 80 ka have also been recognized

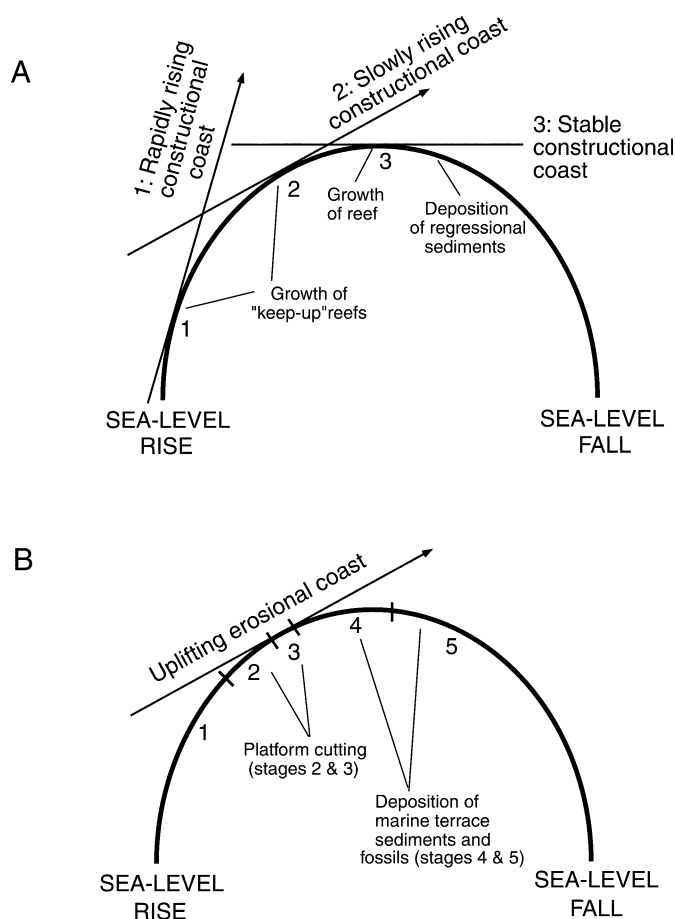


Figure 2. Models of the timing of marine-terrace formation as a function of sea-level highstands during an interglacial period. A: Timing of constructional reef-terrace formation as a function of uplift rate and reef type (modified from Edwards et al. [1987] and Neumann and MacIntyre [1985]). B: Timing of erosional marine-terrace formation, such as that found on the Pacific Coast of North America (from Bradley and Griggs, 1976).

on many coastlines. Work on the record of these sea stands began with reef mapping and alpha-spectrometric U-series ages of corals from what are now referred to as the Ventnor (ca. 105 ka) and Worthing (ca. 80 ka) terraces on Barbados (Broecker et al., 1968; Ku, 1968; Mesolella et al., 1969; Bender et al., 1979; Ku et al., 1990). More recent high-precision TIMS U-series analyses of these terraces have confirmed the earlier age estimates (Gallup et al., 1994; Edwards et al., 1997). The same sea-level highstands are recorded as emergent reefs on tectonically rising New Guinea and Haiti (Bloom et al., 1974; Dodge et al., 1983; Chappell and Shackleton, 1986) and also correspond to global ice-volume minima designated as substage 5c (ca. 105 ka) and substage 5a (ca. 80 ka) of the deep-sea oxygen isotope record (Martinson et al., 1987).

In this study, we test the just-outlined hypotheses of the timing of last interglacial high sea level and sea-surface paleotemperatures by

utilizing marine-terrace fossils from localities in California and Baja California. We have dated well-preserved and unrecrystallized marine-terrace corals by U-series methods using TIMS, which yields much higher precision than is possible with alpha-spectrometric methods and also allows analysis of coral individuals. We have used a zoogeographic approach to estimating *relative* (i.e., warmer or cooler than present) sea-surface temperatures along the Pacific Coast of North America during the last interglacial period (Kennedy et al., 1982, 1992; Kennedy, 2000).

URANIUM-SERIES SYSTEMATICS

All corals, whether colonial or solitary, take up U in isotopic equilibrium with seawater and frequently behave as closed systems with respect to ^{238}U and its long-lived daughter products—i.e., ^{234}U and ^{230}Th —after death and emergence. The solitary coral *Balanophyllia*

elegans currently lives along the Pacific Coast of North America from southeastern Alaska to central Baja California (Gerrodette, 1979; O'Clair and O'Clair, 1998). This coral also occurs as a fossil in marine-terrace deposits on the Pacific Coast of North America. It is potentially suitable for U-series dating because living specimens incorporate measurable U in isotopic equilibrium with seawater (Stein et al., 1991; Muhs et al., 1994b). TIMS U-series analyses of solitary corals by Stein et al. (1991) did not yield results that were optimistic for high-precision geochronology, as most samples gave evidence of open-system history. However, later alpha-spectrometric U-series analyses suggest that *B. elegans* has potential for dating (Muhs et al., 1994b).

All *Balanophyllia* specimens were prepared by hand removal of detrital mineral grains and careful scraping of secondary carbonates under magnification, followed by multiple ultrasonic baths in distilled water. The cleaned corals that were analyzed were all well preserved and 95%–100% aragonite, as determined by X-ray diffractometry. After cleaning, sample preparation followed methods outlined by Ludwig et al. (1992) and are summarized briefly here. Cleaned corals were dissolved in HNO_3 , spiked with ^{229}Th , ^{233}U , and ^{236}U and purified with ion-exchange methods. Purified U and Th were loaded with colloidal graphite on separate Re filaments; isotopic abundances were determined by thermal-ionization mass spectrometry (TIMS). Ages were calculated by using a half-life of 75 381 yr for ^{230}Th and 244 600 yr for ^{234}U (Table 1). Cheng et al. (2000) have redetermined the half-life of ^{230}Th to be 75 690 yr and the half-life of ^{234}U to be 245 250 yr. Recalculation of our U-series data using these new half-lives results in ages that are in agreement, within analytical uncertainty, with the ages reported in Table 1. Duplicate analyses of individual coral samples generally show excellent agreement, within limits of analytical uncertainty.

URANIUM-SERIES AGES OF MARINE-TERRACE CORALS

U-Series Systematics in Modern Corals

A previous study, using alpha spectrometry, showed that U concentrations in living *Balanophyllia elegans* from California and Oregon are ~3.2 ppm, whereas U concentrations in fossils of this species range from ~3.7 to 5.7 ppm (Muhs et al., 1994b). Muhs et al. (1994b) suggested that secondary U uptake could have occurred after death but before emergence from seawater, in which case the

TABLE 1. U AND Th CONCENTRATIONS, ISOTOPIC RATIOS, AND AGES OF CORALS FROM CALIFORNIA AND BAJA CALIFORNIA

Locality and sample number	Terrace and LACMIP locality	U (ppm)	Error	²³² Th (ppm)	²³⁴ U/ ²³⁸ U AR	Error	²³⁰ Th/ ²³² Th AR	Error	²³⁰ Th/ ²³² Th AR	²³⁰ Th/ ²³⁸ U age (ka)	Error	²³⁴ U/ ²³⁸ U initial AR	Error
Cayucos, California—Cayucos terrace													
Cay-10731-A	10731	4.35	0.11	0.0153	1.1343	0.0016	0.7614	0.0031	656	117.1	0.9	1.1872	0.0021
Cay-10731-A dup	10731	4.17	0.11	0.0207	1.1387	0.0017	0.7654	0.0029	467	117.3	0.8	1.1934	0.0022
Cay-10731-B	10731	4.85	0.12	0.0178	1.1313	0.0018	0.7324	0.0049	605	110.1	1.3	1.1794	0.0024
Cay-10731-C	10731	3.88	0.11	0.0194	1.1240	0.0017	0.7212	0.0022	437	108.7	0.6	1.1687	0.0022
Cay-10731-E	10731	4.56	0.11	0.0272	1.1232	0.0015	0.7237	0.0019	368	109.4	0.6	1.1680	0.0019
Cay-10731-F	10731	4.07	0.11	0.0304	1.1254	0.0016	0.7505	0.0025	305	116.0	0.8	1.1742	0.0021
Cay-10731-G	10731	4.83	0.11	0.0209	1.1164	0.0019	0.7434	0.0028	521	115.9	0.9	1.1617	0.0025
Cay-10731-H	10731	4.59	0.11	0.0252	1.1317	0.0058	0.7815	0.0050	432	123.3	1.9	1.1867	0.0076
GK-89-07-A	11923	5.06	0.12	0.0452	1.1294	0.0019	0.8037	0.0055	273	130.3	1.7	1.1872	0.0027
GK-89-07-B	11923	4.82	0.11	0.0504	1.1202	0.0019	0.8289	0.0038	241	140.8	1.4	1.1791	0.0027
GK-89-07-C	11923	4.29	0.11	0.0201	1.1370	0.0022	0.7918	0.0023	514	125.0	0.8	1.1953	0.0028
GK-89-07-D	11923	4.98	0.11	0.0449	1.1295	0.0023	0.7911	0.0026	266	126.5	0.9	1.1854	0.0030
GK-89-07-E	11923	3.69	0.11	0.0209	1.1838	0.0032	0.8712	0.0072	48	137.1	2.3	1.2710	0.0044
GK-89-07-F	11923	4.60	0.11	0.0375	1.1398	0.0020	0.7923	0.0039	295	124.5	1.2	1.1990	0.0026
GK-89-07-G	11923	4.70	0.11	0.0163	1.1366	0.0027	0.8086	0.0033	709	130.0	1.2	1.1975	0.0036
GK-89-07-H	11923	4.79	0.12	0.0120	1.1306	0.0018	0.7669	0.0022	932	119.4	0.7	1.1832	0.0024
GK-89-07-I	11923	4.14	0.11	0.0187	1.1299	0.0017	0.7837	0.0024	525	124.3	0.8	1.1847	0.0022
GK-89-7	11923	4.30	0.11	0.0332	1.1425	0.0020	0.7914	0.0025	312	123.6	0.8	1.2023	0.0026
GK-89-06-A	11922	4.68	0.23	0.0313	1.1508	0.0091	0.8613	0.0041	390	142.9	2.9	1.2261	0.0120
GK-89-06-B	11922	4.57	0.11	0.0488	1.1231	0.0021	0.7976	0.0034	227	130.0	1.2	1.1780	0.0028
GK-89-06-C	11922	4.44	0.11	0.0393	1.1286	0.0016	0.8218	0.0072	282	136.1	2.3	1.1892	0.0025
Point Loma, San Diego, California—Bird Rock terrace													
GK-93-01-A	11701	4.97	0.11	0.0918	1.1397	0.0019	0.6398	0.0042	105	87.7	0.9	1.1792	0.0024
GK-93-01-B	11701	4.70	0.14	0.1112	1.1497	0.0023	0.6878	0.0030	88	96.6	0.7	1.1968	0.0029
GK-93-01-D	11701	4.45	0.11	0.0563	1.1458	0.0020	0.8067	0.0027	194	127.3	0.9	1.2091	0.0026
Point Loma, San Diego, California—Nestor terrace													
NT-SD-A	10167	5.34	0.11	0.0293	1.1249	0.0016	0.7468	0.0019	413	115.1	0.6	1.1731	0.0021
NT-SD-B	10167	4.77	0.12	0.0340	1.1359	0.0017	0.7561	0.0035	322	115.4	1.0	1.1885	0.0023
NT-SD-C	10167	6.96	0.11	0.0148	1.1592	0.0021	0.7382	0.0019	1052	106.6	0.6	1.2153	0.0026
NT-SD-D	10167	4.87	0.11	0.0244	1.1361	0.0023	0.8021	0.0027	486	128.2	1.0	1.1958	0.0030
NT-SD-E	10167	6.08	0.11	0.0605	1.1404	0.0022	0.7490	0.0020	229	112.7	0.7	1.1932	0.0028
NT-SD-F	10167	4.78	0.11	0.0129	1.1364	0.0017	0.7322	0.0018	827	109.1	0.5	1.1859	0.0022
NT-SD-G	10167	5.56	0.11	0.0325	1.1233	0.0014	0.7359	0.0030	382	112.6	0.8	1.1696	0.0018
NT-SD-H	10167	3.87	0.11	0.0181	1.1276	0.0017	0.7916	0.0028	513	127.1	0.9	1.1830	0.0023
NT-SD-I	10167	5.15	0.11	0.0445	1.1464	0.0017	0.7605	0.0040	267	114.5	1.1	1.2025	0.0023
NT-SD-J	10167	5.80	0.11	0.0310	1.1436	0.0017	0.6924	0.0024	393	98.5	0.6	1.1898	0.0022
NT-SD-K	10167	4.22	0.11	0.0315	1.1326	0.0018	0.8650	0.0041	352	149.6	1.6	1.2026	0.0026
NT-SD-L	10167	3.91	0.12	0.0254	1.1307	0.0017	0.7966	0.0030	373	127.9	1.0	1.1878	0.0023
NT-SD-N	10167	5.47	0.11	0.0594	1.1389	0.0022	0.7637	0.0033	214	116.8	1.0	1.1934	0.0029
San Clemente Island, California—Eel Point terrace, north side of Eel Point													
SCI-18-A	10725	4.28	0.11	0.0649	1.1078	0.0019	0.8188	0.0029	164	141.0	1.1	1.1607	0.0027
SCI-18-B	10725	3.83	0.11	0.0029	1.1117	0.0026	0.7482	0.0059	2975	118.2	1.7	1.1562	0.0034
SCI-18-C	10725	4.35	0.11	0.0819	1.1097	0.0029	0.8091	0.0026	131	137.2	1.2	1.1619	0.0039
SCI-18-D	10725	3.42	0.11	0.0066	1.1135	0.0026	0.7554	0.0047	1196	119.9	1.4	1.1594	0.0034
SCI-18-E	10725	4.36	0.11	0.0022	1.1083	0.0020	0.7505	0.0025	4582	119.6	0.8	1.1520	0.0026
SCI-18-F	10725	3.54	0.12	0.0070	1.1123	0.0022	0.7580	0.0041	1159	120.9	1.3	1.1582	0.0030
Eel Pt.-A	10725	3.65	0.12	0.0049	1.1085	0.0021	0.7323	0.0028	1657	114.5	0.9	1.1500	0.0028
Eel Pt.-B	10725	4.29	0.11	0.0029	1.1066	0.0025	0.7423	0.0019	3351	117.7	0.8	1.1488	0.0033
Eel Pt.-C	10725	3.65	0.12	0.0018	1.1099	0.0018	0.7458	0.0017	4484	117.9	0.6	1.1535	0.0023
Eel Pt.-D	10725	4.27	0.12	0.0036	1.1078	0.0021	0.7419	0.0035	2631	117.3	1.1	1.1503	0.0028
Eel Pt.-E	10725	4.15	0.11	0.0138	1.1084	0.0014	0.7309	0.0037	669	114.2	1.0	1.1498	0.0019
Eel Pt.-G	10725	4.13	0.11	0.0022	1.1109	0.0019	0.7810	0.0070	4539	128.0	2.2	1.1594	0.0027
Eel Pt.-H	10725	4.17	0.12	0.0061	1.1088	0.0026	0.8548	0.0045	1767	153.7	1.9	1.1682	0.0036
Eel Pt.-I	10725	3.76	0.11	0.0059	1.1145	0.0019	0.7487	0.0046	1456	117.8	1.3	1.1599	0.0025
Eel Pt.-J	10725	4.65	0.11	0.0019	1.1110	0.0020	0.7657	0.0038	5721	123.4	1.2	1.1575	0.0027

U-series ages of *B. elegans* should still provide a reliable chronology for the marine deposits with which they are associated. To test this hypothesis, we analyzed both live-collected *B. elegans* from San Nicolas and San Clemente Islands (Fig. 1) and modern, dead-collected specimens from San Nicolas Island. Living *Balanophyllia* have U concentrations ranging from 2.9 to 3.7 ppm (Fig. 3) and ²³⁴U/²³⁸U values that fall within the range of ratios reported for modern seawater (Chen et al., 1986). Apparent ages of the dead-collected

specimens from modern beaches on San Nicolas Island range from 100 ± 100 yr to 800 ± 100 yr. The modern, dead-collected *Balanophyllia* also have ²³⁴U/²³⁸U values that fall within the range of modern seawater, but have U concentrations that range from 3.2 to 4.7 ppm (Fig. 3). These data support the earlier suggestion that secondary U uptake occurs in *Balanophyllia elegans* after death, but that the source of this U is seawater. Similar results have been reported for live-collected and Holocene mollusks, although the concentrations

of U in living mollusks are about two orders of magnitude lower than those in *Balanophyllia* and other corals (Kaufman et al., 1996). The inference of secondary addition of U from seawater for dead San Nicolas Island corals is supported by detailed analyses of bulk marine-terrace sediments on San Nicolas Island that show ²³⁴U/²³⁸U values consistently much higher than seawater ratios (Muhs et al., 1989). Because the range of U concentrations in fossil *Balanophyllia* (Muhs et al., 1994b) differs little from that in modern, dead-collected *Bal-*

TABLE 1. (CONTINUED.)

Locality and sample number	Terrace and LACMIP locality	U (ppm)	Error	²³² Th (ppm)	²³⁴ U/ ²³⁸ U AR	Error	²³⁰ Th/ ²³⁸ U AR	Error	²³⁰ Th/ ²³² Th AR	²³⁰ Th/ ²³⁸ U age (ka)	Error	²³⁴ U/ ²³⁸ U initial AR	Error
San Clemente Island, California—Eel Point terrace, south side of Eel Point													
GK-99-10-B	12007	3.46	0.11	0.0051	1.1127	0.0019	0.7607	0.0025	1567	121.5	0.8	1.1591	0.0025
GK-99-10-B dup	12007	3.46	0.13	0.0050	1.1127	0.0021	0.7592	0.0026	1587	121.1	0.9	1.1589	0.0028
GK-99-10-C	12007	3.28	0.10	0.0059	1.1175	0.0013	0.7596	0.0023	1279	120.2	0.7	1.1652	0.0018
GK-99-10-D	12007	4.35	0.11	0.0076	1.1121	0.0019	0.7540	0.0019	1304	119.8	0.7	1.1574	0.0025
GK-99-10-E	12007	3.65	0.11	0.0039	1.1122	0.0019	0.7614	0.0016	2167	121.9	0.6	1.1584	0.0025
GK-99-10-F	12007	4.03	0.11	0.0117	1.1126	0.0021	0.7520	0.0021	785	119.1	0.7	1.1577	0.0028
GK-99-10-G	12007	3.66	0.11	0.0073	1.1132	0.0016	0.7522	0.0022	1142	119.0	0.7	1.1586	0.0021
GK-99-10-H	12007	3.49	0.11	0.0051	1.1169	0.0018	0.7648	0.0029	1596	121.8	0.9	1.1651	0.0024
GK-99-10-I	12007	3.18	0.11	0.0061	1.1225	0.0019	0.7689	0.0038	1211	121.7	1.2	1.1729	0.0025
GK-99-10-J	12007	3.89	0.11	0.0147	1.1151	0.0018	0.7610	0.0039	612	121.1	1.2	1.1622	0.0024
GK-99-10-K	12007	3.71	0.11	0.0096	1.1224	0.0016	0.7643	0.0024	900	120.4	0.8	1.1722	0.0021
GK-99-10-L	12007	3.92	0.11	0.0063	1.1154	0.0017	0.7703	0.0042	1458	123.7	1.3	1.1639	0.0023
GK-99-10-M	12007	3.87	0.13	0.0043	1.1126	0.0017	0.7608	0.0020	2075	121.6	0.7	1.1590	0.0022
GK-99-10-O	12007	4.09	0.12	0.0220	1.1203	0.0018	0.7785	0.0034	441	125.0	1.1	1.1715	0.0024
Punta Banda, Baja California—Lighthouse terrace													
PB-Lth-01-A	10619	3.69	0.12	0.0053	1.1266	0.0027	0.6022	0.0015	1280	81.7	0.4	1.1595	0.0033
PB-Lth-01-A dup #1	10619	3.68	0.12	0.0056	1.1259	0.0019	0.6007	0.0017	1187	81.4	0.4	1.1586	0.0023
PB-Lth-01-Aa	10619	3.33	0.13	0.0071	1.1313	0.0023	0.6100	0.0046	867	82.7	0.9	1.1659	0.0028
PB-Lth-01-B	10619	4.33	0.12	0.0029	1.1219	0.0017	0.5890	0.0021	2631	79.6	0.5	1.1528	0.0020
PB-Lth-01-C	10619	4.05	0.12	0.0046	1.1201	0.0015	0.6040	0.0024	1608	82.8	0.5	1.1519	0.0018
PB-Lth-01-D	10619	4.41	0.23	0.0087	1.1200	0.0043	0.5921	0.0024	914	80.4	0.7	1.1507	0.0051
PB-Lth-01-E	10619	2.78	0.11	0.0192	1.1349	0.0024	0.6364	0.0055	280	87.6	1.2	1.1729	0.0030
PB-Lth-01-F	10619	3.38	0.12	0.0064	1.1220	0.0017	0.6015	0.0032	960	82.1	0.7	1.1539	0.0021
Punta Banda, Baja California—Sea Cave terrace													
PB-SCT-01-A	10130	3.59	0.12	0.0042	1.1111	0.0018	0.7555	0.0027	1952	120.4	0.9	1.1563	0.0024
PB-SCT-01-B	10130	4.08	0.12	0.0047	1.1103	0.0022	0.7527	0.0027	1976	119.8	0.9	1.1549	0.0029
PB-SCT-01-C	10130	4.20	0.11	0.0036	1.1110	0.0016	0.7514	0.0022	2638	119.3	0.7	1.1556	0.0021
PB-SCT-01-D	10130	3.42	0.12	0.0072	1.1139	0.0025	0.7623	0.0020	1104	121.7	0.8	1.1608	0.0032
PB-SCT-01-Db	10130	3.61	0.13	0.0125	1.1128	0.0022	0.7649	0.0056	673	122.7	1.7	1.1597	0.0030
PB-SCT-01-E	10130	3.51	0.11	0.0054	1.1130	0.0018	0.7651	0.0016	1513	122.8	0.6	1.1600	0.0023
PB-SCT-01-F	10130	4.29	0.11	0.0124	1.1075	0.0018	0.7603	0.0044	799	122.6	1.4	1.1521	0.0024
PB-SCT-01-G	10130	4.09	0.11	0.0060	1.1088	0.0022	0.7477	0.0030	1548	118.7	1.0	1.1523	0.0029
PB-SCT-01-H	10130	3.91	0.13	0.0033	1.1116	0.0030	0.7594	0.0019	2766	121.4	0.9	1.1575	0.0039
PB-SCT-01-I	10130	4.09	0.12	0.0092	1.1085	0.0016	0.7314	0.0023	984	114.3	0.7	1.1500	0.0020
PB-SCT-01-J	10130	3.83	0.11	0.0047	1.1099	0.0020	0.7568	0.0026	1857	121.0	0.9	1.1549	0.0026
PB-SCT-01-K	10130	3.80	0.11	0.0079	1.1094	0.0014	0.7541	0.0033	1097	120.4	1.0	1.1539	0.0019
PB-SCT-01-L	10130	4.34	0.11	0.0087	1.1081	0.0016	0.7555	0.0023	1147	121.1	0.7	1.1524	0.0021
PB-SCT-01-M	10130	3.67	0.11	0.0071	1.1122	0.0013	0.7669	0.0041	1195	123.5	1.2	1.1592	0.0018
PB-SCT-01-N	10130	3.98	0.11	0.0195	1.1129	0.0023	0.7682	0.0028	477	123.7	1.0	1.1603	0.0031
PB-SCT-01-O	10130	3.35	0.12	0.0328	1.1186	0.0028	0.7842	0.0112	243	127.1	3.4	1.1700	0.0041
Isla de Guadalupe, Baja California—Discovery Point Formation, SDSNH localities													
GI-01-a	0644	3.02	0.12	0.0056	1.1119	0.0019	0.7646	0.0021	1264	122.9	0.7	1.1585	0.0025
GI-01-b redo	0644	2.93	0.11	0.0002	1.1137	0.0021	0.7488	0.0044	35472	118.0	1.3	1.1589	0.0028
GI-01-c	0644	3.04	0.12	0.0048	1.1103	0.0012	0.7624	0.0022	1462	122.6	0.7	1.1562	0.0016
GI-2	0633	2.88	0.12	0.0008	1.1128	0.0018	0.7802	0.0042	8924	127.3	1.3	1.1618	0.0024
GI-03-a	2465	2.83	0.11	0.0078	1.1128	0.0017	0.7650	0.0019	845	122.8	0.7	1.1597	0.0022
GI-03-b	2465	2.77	0.11	0.0048	1.1151	0.0017	0.7693	0.0042	1343	123.5	1.3	1.1633	0.0023
GI-4	0633	2.90	0.12		1.1205	0.0020	0.7691	0.0024	23417	122.2	0.8	1.1704	0.0027
Cabo Pulmo, Baja California Sur—Unnamed terrace at +6 m above sea level													
Baja-2	11739	2.75	0.11	0.0073	1.1163	0.0020	0.7821	0.0034	890	127.0	1.1	1.1667	0.0027
Baja-2a	11739	2.78	0.12	0.09	1.1183	0.0025	0.7598	0.0056	71	120.1	1.7	1.1662	0.0033
Baja-5	11739	2.83	0.12	0.08	1.1274	0.0018	0.8304	0.0034	95	139.3	1.2	1.189	0.0025

Note: Ages (and their initial U isotope ratios) in bold type have the highest reliability. AR—activity ratio, dup—duplicate, SDSNH—San Diego Society of Natural History.

anophyllia, we conclude that this species still has the potential for accurate age determination of marine-terrace deposits.

As with hermatypic colonial corals from the tropics, the best criterion for determining closed-system conditions during the postemergence history of a fossil is concordance between ²³⁰Th/²³⁴U and ²³¹Pa/²³⁵U ages. We did not determine ²³¹Pa/²³⁵U ages for our samples. However, a second criterion for closed-system history is whether the calculated initial ²³⁴U/²³⁸U value is within the range of this ratio in modern seawater. Edwards et al. (1997) showed that corals with

calculated initial ²³⁴U/²³⁸U values as high as 1.166 showed concordance between ²³⁰Th/²³⁴U and ²³¹Pa/²³⁵U ages. In this study, we consider as “reliable” any corals with initial ²³⁴U/²³⁸U values from 1.142 (the lowest ratio measured in living *Balanophyllia elegans*) to 1.159 (following Stirling et al., 1998).

Cayucos Area, Central California

The geomorphically well expressed low terrace in the Cayucos area of San Luis Obispo County, California, has long been the focus of

study, both for the timing of high sea level and invertebrate paleontology (Valentine, 1958; Veeh and Valentine, 1967; Stein et al., 1991; Muhs et al., 1994b). The terrace is extensive along the central California coast in this area and is easily mapped (Fig. 4). The Cayucos terrace has a shoreline angle elevation of ~7–8 m, and platform exposures in the modern sea cliff are as high as 5 m. The marine deposits on this platform consist of a lag of boulders overlain by fossiliferous sands, cemented in some places into a coquina. Corals were abundant at four localities that we stud-

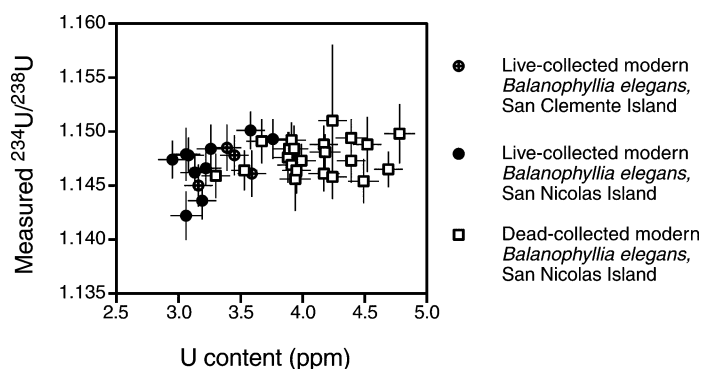


Figure 3. U concentrations and measured $^{234}\text{U}/^{238}\text{U}$ values in modern, live-collected and modern, dead-collected specimens of the solitary coral *Balanophyllia elegans* from San Nicolas Island and San Clemente Island, California.

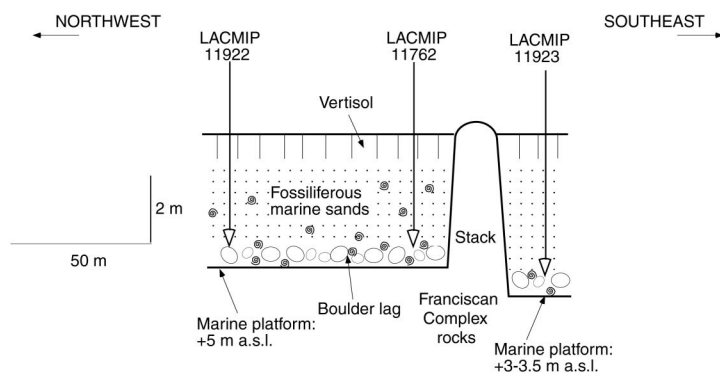
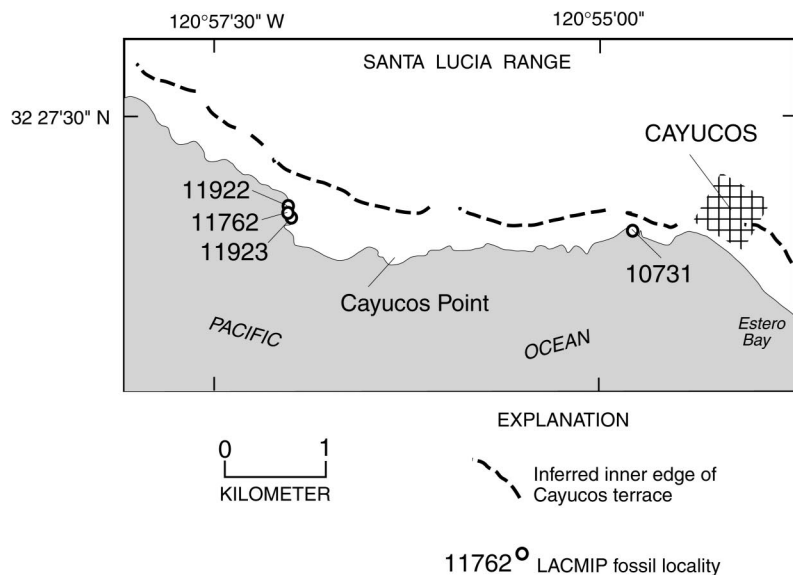


Figure 4. Map showing inferred inner edge of the Cayucos terrace (mapped by the authors), fossil localities, and stratigraphy of fossil localities exposed in sea cliff in the Cayucos area, California.

ied (Fig. 4; LACMIP [Los Angeles County Museum, Invertebrate Paleontology] localities 10731, 11762, 11922, 11923).

Previous TIMS U-series analyses of corals from the Cayucos terrace showed that all samples have been affected by open-system conditions, on the basis of initial $^{234}\text{U}/^{238}\text{U}$ values that are much higher than the ratio in modern seawater (Stein et al., 1991). All of these samples came from, or near, our LACMIP location 10731. The apparent ages, with one exception (ca. 101 ka), ranged from 125 to 113 ka, and the initial $^{234}\text{U}/^{238}\text{U}$ values ranged from 1.161 (101 ka sample) to 1.201 (ca. 114 ka sample) (Stein et al., 1991). Our analyses of corals from this locality yielded similar results. The U contents were within the range of modern, dead-collected corals shown in Figure 3, and the $^{230}\text{Th}/^{232}\text{Th}$ values were high, indicating little or no inherited ^{230}Th . Two samples gave apparent ages of ca. 109 ka (also the lowest initial $^{234}\text{U}/^{238}\text{U}$ value, 1.168), and the rest gave a range of apparent ages from ca. 123 to 116 ka and initial $^{234}\text{U}/^{238}\text{U}$ values of 1.174–1.193. At localities west of Cayucos, and northwest of Cayucos Point, the apparent ages were ca. 143–119 ka, and all samples showed high initial $^{234}\text{U}/^{238}\text{U}$ values.

Anomalously high initial $^{234}\text{U}/^{238}\text{U}$ values are commonly reported in fossil corals. Gallup et al. (1994) presented a model of continuous, postemergence addition of both ^{230}Th and ^{234}U to Barbados corals that explains the higher initial $^{234}\text{U}/^{238}\text{U}$ values and a tendency for such corals to show ages older than those with acceptable $^{234}\text{U}/^{238}\text{U}$ values from the same deposit. Stirling et al. (1998) concluded that the same processes of nuclide additions have been operating on last interglacial corals in Western Australia. Gallup et al. (1994) estimated the degree of age bias in samples on the basis of trends observed in corals on Barbados. For example, if a fossil coral begins with a $^{234}\text{U}/^{238}\text{U}$ value of 1.149 and shows a present $^{234}\text{U}/^{238}\text{U}$ value of 1.153, Gallup et al. (1994) estimated an age bias (to an older age) of ~1000 yr. In both the Stein et al. (1991) Cayucos data set and our own, the least-biased samples would therefore be those that have apparent ages of younger than ca. 110 ka. By using the model of Gallup et al. (1994), the ages of our two youngest samples would be ca. 104 ka. These ages agree reasonably well with the estimated age of the Ventnor terrace on Barbados, on the basis of both alpha-spectrometric U-series dating (Ku, 1968; Mesolella et al., 1969; Ku et al., 1990) and more recent TIMS U-series dating (Gallup et al., 1994; Edwards et al., 1997). The ages also correspond to substage 5c of the deep-sea oxygen isotope record (Martinson et

al., 1987). If the same model were used, other corals from Cayucos would likely be biased by greater amounts, on the order of 10–30 k.y. Some of these corals could have true ages of ca. 108–102 ka, but others (mostly from the localities northwest of Cayucos Point) could have true ages of ca. 133–110 ka, and many others' true ages could be ca. 126–114 ka. Although we think it is premature to use the Gallup et al. (1994) model as a method for *precise* correction of corals that have been affected by open-system conditions, we think, as did Stirling et al. (1998), that it is a reasonable first approximation for the degree of age bias. If this opinion is correct, then our data and those of Stein et al. (1991) suggest that corals from Cayucos represent two distinct sea-level highstands that are recorded on Barbados as separate terraces: the ca. 105 ka Ventnor terrace (formed during deep-sea substage 5c) and the ca. 120 ka Rendezvous Hill terrace (formed during deep-sea substage 5e). There is no significant difference in physical appearance or stratigraphic position of the corals of 120 ka age and those of 105 ka age, suggesting that the reworking process mixed the corals of the two ages efficiently.

Point Loma, San Diego, California

Two low marine terraces are present along the west side of Point Loma near San Diego (Fig. 5). The shoreline angle of the lower Bird Rock terrace lies at an elevation of ~8–9 m and that of the higher Nestor terrace lies at an elevation of ~23–24 m at the south end of the peninsula (Kern, 1977; Kern and Rockwell, 1992). Both are veneered with a thick cover (up to ~15 m on the Bird Rock terrace) of nonmarine sediments and paleosols developed in these deposits (Fig. 5). On the basis of previous alpha-spectrometric U-series analyses, the Nestor terrace is thought to date to the ca. 120 ka sea-level highstand, and the Bird Rock terrace is thought to date to the ca. 80 ka sea-level highstand (Ku and Kern, 1974; Muhs et al., 1994b). By using TIMS U-series analyses, Stein et al. (1991) reported ages of ca. 145–133 ka for four corals from the Nestor terrace and an age of ca. 97 ka for a single coral from the Bird Rock terrace, all with high initial $^{234}\text{U}/^{238}\text{U}$ values.

Our results also showed that all corals from the Nestor and Bird Rock terraces have been subject to open-system conditions, in agreement with Stein et al. (1991). Apparent ages for the Nestor terrace range from ca. 150 to 98 ka and those from the Bird Rock terrace range from 127 to 88 ka. Applying the Gallup et al. (1994) model to the Nestor terrace corals

results in two specimens having possible ages of 90–88 ka, seven having possible ages of 109–100 ka, and four having possible ages of 136–116 ka. On the Bird Rock terrace, two corals could have ages of 85–80 ka, and one could have an age of ca. 112 ka. The two youngest corals from the Nestor terrace (uncorrected ages of ca. 98 and 107 ka) have exceptionally high U contents of 5.8 and 7 ppm, respectively. We suspect that these corals, along with another (sample NT-SD-E, with 6.1 ppm U) have acquired bulk U additions from terrestrial waters well after terrace emergence, which would tend to bias the corals to younger ages. If we do not consider these high-U samples, the range of possible ages of the Nestor terrace corals is similar to the corals in the Cayucos terrace. The Nestor terrace has both a younger (109–100 ka, “corrected”) group that could correspond to the same sea-level highstand as the 105 ka Ventnor terrace on Barbados and an older (136–116 ka, “corrected”) group that could correspond to the ca. 120 ka Rendezvous Hill terrace on Barbados. As with the two apparent age groups of corals from Cayucos, the two age groups of Nestor terrace corals do not show any differences in appearance. The Bird Rock terrace could correspond to the ca. 80 ka Worthing terrace on Barbados, although it apparently has at least one older, reworked coral.

San Clemente Island, California

Marine terraces on San Clemente Island are exceptionally well preserved (Fig. 6). As many as 22 marine terraces may exist on this island, and the youngest of these are very well expressed geomorphically on the northern part of the island (Figs. 7 and 8), where they have been mapped by Muhs (1983). At least 12 terraces are found on the northern part of the island and are cut into Tertiary volcanic rocks, mainly andesite. Marine-terrace deposits are thin, usually less than 1 m thick, and are only rarely fossiliferous. The second terrace is one of the broadest and geomorphically best expressed landforms on the island (Fig. 6). It was informally designated the “Eel Point terrace” by Muhs and Szabo (1982), Muhs (1983), and Muhs et al. (1994b). When first studied by Muhs (1983), two surfaces were included in what was mapped as the “Eel Point terrace”: a narrow, inner (landward) surface that was reported to have a shoreline angle elevation of 30–32 m and a broader, outer (seaward) surface that has an elevation of ~21 m at its inner edge and ~8 m at its outer edge at Eel Point. Muhs (1983) interpreted the inner surface to be either a storm bench or simply

the inner, higher-gradient part of a single terrace that extended seaward all the way to Eel Point (cf. studies of modern shore platforms by Bradley and Griggs, 1976). Pedologic studies indicated little or no difference in degree of soil development on the 30–32 m and 21 m surfaces, but soils on the next higher terrace (inner edge at 45–50 m) are significantly better developed (Muhs, 1982). Later studies by Kennedy et al. (1995) suggested that the surface whose inner edge is at 30–32 m is a separate terrace, distinct from the broader, seaward part of the “Eel Point terrace” whose inner edge elevation is ~21 m. Thus, the 30–32 m surface may have formed during a relatively high sea stand that occurred before the formation of the ~21 m surface. In the present study, we mapped the two surfaces separately (Figs. 7 and 8); the inner (30–32 m) surface is referred to as terrace 2a, and the outer (21 m) surface is referred to as terrace 2b. The term “Eel Point terrace” now refers strictly to what is mapped as terrace 2b in Figures 7 and 8.

The Eel Point terrace has one of the few fossil-bearing localities on the island, at Eel Point itself (Figs. 7 and 8). By using alpha spectrometric U-series methods, Muhs and Szabo (1982) dated the hydrocoral *Styaster californicus* from Eel Point to $127,000 \pm 14,000$ yr (2 σ errors), and Muhs et al. (1994b) dated a collection of *Balanophyllia elegans* corals to $111,000 \pm 6,000$ yr. Specimens of *B. elegans* were re-collected from exposures on both the north and south sides of Eel Point (Fig. 7) and analyzed individually in the present study.

Corals from the Eel Point terrace on San Clemente Island showed much more evidence for closed-system histories than did corals from either Cayucos or Point Loma (Table 1). All San Clemente Island corals have U contents of 3.4–4.6 ppm, similar to the range for modern, dead-collected corals shown in Figure 3. In addition, with two exceptions (samples SCI-18-A and SCI-18-C), corals from San Clemente Island showed very high $^{230}\text{Th}/^{232}\text{Th}$ values, indicating little or no inherited ^{230}Th . Of 29 corals analyzed, 19 had initial $^{234}\text{U}/^{238}\text{U}$ values that ranged from 1.149 to 1.159, which we consider to be indicative of closed-system histories. At worst, according to the model of Gallup et al. (1994), the samples with the highest initial $^{234}\text{U}/^{238}\text{U}$ values in this “acceptable” group could be biased to older ages by only ~2500 yr. Apparent ages of corals in this latter group range from ca. 128 to 114 ka, supporting a correlation to the Rendezvous Hill terrace of Barbados.

Two corals from San Clemente Island (samples SCI-18-A and SCI-18-C) have

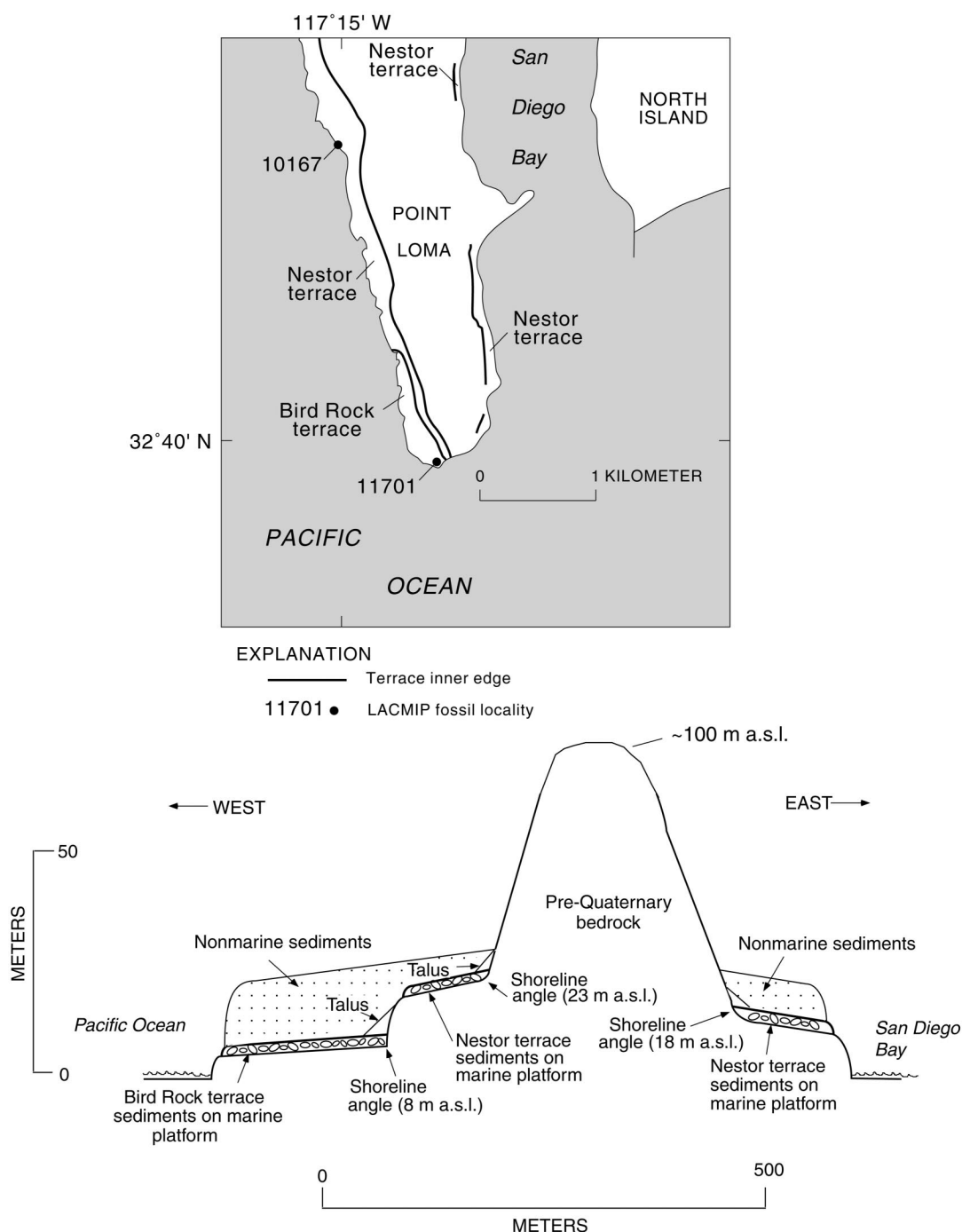


Figure 5. Map showing inferred inner edge of the Nestor and Bird Rock terraces on Point Loma (from Kern, 1977), fossil localities, and cross section of terraces at the south end of Point Loma (stratigraphy by the authors; shoreline angle elevations measured by Kern, 1977).

ages and isotopic ratios that are more difficult to interpret. These two corals have relatively low (<200) $^{230}\text{Th}/^{232}\text{Th}$ values, somewhat high (1.161–1.162) initial $^{234}\text{U}/^{238}\text{U}$ values, and significantly older (ca. 141 and ca. 137 ka) apparent ages. The lower $^{230}\text{Th}/^{232}\text{Th}$ values suggest some inherited ^{230}Th (due to contaminating minerals), which would tend

to bias the results to older ages, as would the higher initial $^{234}\text{U}/^{238}\text{U}$ values. Although we cannot make precise corrections without knowing the $^{230}\text{Th}/^{232}\text{Th}$ value of the contaminating, noncarbonate material, we suspect that these two corals may be biased to older ages by at least several thousand years.

Punta Banda, Northern Baja California

Twelve marine terraces, well expressed geomorphically, as well as higher undifferentiated terraces, are present on Punta Banda in northern Baja California, just south of Ensenada, Mexico (Fig. 9). Because of faulting of the peninsula, the elevation of the shoreline angle

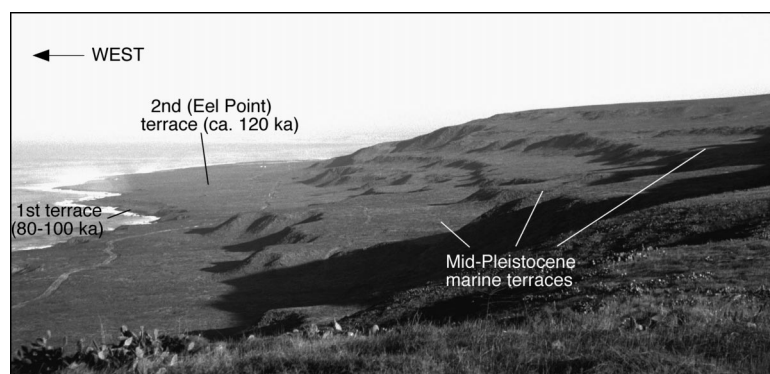


Figure 6. View of marine terraces on the west coast of San Clemente Island, looking northward. Photograph by the authors.

of the first or lowest terrace (Lighthouse terrace) varies from 15 to 18 m, and that of the third terrace (Sea Cave terrace) varies from 34 to 40 m (Rockwell et al., 1989). Fossiliferous sediments on both terraces (Fig. 9) yielded *Balanophyllia elegans*. Sediments on an intermediate terrace (elevation, 22 m) near the western tip of Punta Banda are unfossiliferous. Rockwell et al. (1989) and Muhs et al. (1994b) reported alpha-spectrometric U-series ages of ca. 80 ka for bulk coral samples (multiple individuals) from the Lighthouse terrace and ages of ca. 120 ka for bulk coral samples from the Sea Cave terrace.

TIMS U-series analyses of *Balanophyllia elegans* from the Punta Banda terraces, as with those on San Clemente Island, mostly showed evidence of probable closed-system history and therefore have reliable ages (Table 1). For both the Sea Cave and Lighthouse terraces, concentrations of U are within the range of modern, dead-collected solitary corals; $^{230}\text{Th}/^{232}\text{Th}$ values are high, indicating no inherited ^{230}Th daughter species; and 18 of 24 samples have initial $^{234}\text{U}/^{238}\text{U}$ values that are 1.159 or lower. With one exception (ca. 114 ka), the ages of closed-system corals from the Sea Cave terrace have a narrow range of ca. 123 to ca. 119 ka. The overall range of Sea Cave terrace ages is very similar to that of the Eel Point terrace on San Clemente Island. Six Lighthouse terrace corals with acceptable initial $^{234}\text{U}/^{238}\text{U}$ values also have a narrow range of ages, from ca. 83 to ca. 80 ka.

Isla de Guadalupe and Cabo Pulmo, Baja California

Although the focus of our study has been on U-series dating of solitary, ahermatypic corals, some emergent marine deposits in peninsular Baja California well south of Punta Banda contain colonial hermatypic forms,

such as *Pocillopora* and *Porites*. Muhs et al. (1994b) reported alpha-spectrometric U-series ages of colonial corals from Isla de Guadalupe, to the west of Baja California, and from Cabo Pulmo, on the east coast of Baja California Sur (Figs. 1, 10, 11). In the present study, we redated these corals by using higher-precision TIMS methods.

Isla de Guadalupe is an alkalic seamount on a fossil ridge crest ~330 km west of Baja California. In places, the island has a fossiliferous Pleistocene marine deposit (called the Discovery Point Formation by Lindberg et al., 1980) within a few meters of present sea level (Fig. 10). The fossiliferous deposit is predominantly conglomerate, but unlike coastal California and northern Baja California, a platform is usually not present. Elevations of the deposit range from near sea level to as high as 6 m above sea level (Lindberg et al., 1980). In southernmost Baja California Sur, Squires (1959) and Ortlieb (1987) described spatially limited outcrops of a coral-bearing marine conglomerate resting on a granitic platform near Cabo Pulmo (Fig. 11). Ortlieb (1987) inferred a shoreline angle elevation of ~6 m for the terrace platform at this locality, and new measurements made by us confirm this. Species of the colonial corals *Porites* and *Pocillopora* are currently living subtidally offshore Cabo Pulmo, but do not live as far north as Isla de Guadalupe. However, the Discovery Point Formation contains well-preserved specimens of what has been identified as a new species, *Pocillopora guadalupensis* (Durham, 1980).

Pocillopora from the Discovery Point Formation have U contents of 2.8–3.0 ppm, which is typical of both modern and fossil specimens of *Pocillopora* (Muhs and Szabo, 1994; Szabo et al., 1994; Muhs et al., 2002). All samples have very high $^{230}\text{Th}/^{232}\text{Th}$ values, indicating no inherited daughter species. All

three fragments analyzed from specimen GI-1 have acceptable initial $^{234}\text{U}/^{238}\text{U}$ values (ages of ca. 123–118 ka), as does one fragment from sample GI-3 (age of ca. 123 ka). Two fragments of GI-1 have ages that are in agreement with each other, but the third is significantly younger than the other two. However, the younger sample (ca. 118 ka) may be the closest to the true age, because this fragment has an order-of-magnitude-higher $^{230}\text{Th}/^{232}\text{Th}$ value. None of the samples from Cabo Pulmo has acceptable initial $^{234}\text{U}/^{238}\text{U}$ values, but two specimens of sample Baja-2 (*Porites*) have ratios of 1.1662–1.1667, suggesting a bias toward older ages of perhaps 4000–5000 yr (thus, true ages of ca. 122–115 ka). Baja-5, a *Pocillopora*, is clearly biased toward a much older age. Although it is not possible to determine precise ages at Cabo Pulmo, the corals there and from the Discovery Point Formation on Isla de Guadalupe almost certainly represent the same sea-level highstand represented by the Eel Point (San Clemente Island), Sea Cave (Punta Banda), and Rendezvous Hill (Barbados) terraces, all of which correlate to the peak of the last interglacial period, i.e., oxygen isotope substage 5e.

DISCUSSION

Timing of the Last Interglacial Sea-level Highstand on the Pacific Coast of North America

The marine-terrace record of the Pacific Coast of North America can be compared with tectonically rising islands found in the tropics, where there have been numerous TIMS U-series studies. In this comparison, we refer only to ages that were measured in fossils that showed closed-system conditions, according to the criteria already discussed. On slowly rising Barbados, Hamelin et al. (1991) reported a range of ages for the last interglacial Rendezvous Hill terrace of ca. 133–113 ka, which overlaps the range of 130–117 ka reported by Gallup et al. (1994). Edwards et al. (1987, 1997) reported a more restricted range of ages from 129 to 122 ka. On the rapidly uplifting Huon Peninsula of New Guinea, Stein et al. (1993) reported two clusters of ages for reef VIIb, which is also correlated with marine oxygen isotope substage 5e. The older group ranges from ca. 136 to 132 ka whereas the younger group ranges from ca. 119 to 116 ka. The majority of coral ages from the Eel Point terrace on San Clemente Island (ca. 128–114 ka, with all but one 123–114 ka) and the Sea Cave terrace on Punta Banda (ca. 123–114 ka)

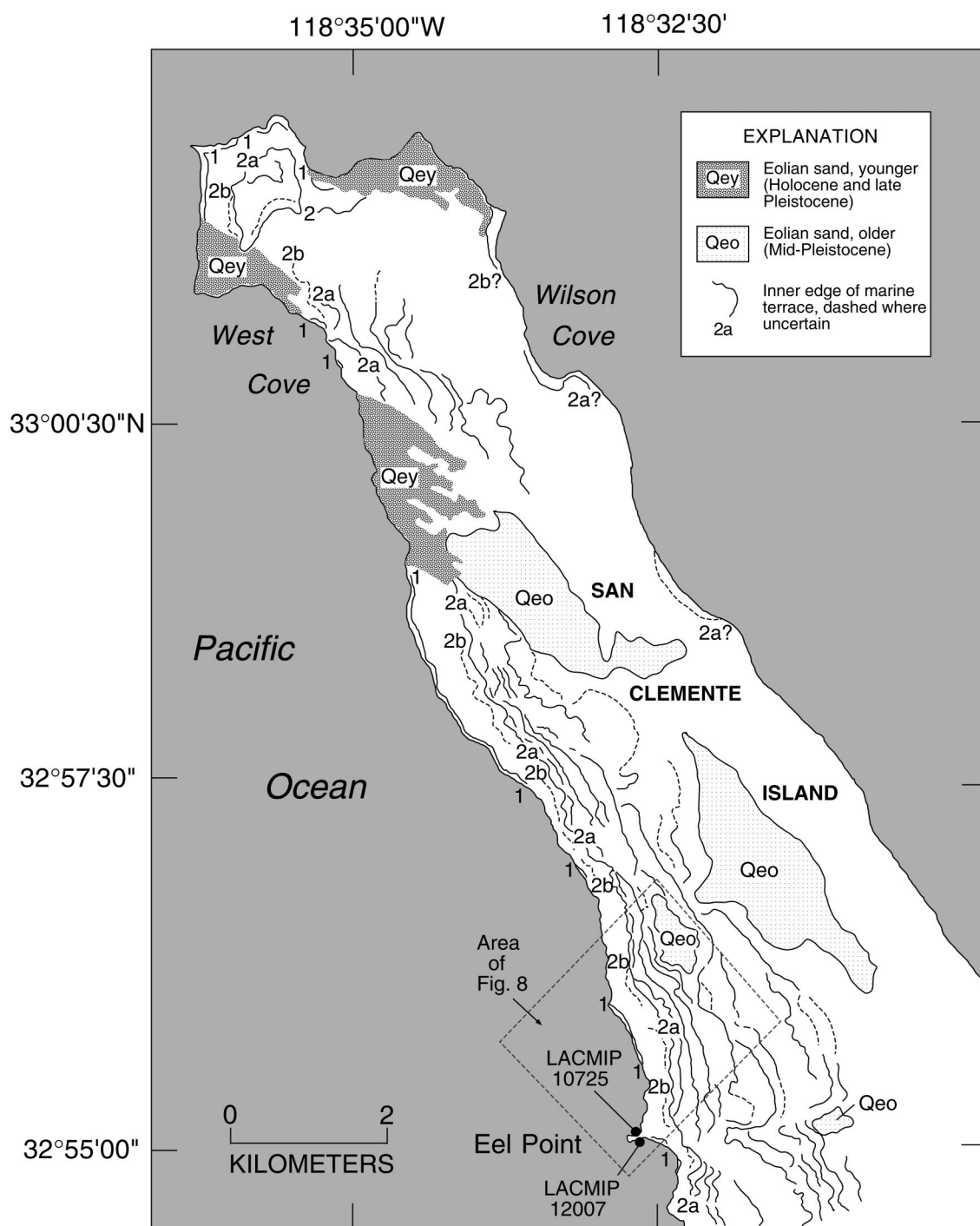


Figure 7. Map of northern San Clemente Island showing Quaternary deposits, inferred inner edges of marine terraces (mapped by the authors, modified from Muhs, 1983), and fossil localities at Eel Point.

overlap the youngest range of ages found on Barbados and New Guinea.

There are also numerous U-series ages from tectonically stable or very slowly uplifting coastlines such as the Bahamas, Hawaii, and Western Australia. Emergent reefs on San Salvador Island and Grand Inagua Island in the Bahamas have corals in growth position at elevations of up to 5 m. U-series ages of these corals reported by Chen et al. (1991) range

from ca. 130 to ca. 120 ka. On other islands of the Bahamas, corals are as young as ca. 110 ka (Muhs et al., 1994a). U-series ages of last interglacial corals from Hawaii range from ca. 133 to 110 ka (Szabo et al., 1994; Muhs et al., 2002). On the mainland coast and islands of tectonically stable Western Australia, emergent reefs and marine deposits are widespread, and the degree of coral preservation is generally high. The tops of most of the emergent

reefs at many localities range from ~2 to 4 m above sea level. U-series ages of Western Australian corals range from ca. 134 to 116 ka (Zhu et al., 1993; Collins et al., 1993; Stirling et al., 1995, 1998).

We conclude that the ages of last interglacial corals from San Clemente Island, Punta Banda, and Isla de Guadalupe overlap with the ranges of ages of hermatypic colonial corals from the tropics (Figs. 12 and 13). From the

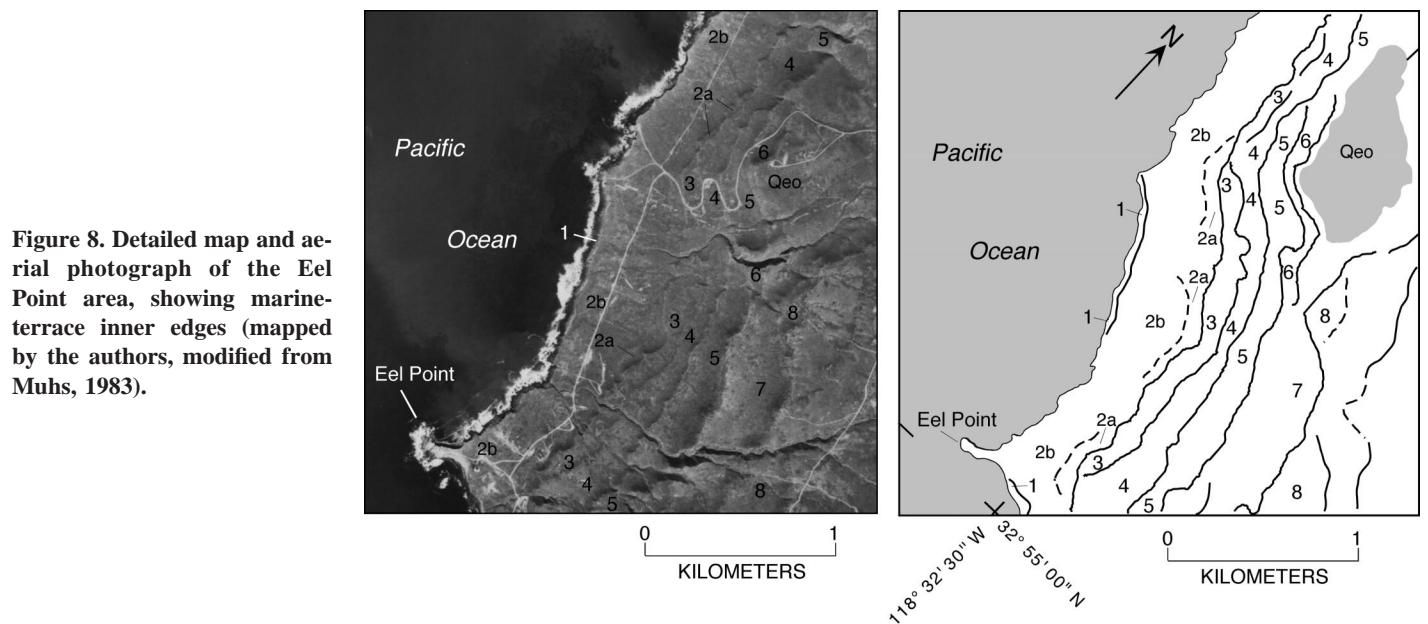


Figure 8. Detailed map and aerial photograph of the Eel Point area, showing marine-terrace inner edges (mapped by the authors, modified from Muhs, 1983).

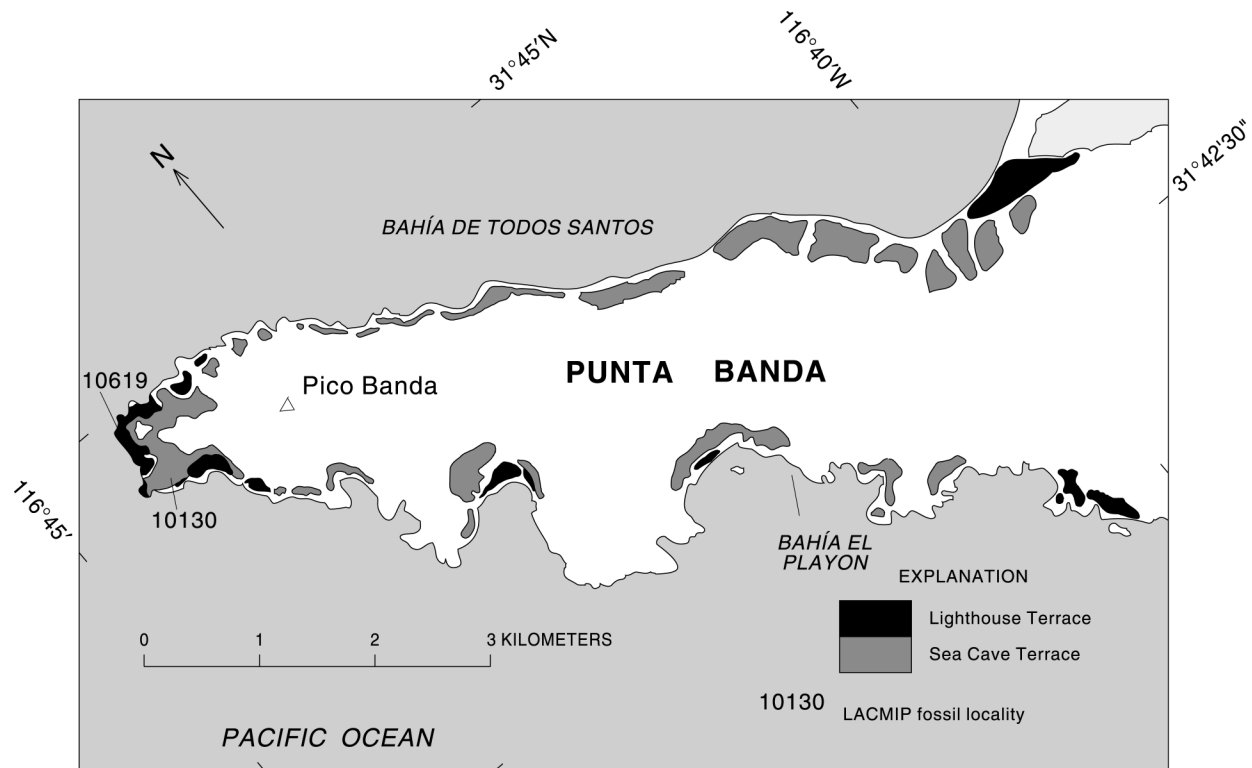


Figure 9. Map showing extent of the lowest two marine terraces on Punta Banda, Baja California, and fossil localities. Mapped by the authors, slightly modified from Rockwell et al. (1989).

three Pacific Coast localities, 27 corals with acceptable initial $^{234}\text{U}/^{238}\text{U}$ values showed no ages greater than ca. 123 ka, and some are as young as ca. 114 ka. This ~ 9 k.y. span of time overlaps with the youngest ages of corals on all tropical coastlines, whether tectonically ris-

ing or stable. The results support the model proposed by Bradley and Griggs (1976), shown in Figure 2, in that Pacific Coast marine-terrace deposits are recording the final stage of the last interglacial sea-level high-stand. Key to the support of this conclusion is

the model of Neumann and MacIntyre (1985), in which they point out that "keep-up" reefs, such as barrier or fringing reefs found on Barbados, New Guinea, and the Bahamas, should have the earliest reef growth during an interglacial. This concept is based on the obser-

vation that shallow-water corals, such as *Acropora palmata*, grow rapidly enough to keep pace with rising sea level (Buddemeier and Smith, 1988).

Numerous ages of ca. 116–114 ka from the Pacific Coast of North America, Hawaii, and the Bahamas show that sea level must have been relatively high during a time that has been considered to be a period of global ice-sheet growth, i.e., deep-sea oxygen isotope substage 5d (Martinson et al., 1987). This time period coincides with the lowest summer insolation at northern high latitudes of the past 200 k.y. (Figs. 12 and 13). Coral ages reported here and elsewhere challenge the view that there was significant ice growth in the period from ca. 116 to 114 ka. Studies of deep-sea cores from the North Atlantic have suggested that relatively warm, interglacial-like conditions existed not only during substage 5e, but persisted well into substage 5d (McManus et al., 1994; Kukla et al., 1997; Broecker, 1998; Kukla, 2000).

Later Sea-level Highstands During the Last Interglacial Period

The new coral ages presented here provide the first substantial evidence for a sea-level highstand on the Pacific Coast of North America at ca. 105 ka, as recorded by the Ventnor terrace on Barbados and reef VI on New Guinea. Although initial $^{234}\text{U}/^{238}\text{U}$ values are high, both the Cayucos terrace and the Nestor terrace on Point Loma have corals that are likely ca. 105 ka, mixed with older corals that are likely ca. 120 ka. These data raise the question of how high sea level was during the ca. 105 ka sea-level highstand.

There are significant differences in estimates of paleo-sea levels for the ca. 105 and ca. 80 ka sea-level highstands. On Barbados, paleo-sea levels of about –20 m are estimated for both the ca. 105 and ca. 80 ka sea stands by Bard et al. (1990). On New Guinea, Chappell and Shackleton (1986) estimated paleo-sea levels of about –18 m at ca. 105 ka and about –16 m at ca. 80 ka. The sea-level estimates for both Barbados and New Guinea were calculated by using assumptions of a paleo-sea level of +6 m at ca. 120 ka and a constant uplift rate. By using the same method, Ota and Omura (1992) reported that on Hateruma Island (Japan), sea level at ca. 105 ka could have been about –3 m and sea level at ca. 80 ka could have been near the present height. The latter estimate is in agreement with data from tectonically stable Bermuda, Florida, and the Atlantic Coastal Plain of the eastern United States, where there are numerous ca. 80 ka

U-series ages of corals from deposits above or near present sea level (Szabo, 1985; Ludwig et al., 1996; Wehmiller et al., 1997; Muhs et al., 2002). On the Pacific Coast, the only locality that allows independent calculations of paleo-sea levels at these times is Punta Banda. The U-series ages presented here indicate that the Sea Cave terrace (shoreline angle elevation of ~34 m) has only ca. 120 ka corals and the Lighthouse terrace (shoreline angle elevation of ~16 m) has only ca. 80 ka corals. We infer, on the basis of these ages and correlation to Barbados and New Guinea, that the intermediate, ~22 m terrace on Punta Banda corre-

sponds to the 105 ka sea-level highstand, as suggested by Rockwell et al. (1989). If this is the case, then calculation of paleo-sea levels using the constant-uplift-rate method yields estimates of about –2 m and about –3 to –4 m for the 105 and 80 ka sea-level highstands, respectively. Finally, paleo-sea levels can be calculated from terrace data by a means other than the constant-uplift-rate method. Bloom and Yonekura (1985) used the same terrace data presented in Bloom et al. (1974) for New Guinea and calculated paleo-sea levels with a graphical method that is mathematically different from the constant-uplift-rate method.

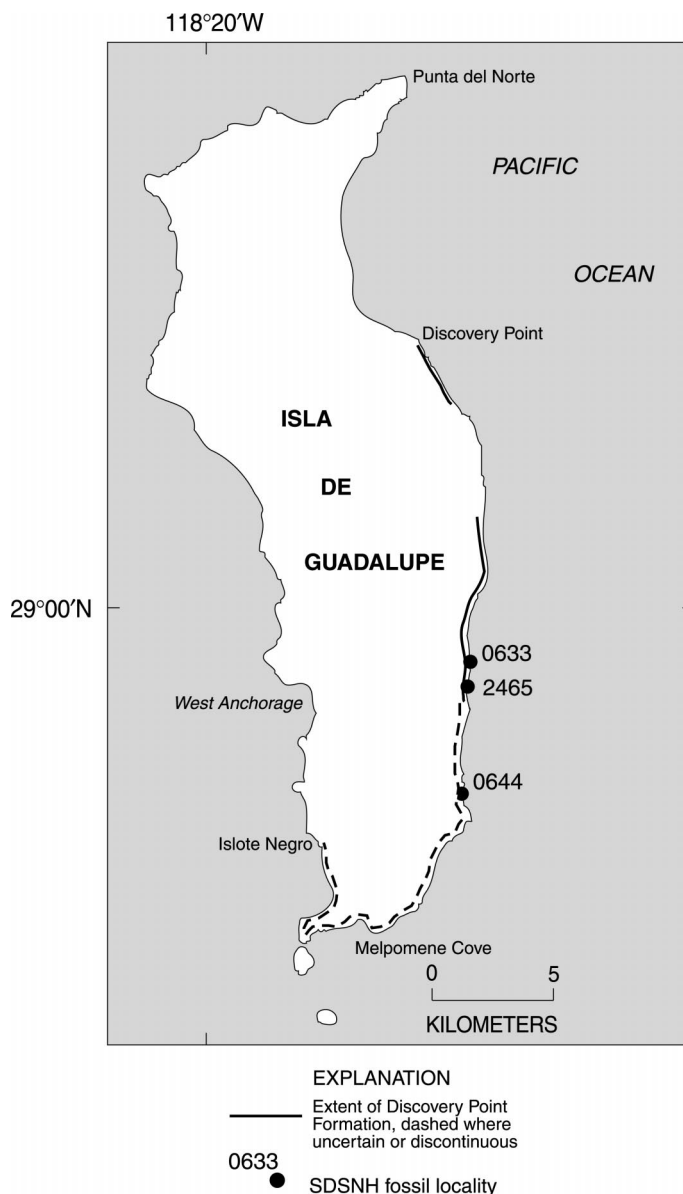


Figure 10. Map showing inferred extent of the Discovery Point Formation marine-terrace deposit and fossil localities on Isla de Guadalupe, Baja California. Extent of marine-terrace deposits inferred by the authors from data in Lindberg et al. (1980).

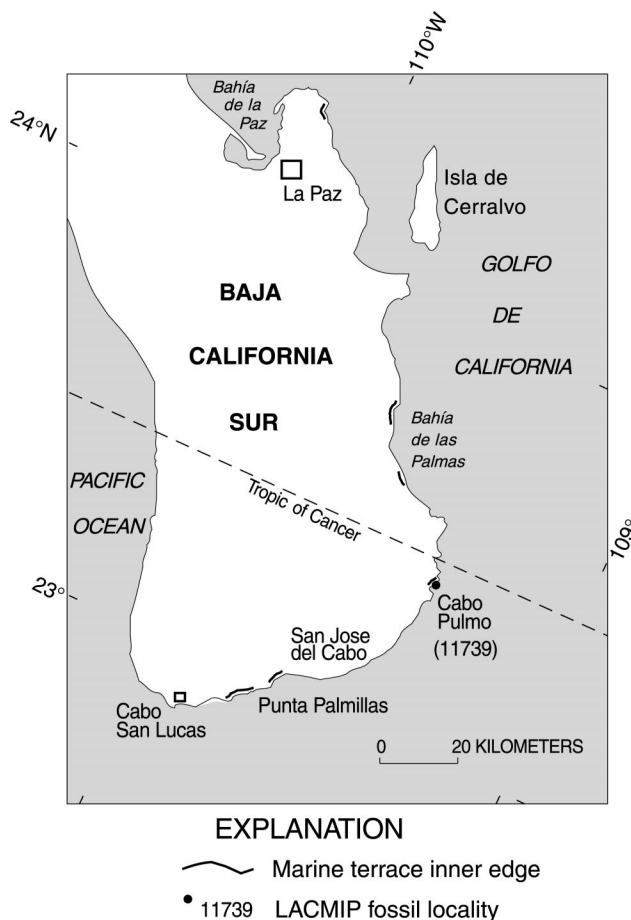


Figure 11. Map showing extent of marine-terrace deposits in southernmost Baja California Sur (from Ortlieb, 1987) and fossil locality in the Cabo Pulmo area.

Their results suggested that sea level at ca. 105 ka could have been close to the present height and sea level at ca. 80 ka could have been about -7 m.

If the estimates of sea level close to the present height at ca. 105 ka are correct, then the mixtures of apparent ca. 105 ka and ca. 120 ka corals on the Cayucos terrace and Nestor terrace are explained. The observations made here suggest that in areas of relatively low uplift rate, at least the distal (seaward) part of a terrace created by the ca. 120 ka sea-level highstand was later reoccupied by the sea-level highstand of ca. 105 ka. The shoreline angle elevation of the Cayucos terrace is only ~ 7 – 8 m and is therefore barely above the maximum elevation of the ca. 120 ka sea-level highstand, on the basis of last interglacial reef elevations from tectonically stable coastlines and islands such as Isla de Guadalupe (reported here), the Bahamas (Chen et al., 1991; Muhs et al., 1994a), and Western Australia (Zhu et al., 1993; Collins et al., 1993; Stirling et al., 1995, 1998). Thus, if the sea-level stand

of ca. 105 ka were near the present height, the probability is high that it would reoccupy at least a part of the terrace created by the ca. 120 ka stand at Cayucos. The uplift rate at Point Loma, although higher than that at Cayucos, is still low compared to that for Punta Banda. Thus, the sea-level highstand of ca. 105 ka may also have partially reoccupied the ca. 120 ka platform at Point Loma before much uplift took place. If the estimates of an approximately -20 m sea level for the ca. 105 ka sea level are correct (e.g., Bard et al., 1990), then it is more difficult to explain the mixture of fossils on the Cayucos and Nestor terraces, unless highly nonlinear tectonics are invoked.

At Punta Banda, six *Balanophyllia* samples from the Lighthouse terrace yielded reliable U-series ages that range from ca. 83 to 80 ka and, as already indicated, suggest a paleo-sea level no more than a few meters below that at present. There are few reliable TIMS U-series ages from the correlative Worthing terrace (a “keep-up” reef) on Barbados for age compar-

isons, but those that exist (and that have at least marginally acceptable initial $^{234}\text{U}/^{238}\text{U}$ values) are somewhat older than the Lighthouse terrace corals (Fig. 14). This difference is similar to that between the older Sea Cave (Punta Banda) and Rendezvous Hill (Barbados) terraces (Fig. 13). In contrast, the ages of corals from Bermuda (derived from what was probably a “catch-up” patch reef) reported by Ludwig et al. (1996) and Muhs et al. (2002) are similar to those from the Lighthouse terrace on Punta Banda (Fig. 14). Thus, we hypothesize that terraces on the Pacific Coast that were generated during the ca. 80 ka sea-level highstand may also record the final stages of this later high sea level. High-precision dating of corals from other localities that have ca. 80 ka corals (see Muhs et al., 1994b) could provide a more rigorous test of this hypothesis.

Paleozoogeography and Marine Temperatures During Last Interglacial Sea-level Highstands

Fossil mollusks from marine terraces provide a powerful tool for estimating marine paleotemperatures during interglacial sea-level highstands (Kennedy, 2000). Before modern geochronological methods were developed, however, a persistent question in the paleontological community was why there were apparent mixtures of extralimital northern and southern species (i.e., species whose northern or southern range endpoints are beyond the study area) in what were perceived to be marine deposits of similar age. Critical to this apparent contradiction was an assumption that the lowest marine-terrace deposits at all localities along the Pacific Coast were of similar age. For example, Arnold (1903), Woodring (1935, 1957), Woodring et al. (1946), Valentine (1961), and Valentine and Meade (1961) have all pointed out that deposits of the “first” terrace in northern San Pedro, California, have a distinct warm-water fauna, whereas deposits of the “first” terrace in central and southern San Pedro have a distinct cool-water fauna. These workers proposed various mechanisms to explain this geographic zonation including upwelling, transportation of the cool-water species from greater depths by storm waves, reworking from older units, and changes in depth or temperature tolerances. Aminostratigraphic studies (Wehmiller et al., 1977; Kennedy et al., 1982) with good paleontological characterization showed that the assumption of an identical age for the lowest marine terrace all along the Pacific Coast is incorrect and that terrace deposits with cool-

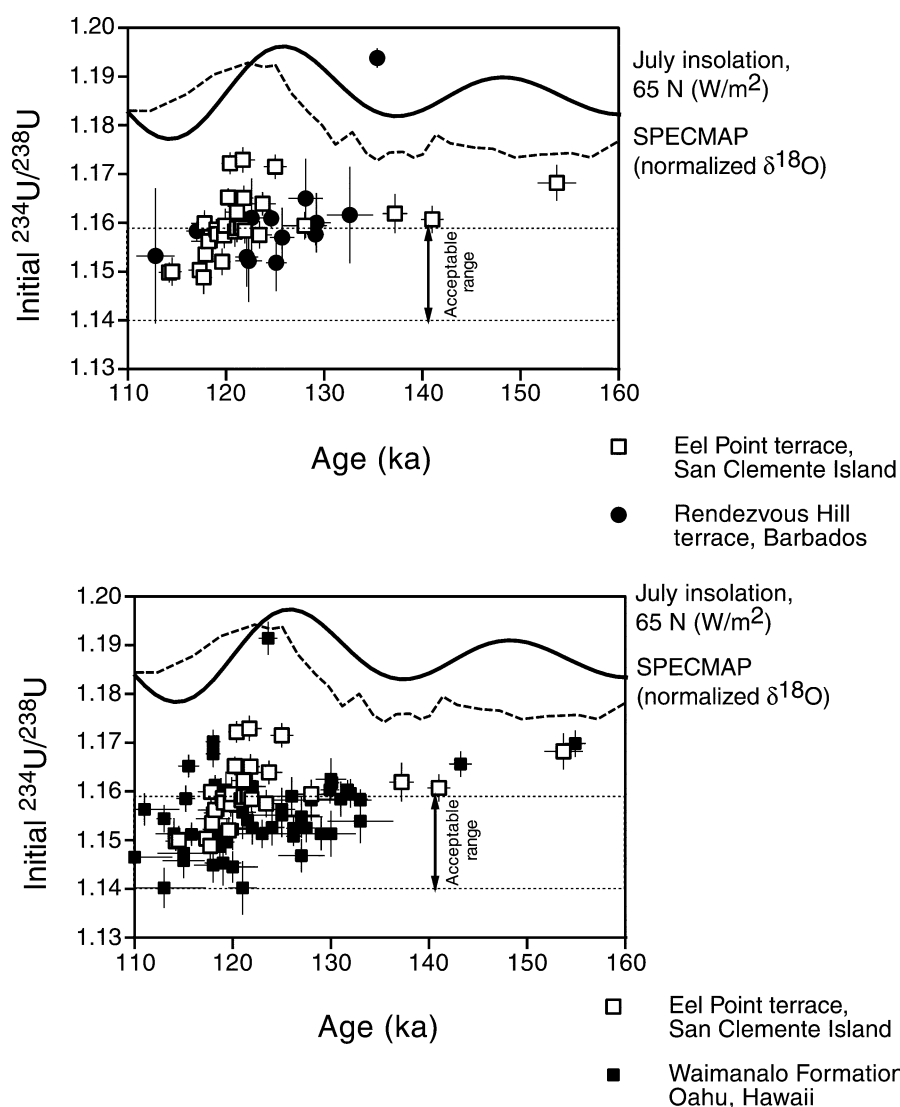


Figure 12. Ages of marine-terrace corals from the Eel Point terrace (San Clemente Island), the Rendezvous Hill terrace (Barbados), and the Waimanalo Formation (Oahu, Hawaii), shown as a function of initial $^{234}\text{U}/^{238}\text{U}$ values. Shown for comparison are curves of July insolation at 65°N (from Berger and Loutre, 1991) and the generalized SPECMAP oxygen isotope record (from Martinson et al., 1987). San Clemente Island data from this study; Barbados data from Edwards et al. (1987, 1997), Bard et al. (1990), Hamelin et al. (1991), and Gallup et al. (1994); Oahu data from Szabo et al. (1994) and Muhs et al. (2002).

water faunas are probably correlative with substage 5a or 5c and those with neutral or warm-water faunas are probably correlative with substage 5e (Kennedy, 1978; Kennedy et al., 1982). Subsequent alpha-spectrometric U-series dating of corals from many of these terraces confirmed the aminostratigraphic interpretations (Muhs et al., 1990, 1994b).

Despite the explanation of differing ages for most cool vs. warm faunal localities on the Pacific Coast, some localities still showed apparently contradictory mixtures of cooler- and warmer-water species. Examples include the

Nestor terrace on Point Loma (Valentine and Meade, 1961; Kern, 1977), the second terrace on San Nicolas Island (Vedder and Norris, 1963), and the Cayucos terrace in central California (Valentine, 1958). We review these apparently anomalous localities in this section in light of the new U-series ages reported here.

A first step toward understanding the faunal aspects of different sea-level highstands is to examine those localities where there are U-series ages of corals that are tightly clustered and where there is no evidence of mixing of fossils from older sea-level highstands.

On Isla de Guadalupe, the Discovery Point Formation has ages of ca. 123–118 ka, and the island has no higher terraces as a source of older, reworked fossils. We plotted the geographic ranges of extralimital or northward- and southward-ranging species from this formation (reported by Lindberg et al., 1980) in Figure 15.¹ Although two species range mainly to the north of Isla de Guadalupe, both live around the island today. All other species shown in Figure 15 are strictly extralimital southern species, and the majority of these have ranges that extend into or beyond the Surian and Panamic provinces (Fig. 1). The Discovery Point Formation even has a gastropod, *Cypraea cernica* [*Erosaria cernica* (Sowerby, 1870)], that currently lives only in the Indo-Pacific province, from South Africa to Easter Island (Lorenz and Hubert, 2000). The closest living occurrence of this species to North America may be Hawaii (Kay, 1979); if so, the Discovery Point occurrence represents a range extension of >4000 km. Lindberg et al. (1980) interpreted these warmer-water species to indicate last interglacial waters at least seasonally warmer than those that occur around Isla de Guadalupe today. Indeed, the very presence of the hermatypic coral *Pocillopora*, dated here, is indicative of warmer-than-modern waters. The closest living species of *Pocillopora* is found at Cabo San Lucas (Fig. 11), >1100 km to the southeast of Isla de Guadalupe (Wilson, 1988). On the Pacific Coast of the Americas, *Pocillopora* lives only from Cabo San Lucas southward to Ecuador.

At Punta Banda, there is no evidence of reworking of corals in either the ca. 120 ka Sea Cave terrace or the ca. 80 ka Lighthouse terrace. Fossil localities of the Sea Cave terrace are found on both sides of Punta Banda (Rockwell et al., 1989). However, modern water temperatures differ significantly in these two areas owing to strong seasonal upwelling on the exposed, southwestern side (Hubbs and Roden, 1964). Thus, fossil localities of the Sea Cave terrace on the two sides of Punta Banda also differ markedly in their faunal compositions. On the cooler, southwestern, open-ocean side of Punta Banda, Rockwell et al. (1989) reported no extralimital northern or southern species. However, the protected, northeastern side of Punta Banda is bathed by the warm waters of Bahía de Todos Santos. Last interglacial faunas from this side of Punta Banda

¹GSA Data Repository item 2002060, modern geographic ranges of fossils, is available on the Web at <http://www.geosociety.org/pubs/ft2002.htm>. Requests may also be sent to editing@geosociety.org.

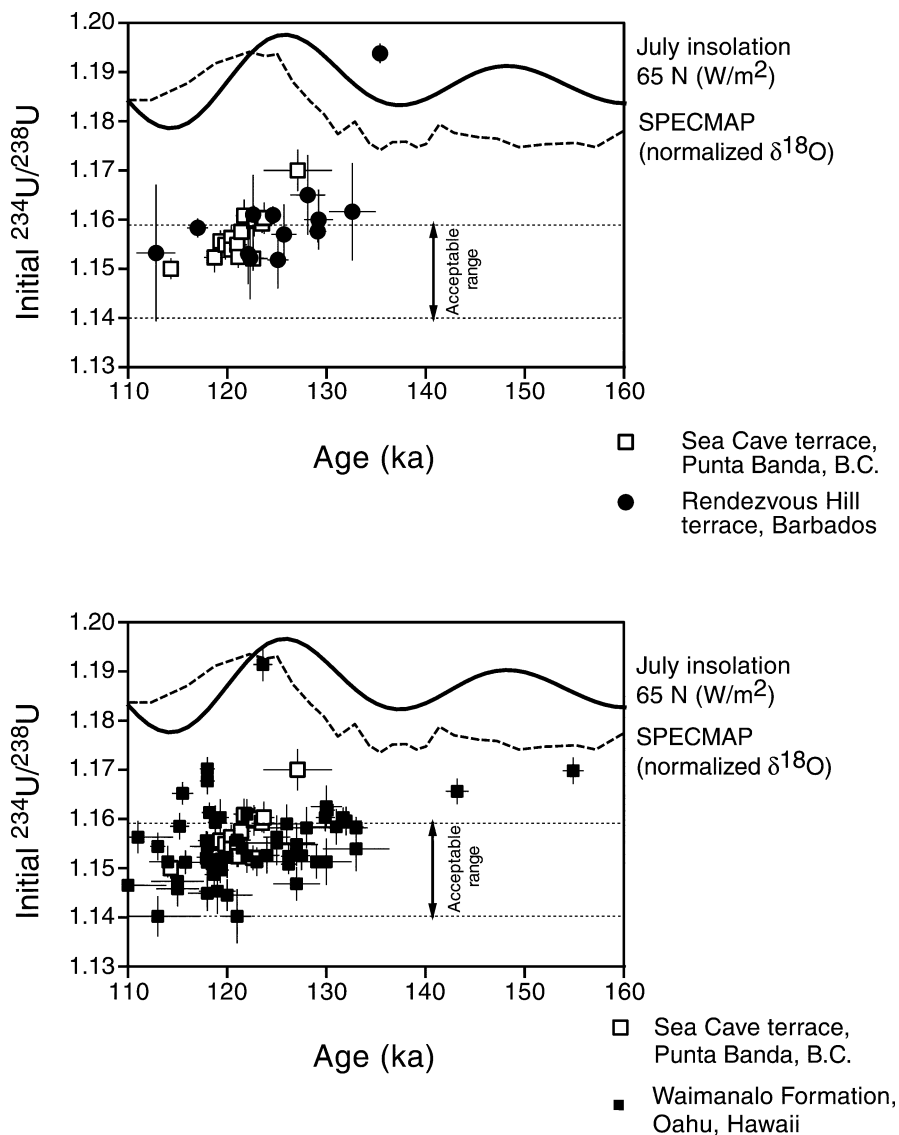


Figure 13. Ages of marine-terrace corals from the Sea Cave terrace (Punta Banda, Baja California), the Rendezvous Hill terrace (Barbados), and the Waimanalo Formation (Oahu, Hawaii), shown as a function of initial $^{234}\text{U}/^{238}\text{U}$ values. Shown for comparison are curves of July insolation at 65°N (from Berger and Loutre, 1991) and the generalized SPECMAP oxygen isotope record (from Martinson et al., 1987). Punta Banda data from this study; Barbados data from Edwards et al. (1987, 1997), Bard et al. (1990), Hamelin et al. (1991), and Gallup et al. (1994); Oahu data from Szabo et al. (1994) and Muhs et al. (2002).

contain one southward-ranging (*Acanthina lugubris*) and two extralimital southern (*Macronaethiops* and *Stramonita biserialis*) species (Fig. 16). Modern *A. lugubris* has an extreme range as far north as Newport Bay, California, but typically ranges no farther north than San Diego (Abbott, 1974); at Punta Banda it is therefore near its northern limit. *Stramonita biserialis* ranges no farther north than Isla de Cedros. Both species have modern ranges that extend southward into the Panamic province

(Fig. 1). Thus, whereas the fossils in the Sea Cave terrace deposits do not contain as many extralimital southern species as the Discovery Point Formation, those present are still indicative of warmer-than-modern waters at the time of the ca. 120 ka sea-level highstand.

In contrast to that of the Sea Cave terrace, the ca. 80 ka Lighthouse terrace fauna lacks extralimital southern species but does contain five extralimital northern species and two northward-ranging species (Fig. 16). The ex-

tralimital northern species span the Californian, Oregonian, and even Aleutian provinces (Fig. 1). These data indicate that during the ca. 80 ka sea-level highstand, waters off Punta Banda were considerably cooler than at present. The observation of cooler waters at ca. 80 ka is consistent with other data from the Pacific Coast of North America, at least as far north as southern Oregon (Kennedy, 1978; Kennedy et al., 1982, 1992; Muhs et al., 1990), the northernmost dated 80 ka terrace in North America.

On San Clemente Island, the ca. 120 ka Eel Point terrace has a typical exposed, open-coast, rocky-shore fossil assemblage. The terrace fauna from this locality has not been reported previously, and a full analysis of the species is beyond the scope of the present study. However, it is worth noting that in the fauna from Eel Point, all the bivalves (*Crassadoma gigantea*, *Cumingia californica*, *Epilucina californica*, *Glans subquadrata*, and *Mytilus californianus*) and most of the gastropods (*Acmaea mitra*, *Conus californicus*, *Crepidatella dorsata*, *Diodora aspera*, *Fisurella volcano*, *Haliotis cracherodii*, *Megathura crenulata*, *Norrisia norrisi*, *Tegula funebris*, *Zonaria spadicea*, and five species of *Lottia*) have modern ranges that extend well to the north and south of San Clemente Island. Some, such as *Lottia digitalis* and *Crassadoma gigantea*, have ranges that span the Aleutian to Surian provinces. It is important, however, to note that the deposit does not contain any extralimital northern species. In addition, two gastropods, *Acanthina lugubris* and *Stramonita biserialis* (reported by Kennedy et al., 1995), are north of their known modern, exposed-coastal range limit (San Diego and Isla de Cedros, respectively) and suggest warmer-than-modern climatic conditions.

Identification of a warm-water signature for deposits with confidently dated ca. 120 ka corals and a cool-water signature for deposits with confidently dated ca. 80 ka corals may explain the coexistence of warmer- and cooler-water faunas in terrace deposits at Point Loma, Cayucos, and elsewhere on the Pacific Coast. Although there are no prior U-series-dated ca. 105 ka marine-terrace deposits that also have detailed published faunal data, the second terrace in western Santa Barbara County likely correlates to this sea-level highstand on the basis of geomorphic position and amino-acid ratios in mollusks (Kennedy et al., 1992). These terrace deposits contain four extralimital northern species of mollusks and no extralimital southern species. Thus, if correlation of the second terrace in southwestern Santa Barbara County to the ca. 105 ka high

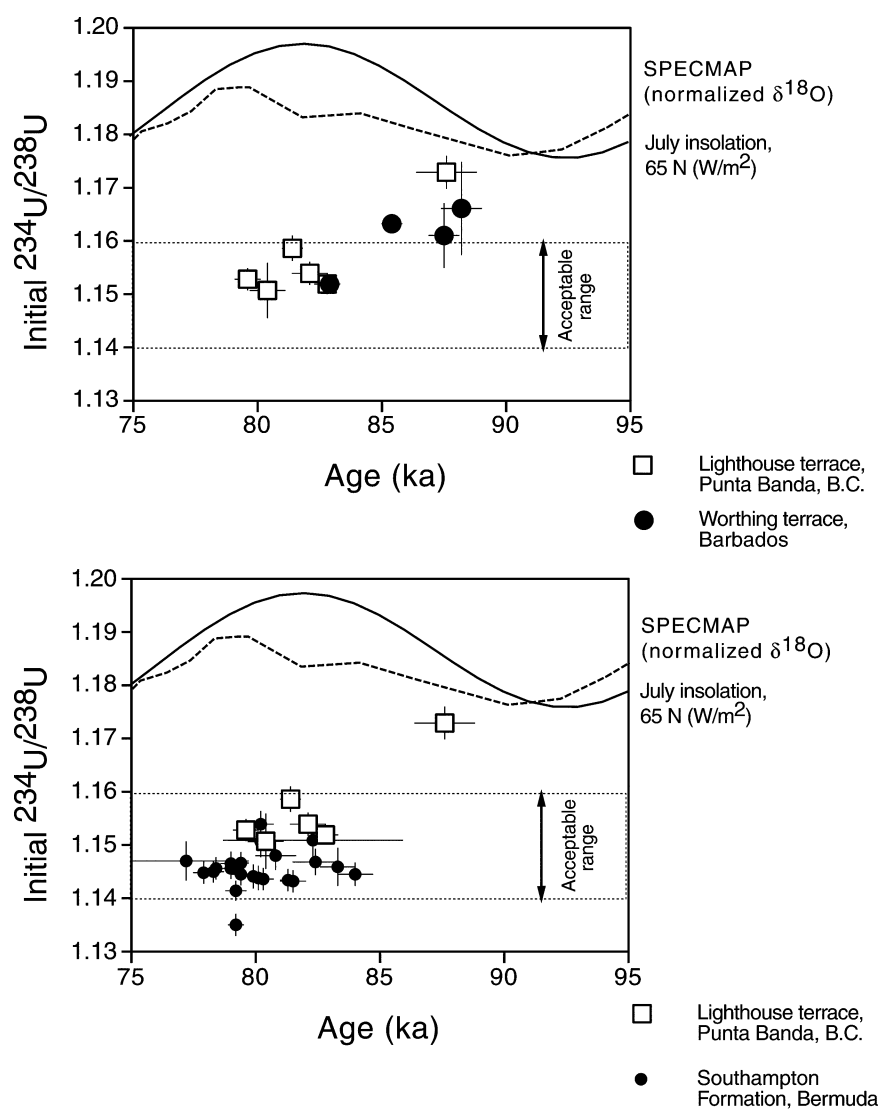


Figure 14. Ages of marine-terrace corals from the Lighthouse terrace (Punta Banda, Baja California), the Worthing terrace (Barbados), and the Southampton Formation (Bermuda), shown as a function of initial $^{234}\text{U}/^{238}\text{U}$ values. Shown for comparison are curves of July insolation at 65°N (from Berger and Loutre, 1991) and the generalized SPECMAP oxygen isotope record (from Martinson et al., 1987). Punta Banda data from this study; Barbados data from Edwards et al. (1987, 1997), Bard et al. (1990), and Gallup et al. (1994); Bermuda data from Ludwig et al. (1996) and Muhs et al. (2002).

stand is correct, then it is likely that the ca. 105 ka high stand, like the ca. 80 ka high stand, was accompanied by cooler-than-modern waters off the Pacific Coast of North America. Cooler-than-modern waters are also inferred for well-dated ca. 80 ka and 105 ka terraces on New Guinea and Barbados, on the basis of oxygen isotope analyses of mollusks and corals (Aharon and Chappell, 1986; Fairbanks and Matthews, 1978). On New Guinea, cooler-than-modern waters are also inferred for relatively high sea stands (but much lower

than at present) recorded between ca. 70 ka and 30 ka (Aharon and Chappell, 1986).

The Nestor terrace at Point Loma contains a mixture of southern and northern species (Fig. 17). Although the Nestor terrace fauna has been described as having a dominance of warmer-water species (e.g., Kern, 1977; Kennedy et al., 1982), updating of the geographic ranges reveals that there are actually more cool-water forms than warm-water forms. Five of the cool-water species found in the Nestor terrace are also found in the Bird Rock

terrace, which contains only cooler-water species. However, the Nestor terrace deposits contain eight extralimital southern species and one southward-ranging species. As discussed earlier, the Nestor terrace corals all showed open-system histories, but most have likely ages of 109–100 ka and 136–116 ka, if the secondary U and Th uptake model of Gallup et al. (1994) is correct. We hypothesize that the warm-water species in the Nestor terrace deposits date to the older sea-level highstand (136–116 ka) and the cool-water species date to the younger sea-level highstand (109–100 ka).

A similar interpretation can be made for the mixture of warm- and cool-water species found in deposits of the Cayucos terrace (Fig. 18). On the basis of updated modern geographic ranges, this deposit has more extralimital forms than originally suggested by Valentine (1958). *Acmaea persona*, *Nucella lamellosa*, and *Velutina velutina* are all extralimital northern species, and *Alvania montereyensis* and *Nucella canaliculata* are both northward-ranging species. In contrast, *Crepidula incurva*, *C. onyx*, *Diodora inaequalis*, *Rissoina coronadoensis*, *Serpulorbis squamigeris*, and *Semele decisa* are all extralimital southern species. In addition to these strictly extralimital southern species, the Cayucos terrace deposits contain an additional 12 southward-ranging species whose northern range limits occur either at Cayucos or only slightly farther north, at Monterey. As with the Nestor terrace, the Cayucos terrace deposits contain corals that have been subject to open-system conditions, but most have estimated ages that fall into two groups: ca. 108–102 ka and ca. 133–114 ka. Again, we hypothesize that the warm-water forms may date to the earlier highstand and the cool-water forms may date to the later highstand during a period of terrace reoccupation.

Roy et al. (1995) suggested that on the Pacific Coast of North America during the Pleistocene, water-mass boundaries may have been more effective barriers for southern species migrating north than for northern species moving south. This hypothesis could explain the decrease in the number of extralimital southern species in ca. 120 ka deposits moving from south to north, from Isla de Guadalupe to Punta Banda to San Clemente Island. The model is also consistent with the observation of approximately similar numbers of extralimital northern species in ca. 80 ka deposits regardless of latitude. For example, the lowest marine terrace at Coquille Point in Bandon, Oregon, is dated to ca. 80 ka (Muhs et al., 1990). Kennedy (1978) reported that

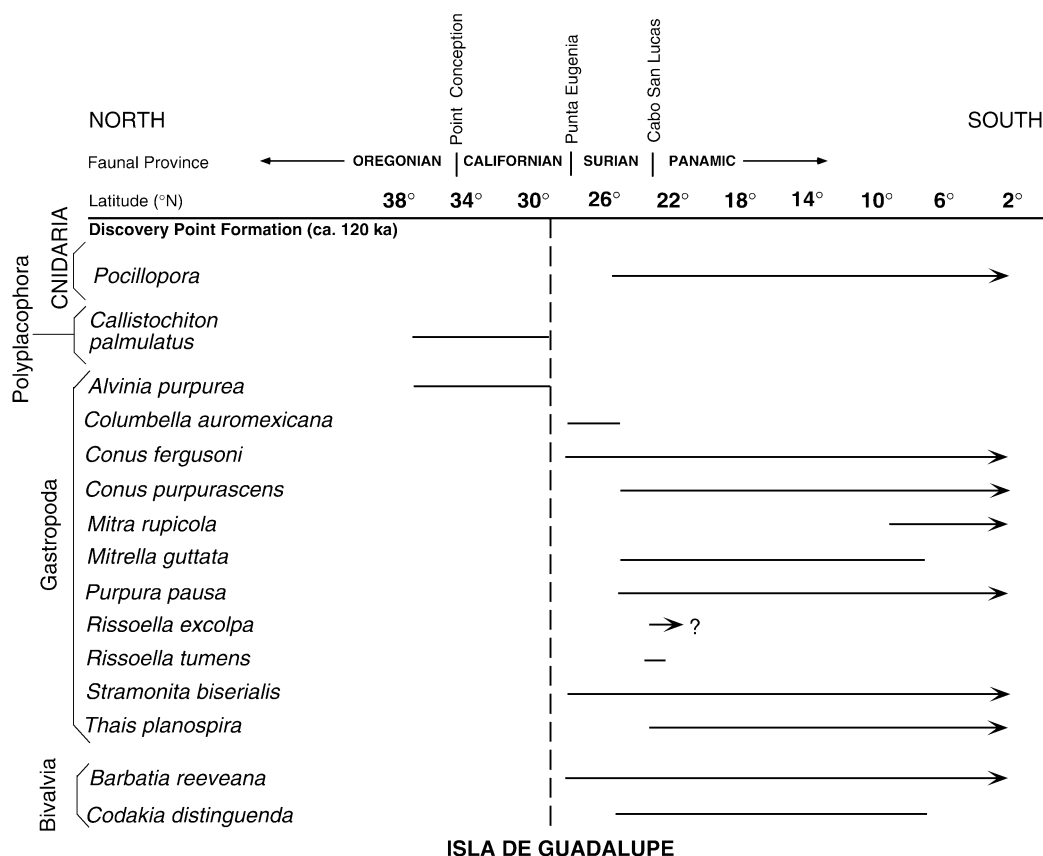


Figure 15. Modern geographic ranges of extralimital species, i.e., species whose northern or southern range endpoints are beyond or near the study area, from the ca. 120 ka Discovery Point Formation, Isla de Guadalupe, Baja California. Species are from Lindberg et al. (1980); range of *Pocillopora* is from Wilson (1988), and ranges of molluscan species are from Keen (1971). See Data Repository Table A (see footnote 1) for detailed information on ranges and sources.

these southern Oregon terrace deposits have about the same number of extralimital northern species as found in the ca. 80 ka Light-house terrace deposits in northern Baja California. However, Cayucos and Point Loma are both farther north than Punta Banda, and Cayucos is also farther north than San Clemente Island. Last interglacial terraces at Point Loma and Cayucos both have a greater number of extralimital southern species than last interglacial terraces on Punta Banda or San Clemente Island, an observation that does not support the hypothesis of Roy et al. (1995). However, a better test might be to examine the fossil record of ca. 120 ka terrace deposits, if they can be found, in northern California or Oregon.

Northward extension of warmer-water species during the ca. 120 ka sea-level highstand is documented with localities discussed in the present study and those reported by other investigators. In Figure 19, we show terrace localities in southern California and Baja California that contain the warm-water gastropods

Acanthina lugubris and *Stramonita biserialis*. All but three of these localities have corals with ca. 120 ka ages; the other three localities (Santa Barbara, San Pedro, and Bahía de Tortugas) have amino-acid ratios in fossil mollusks that allow correlation to nearby, well-dated 120 ka deposits. These two gastropods are found in 120 ka deposits in Baja California Sur, south of their modern northern range limits, which is not surprising. However, *A. lugubris* is also found in 120 ka terrace deposits at five localities at or north of its modern northern limit (near San Diego), and *S. biserialis* is found at five 120 ka localities north of its modern northern limit (Isla de Cedros). These occurrences indicate last interglacial northward range extensions, relative to present ranges, of >300 km for *A. lugubris* and >600 km for *S. biserialis*. We interpret the warmer-water conditions represented by these species during the last interglacial period to be the result of decreased strength of the cool California Current. It can be hypothesized that, at least during part of the year, the last interglacial

ocean off southern California and Baja California may have had a greater component of water derived from the tropical eastern Pacific. Coan et al. (2000) reported that during El Niño years, when tropical eastern Pacific waters reach southern California, species that are usually present only off Baja California are found much farther north. A weaker California Current, with a greater frequency of El Niño years than is the case at present, may have characterized much of the last interglacial period.

Comparison of Marine-Terrace Faunas with Other Records of Marine Paleotemperatures

One of the most important developments in eastern Pacific paleoceanography has been the successful recovery of long sediment cores with detailed Quaternary paleoclimate records from basins off the California coast (Kennett, 1995; Kennett and Venz, 1995; Herbert et al., 1995, 2001; Kreitz et al., 2000; Mangelsdorf

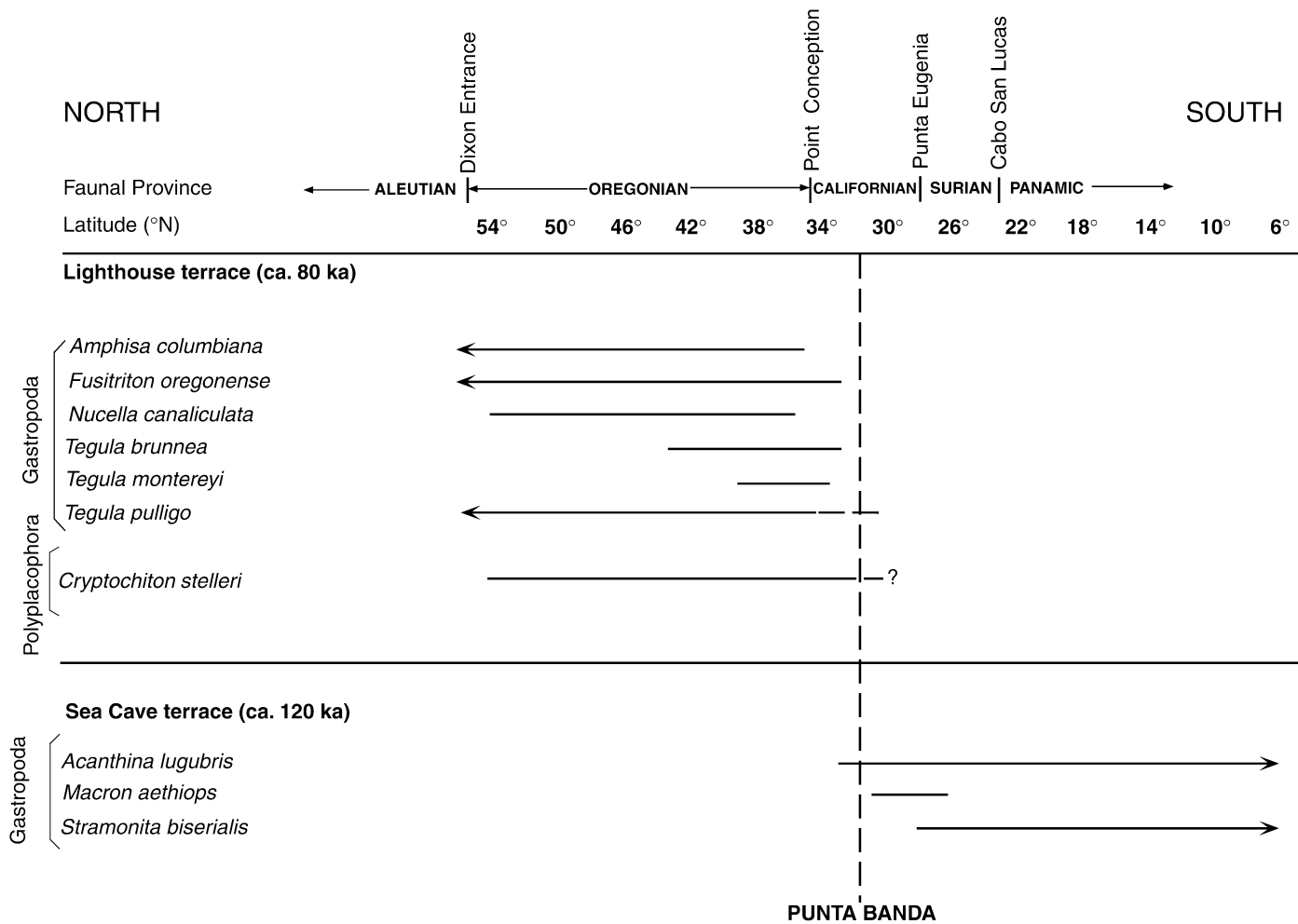


Figure 16. Modern geographic ranges of extralimital and northward- or southward-ranging species from the ca. 120 ka Sea Cave terrace and the ca. 80 ka Lighthouse terrace on Punta Banda, Baja California. Species and geographic ranges are from Rockwell et al. (1989). See Data Repository Table A (see footnote 1) for detailed information on ranges and sources.

et al., 2000). Well-characterized cores with high-resolution foraminiferal and alkenone records have been obtained from sites off northern Baja California, San Diego, Santa Barbara, Point Conception, Santa Cruz, Eureka, and Crescent City. The core from Hole 893 in the Santa Barbara Basin has one of the most complete and detailed records studied thus far, and because we have marine-terrace localities both north and south of this site (Fig. 1), we compare our results to this high-resolution record.

Santa Barbara Basin Hole 893 has the familiar benthic oxygen isotope record of marine stages (Fig. 20), from the present interglacial, i.e., stage 1, back to the penultimate glacial, i.e., stage 6 (Kennett, 1995). The benthic foraminifera oxygen isotope record provides the stratigraphic framework whereas surface-water paleotemperature estimates have been made by using planktonic foraminifera counts (Kennett and Venz, 1995) and alkenone-

unsaturation indices in phytoplankton (Herbert et al., 1995). Paleotemperature estimates from foraminifera are derived from relative abundances of dextral-coiling vs. sinistral-coiling *Neogloboquadrina pachyderma*. Santa Barbara Basin waters are characterized at present by dextral-coiling *N. pachyderma*. Fossil assemblages dominated by this form exist where summer surface-water temperatures are between 10 and 20 °C (Kennett, 1976). In contrast, sinistral-coiling *N. pachyderma* is characteristic of subarctic waters in the northeastern Pacific Ocean and elsewhere. Populations dominated (90%–100%) by this form occur in waters that have summer temperatures lower than 6 °C (Bandy, 1968).

The Santa Barbara Basin record shows that only during the peak of the last interglacial period (substage 5e) and in the Holocene (stage 1) were surface waters dominated by dextral-coiling (warm-water) *N. pachyderma*

(Fig. 20). During isotope substages 5c and 5a, abundances of dextral-coiling *N. pachyderma* were much lower, and commensurately higher abundances of sinistral-coiling (cool water) *N. pachyderma* are observed (Kennett and Venz, 1995). The alkenone record also shows that substage 5e was characterized by warm waters, significantly warmer, in fact, than at present (Fig. 20). However, in contrast to the foraminiferal record, the alkenone record suggests that substages 5c and 5a were relatively warm, on a par with the present interglacial temperatures of 15–16 °C in Santa Barbara Basin. Warm waters during these substages are also reported for two cores off northern Baja California, not far from Punta Banda (Herbert et al., 2001).

The reason for the discrepancy between the planktonic foraminiferal and phytoplankton (alkenone) records in Santa Barbara Basin is not understood, but marine-terrace faunas pro-

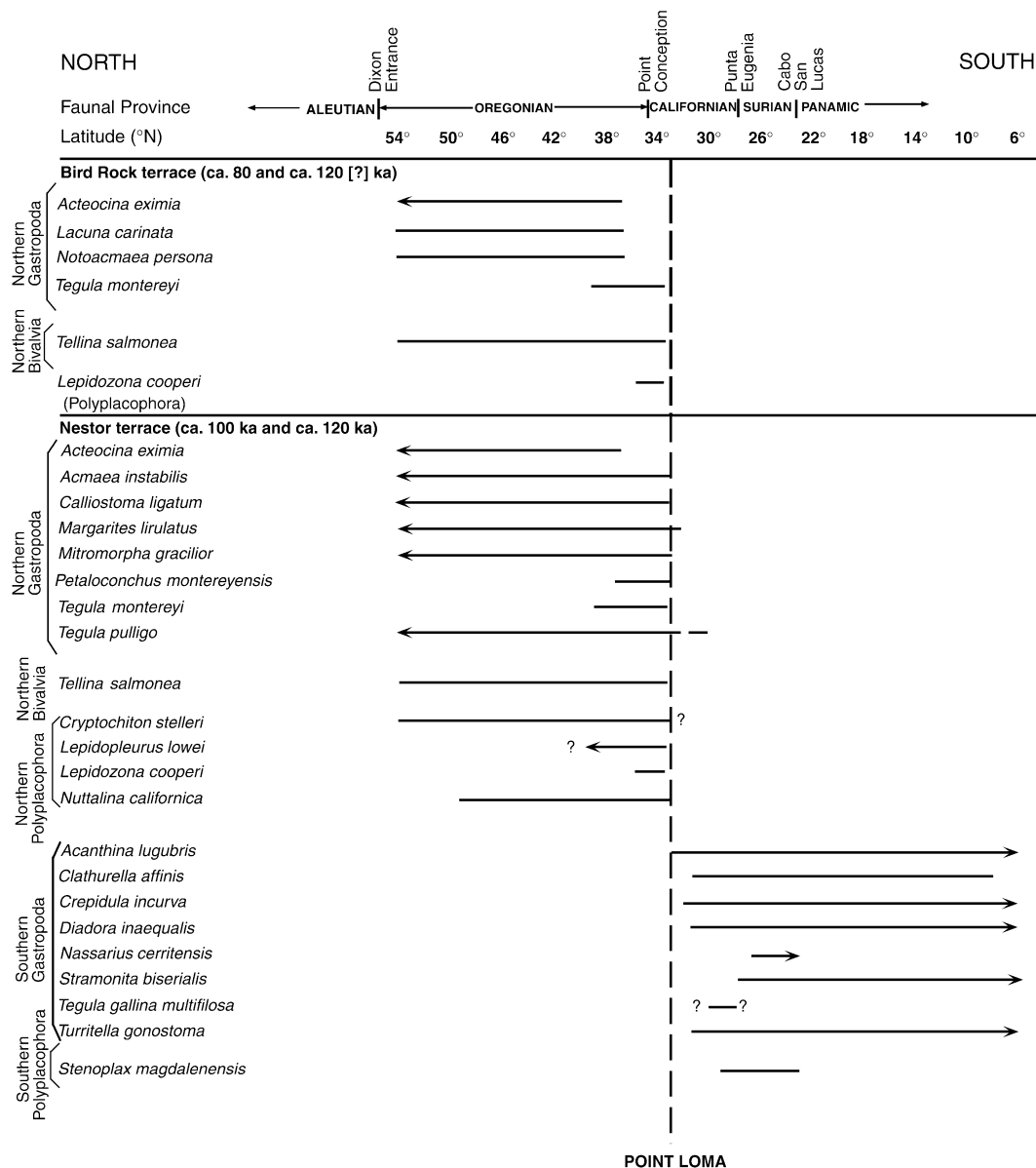


Figure 17. Modern geographic ranges of extralimital and northward- or southward-ranging species from the Nestor and Bird Rock terraces on Point Loma, San Diego, California. Species are from Valentine and Meade (1961) and Kern (1977). See Data Repository Table A (see footnote 1) for detailed information on ranges and sources.

vide an independent record of marine paleotemperatures. The terrace faunal data compiled in this study agree with both Santa Barbara Basin sediment records that substage 5e was characterized by water temperatures warmer than at present (Fig. 20). According to the alkenone record, marine temperatures during the peak of the last interglacial period in Santa Barbara Basin could have been as warm as $\sim 19^{\circ}\text{C}$, equivalent to modern temperatures off central to southern Baja California (Lynn, 1967). This warmth should have resulted in a greater number of Surian province (Fig. 1) species in marine-terrace deposits

of southern California and northern Baja California during at least some part of the last interglacial period. The presence of southern forms, particularly at Isla de Guadalupe and Punta Banda, permits such an interpretation, although we are not certain that water temperatures as far north as Punta Banda were as warm as $\sim 19^{\circ}\text{C}$. However, alkenone-derived temperature estimates of $15\text{--}16^{\circ}\text{C}$ during substages 5a and 5c are not consistent with marine-terrace faunas that indicate water temperatures at these times significantly cooler than at present. The Lighthouse terrace at Punta Banda and the Bird Rock terrace at Point

Loma (if it contains dominantly ca. 80 ka fossils) indicate much cooler temperatures off southern California and northern Baja California during substage 5a. If the cooler-water forms present in the Nestor and Cayucos terrace deposits date from the ca. 105 ka sea-level highstand, as our U-series ages suggest, then cooler-than-modern waters would also be inferred for isotope substage 5c (Fig. 20). These observations are consistent with the presence of low abundances of dextral-coiling *N. pachyderma* and high abundances of sinistral-coiling *N. pachyderma*. Thus, the benthic foraminiferal and marine-terrace faunal data

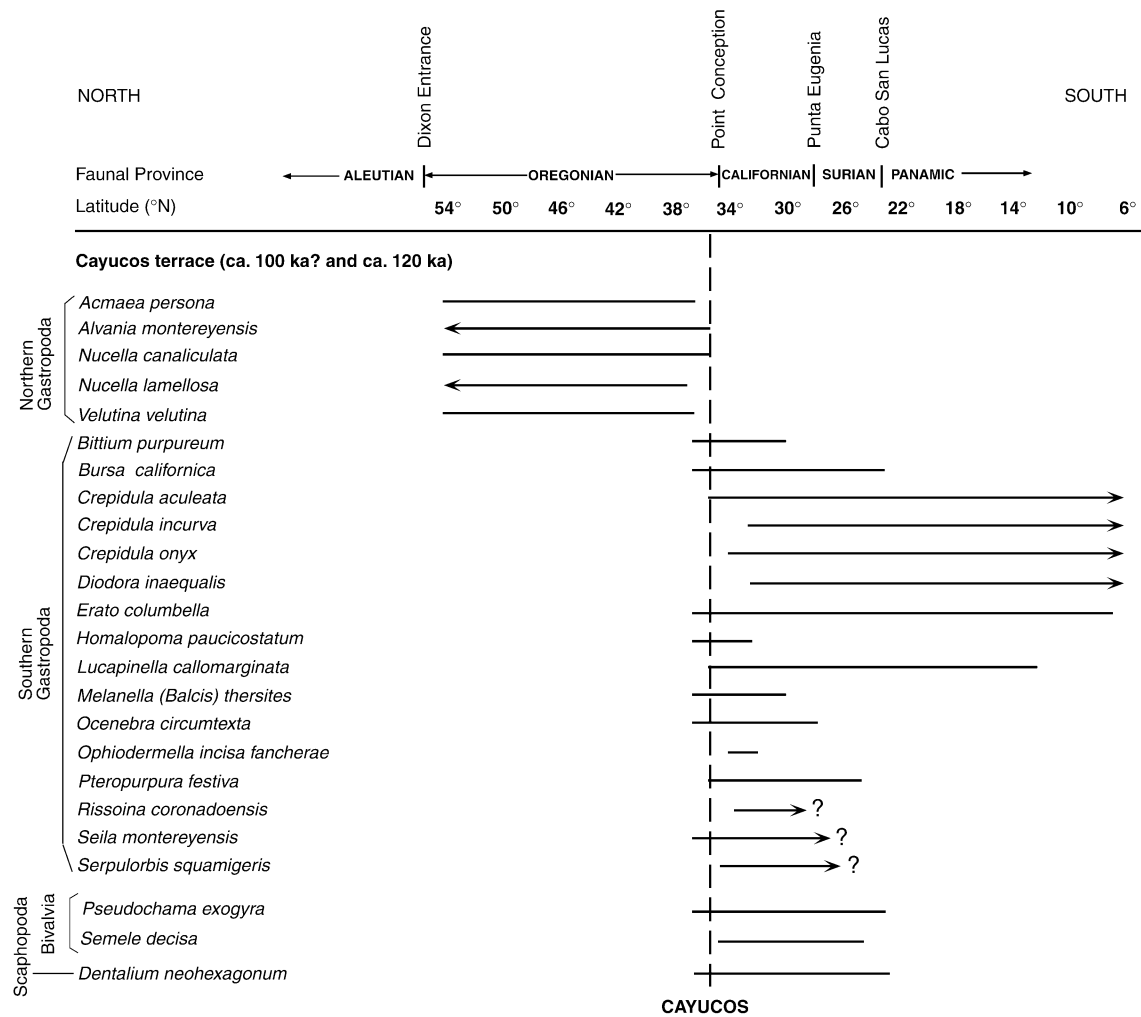


Figure 18. Modern geographic ranges of extralimital species and northward- or southward-ranging species from the Cayucos terrace, California. Species are from Valentine (1958). See Data Repository Table A (see footnote 1) for detailed information on ranges and sources.

suggest that alkenone data may not always faithfully record sea-surface temperatures, at least in an absolute sense. Alternatively, if the warm periods represented by the alkenone record during substages 5a and 5c were relatively short-lived, and if marine-terrace deposits on the Pacific Coast record mainly the end, or regressive phase of sea-level high-stands (Fig. 2), then a precise concordance between the two records should not be expected.

Alkenone-derived paleotemperature estimates from other core localities off the Pacific Coast (Fig. 1), such as holes 1012 (off northern Baja California), 1017 (off Point Conception), 1018 (off central California), and 1019 and 1020 (both off northern California) have also been reported (Mangelsdorf et al., 2000; Herbert et al., 2001). They all indicate that at least parts of substage 5e were warmer than at present, in good agreement with the Santa

Barbara Basin record. Alkenone records for the main parts of substage 5c (ca. 105 ka) indicate water temperatures about as warm as at present (Holes 1012 and 1017) and slightly cooler than at present (Holes 1018 and 1020). The alkenone records reported from these cores for substage 5a (ca. 80 ka) are similarly variable: Holes 1012 and 1019 indicate relatively warm temperatures, whereas Holes 1017, 1018, and 1020 indicate relatively cool temperatures.

For comparison with the younger part of the Santa Barbara Basin record, there is only a single dated, Pleistocene marine-terrace locality younger than substage 5a that has a well-characterized fauna. This locality, at Isla Vista in Goleta, California (near Santa Barbara), is a low-elevation marine-terrace deposit that was thought, on the basis of amino acid ratios in fossil mollusks, to be on the

order of ca. 50 ka (Wehmiller et al., 1977; Kennedy et al., 1982). This early age estimate is confirmed by a TIMS U-series age on a specimen of *Balanophyllia elegans* from the deposit, which is 47 ± 0.5 ka (Gurrola et al., 1996; Trecker et al., 1998), indicating a correlation with a relatively high (but lower than at present) sea stand within isotope stage 3 (Fig. 20). The fauna from this terrace has been well characterized by Wright (1972), who reported no extralimital southern species, but a number of extralimital northern species, including *Macoma expansa*, *M. obliqua*, *Saxidomus gigantea*, and *Tresus capax* (bivalves) as well as *Lacuna carinata* (a gastropod). Thus, the ca. 47 ka fauna at Isla Vista indicates cooler-than-modern waters, which is in broad agreement with both the alkenone and planktonic foraminiferal records (Fig. 20).

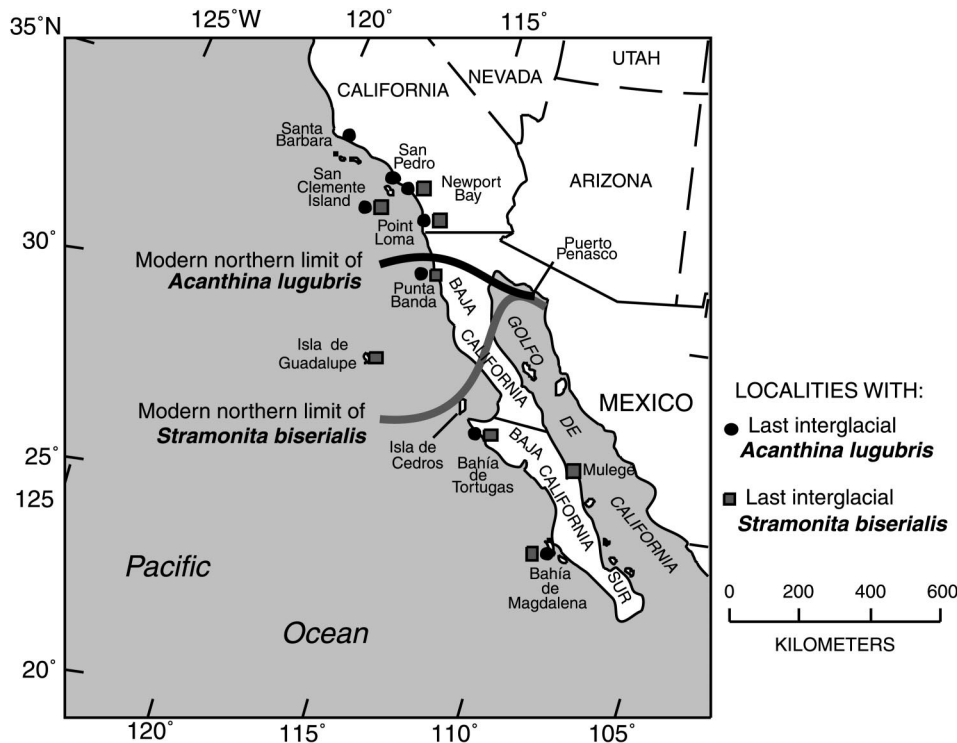


Figure 19. Map of southern California and Baja California showing the modern northern limits of two warm-water species, *Stramonita biserialis* and *Acanthina lugubris*, and terrace deposits containing these species that date or probably date to ca. 120 ka. Modern northern limits for *Acanthina lugubris* are from Rockwell et al. (1989) for the Pacific Coast and from L. Groves (Los Angeles County Museum of Natural History, 2001, written commun.; specimen record LACM 68565) and S. Walker (University of Georgia, 2001, written commun.) for the Gulf of California. Modern northern limits for *Stramonita biserialis* are from Keen (1971) for the Pacific Coast and from L. Groves (Los Angeles County Museum of Natural History, 2001, written commun.; specimen record LACM 22832) for the Gulf of California. Terrace faunas of last interglacial age that contain these species are from sources as follows: (1) Santa Barbara area—age and faunal data from Kennedy et al. (1992); (2) San Pedro area—faunal data from Valentine (1962), age data from Muhs et al. (1992); (3) Newport Bay—faunal data from Kanakoff and Emerson (1959), age data from Grant et al. (1999); (4) San Clemente Island—faunal and age data from this study; (5) Point Loma—faunal data from Valentine and Meade (1961) and Kern (1977), age data from this study; (6) Punta Banda—faunal data from Rockwell et al. (1989), age data from this study; (7) Isla de Guadalupe—faunal data from Lindberg et al. (1980), age data from this study; (8) Bahía de Tortugas—faunal and age data from Emerson et al. (1981); (9) Bahía de Magdalena—faunal data from Jordan (1936), age data from Omura et al. (1979); (10) Mulegé—faunal data from Ortlieb (1987), age data from Ashby et al. (1987).

CONCLUSIONS

1. The solitary coral *Balanophyllia elegans*, which ranges along the Pacific Coast of North America, takes up U in isotopic equilibrium with seawater during growth. After death, but before emergence, additional U is taken up from seawater. Thus, these corals can be used for U-series dating by using all prior criteria for closed-system conditions, with the exception of U content.

2. Results of U-series analyses of corals from the Cayucos (central California) and Nestor (San Diego) terraces show an open-system history, similar to what has been reported by other workers for these terraces. However, analyses of larger suites of corals and a model of continuous, secondary U and

Th uptake show that despite the open-system conditions, two age groups of corals are present, probably representing the ca. 105 and ca. 120 ka sea-level highstands reported elsewhere.

3. Corals from San Clemente Island, California, and Punta Banda and Isla de Guadalupe, Baja California, show closed-system history and probably yield reliable ages. The peak last interglacial sea-level highstand is represented by terrace deposits at all of these localities, and corals have a range of ages from ca. 128 to 114 ka. In addition, two lower terraces are found on Punta Banda, and the lowest of these has corals with reliable ages of ca. 83–80 ka.

4. U-series ages of last interglacial corals from the Pacific Coast overlap with, but are

on average younger than, corals from Barbados, the Bahamas, and Hawaii. This age difference is explained by the nature of the geomorphic response to sea-level change: Fringing or barrier reefs on low-latitude coastlines have “keep-up” corals with accretionary growth that can keep pace with rising sea level, whether on a tectonically rising or stable coastline. In contrast, midlatitude, high-energy coastlines undergo platform cutting during the early part of a sea-level highstand. On such coastlines, sediment and fossil deposition take place as sea level starts to recede. Nevertheless, the youngest ages of corals from San Clemente Island and Punta Banda overlap with the intermediate-aged and younger corals in Hawaii and the Bahamas and suggest that sea level was still relatively high at ca. 116

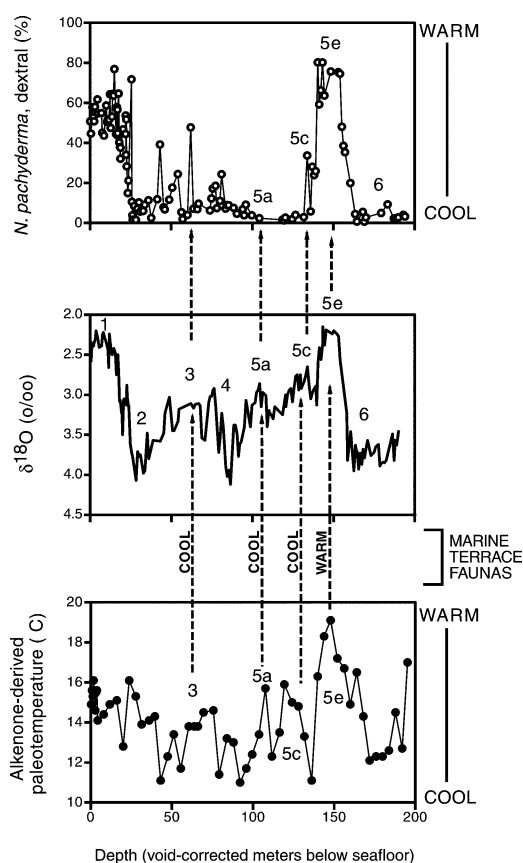


Figure 20. Paleoclimatic records from sediments of Santa Barbara Basin compared to marine-terrace faunas from this study. Middle panel: Oxygen isotope record of benthic foraminifera and isotope substages (data from Kennett, 1995). Upper panel: Abundances of warm-water planktonic foraminifer *Neogloboquadrina pachyderma*, dextral-coiling (data from Kennett and Venz, 1995). Lower panel: Surface-water paleotemperature estimates derived from alkenone-unsaturation index from phytoplankton (data from Herbert et al., 1995). Marine-terrace-fauna temperature aspect derived from paleozoogeographic inferences and U-series ages herein (see text for references).

ka. This finding conflicts with estimates of a relatively large global ice volume during isotope substage 5d, a time of low summer insolation at high latitudes in the Northern Hemisphere.

5. Fossil mollusks from reliably dated, ca. 120 ka marine-terrace deposits include extralimital southern species that indicate ocean temperatures as warm as, or warmer than present. Northward range extensions (compared to the present range) were as much as 300–600 km and may have been due to a weaker California Current and a stronger flow of tropical eastern Pacific waters northward. In contrast, ca. 80 ka marine deposits reported here and elsewhere have extralimital northern species indicating cooler-than-modern water temperatures. The presence of both ca. 105 ka and ca. 120 ka corals on the Nestor and Cayucos terraces may explain the previously enigmatic

mixture of extralimital southern and northern species in these deposits that has been noted for decades. Reoccupation of at least a part of ca. 120 ka terraces during the ca. 105 ka sea-level highstand suggests that both highstands may have been close to the present height.

6. The inference of cooler-than-modern waters off the Pacific Coast of North America at ca. 80 ka and ca. 105 ka from terrace mollusks does not agree with estimates of sea-surface temperatures derived from alkenone studies in Santa Barbara Basin and in certain other cores. However, cooler water temperatures at these times are in agreement with planktonic foraminiferal data from Santa Barbara Basin that do indicate cooler-than-modern temperatures. All records (terrace faunas, benthic foraminifera, and alkenones) have inferences of warmer-than-modern waters during the peak of the last interglacial period at ca. 120 ka.

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