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A cool eastern Pacific Ocean at the close of the Last Interglacial complex

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Abstract

New high-precision thermal ionization mass-spectrometric (TIMS) U-series ages of solitary corals (*Balanophyllia elegans*) from several marine terrace localities along the California and southern Oregon coasts date to the ~80,000 yr BP high stand of sea, correlative with marine isotope substage 5a, late in the last interglacial complex. Ages of multiple corals from localities north of Point Año Nuevo (central California) and San Nicolas Island (southern California) suggest that this high sea stand could have lasted at least 8000 yr, from ~84,000 to ~76,000 yr BP. These ages overlap with those from marine deposits on tectonically stable Bermuda and tectonically emergent Barbados. Higher-elevation terraces at two California localities, in the Palos Verdes Hills and on San Nicolas Island, have corals with ages that range mostly from ~121,000 to ~116,000 yr BP, correlative with marine isotope substage 5e. These ages are similar to those reported for other terraces in southern California but are younger than some ages reported from Hawaii, Barbados and the Bahamas.

Marine terrace faunas are excellent proxies for nearshore marine paleotemperatures during past high sea stands. Terraces on the Palos Verdes Hills and San Nicolas Island dated to the ~120,000 yr BP high sea stand have dominantly zoogeographically “neutral” species in exposed coastal localities, indicating nearshore waters similar to those of today. In contrast, ~80,000 yr BP, exposed coastal localities typically have molluscan faunas characterized by numerous extralimital northern species and a lack of extralimital southern species. These fossil assemblages are indicative of nearshore water temperatures that were cooler than modern temperatures at ~80,000 yr BP. Waters at least as warm as today’s at ~120,000 yr BP and cooler than present at ~80,000 yr BP are in excellent agreement with marine alkenone records and coastal vegetation records derived from pollen data, from both southern and northern California. Decreased insolation or increased upwelling seem inadequate to explain the cool waters off the Pacific Coast from southern Oregon to southern California at ~80,000 yr BP. We propose that a stronger California Current (or at least one with a greater component of subarctic waters) may explain cooler-than-modern coastal waters during the ~80,000 yr BP high sea stand.

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1. Introduction

The potential for significant global warming in the near future has led to an increased study of past warm

periods as possible analogs, such as the last interglacial period (Broecker, 1998; Kukla, 2000; Kukla et al., 2002). The last interglacial complex, in its broadest sense, is all of what is recorded as stage 5 in the marine oxygen isotope record (Martinson et al., 1987). Considerable effort has been made to determine the timing, duration and paleotemperature regime of the peak of the last interglacial period, ~120,000 yr BP, recorded

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by marine oxygen isotope substage 5e (Kukla et al., 2002; Muhs et al., 2002b). This warm period is also represented, on tectonically stable coasts, by marine deposits a few meters above modern sea level, indicating a major high stand of sea (Chen et al., 1991; Stirling et al., 1998; Muhs et al., 2002b).

There has been far less study of the other relatively high sea level events that occurred during the last interglacial complex, i.e., during substages 5c (~100,000 yr BP) and 5a (~80,000 yr BP). Nevertheless, there is important evidence of these high sea stands outside of the marine oxygen isotope record. Some of the best records of these events, and those that can be dated directly, are the emergent coral reefs and coral-bearing, clastic marine deposits on Barbados (Mesolella et al., 1969; Gallup et al., 1994; Edwards et al., 1997; Potter et al., 2004), New Guinea (Bloom et al., 1974; Chappell and Shackleton, 1986; Cutler et al., 2003), Bermuda (Ludwig et al., 1996; Muhs et al., 2002b), the US Atlantic Coastal Plain (Wehmiller et al., 2004) and the Pacific Coast of North America (Muhs et al., 1994, 2002a, 2003).

Despite the many localities where ~80,000-yr-old (substage 5a) marine deposits exist, there have been few studies of the precise timing and paleoclimatic aspects of this relatively high stand of sea. Part of this gap has been filled by recent Ocean Drilling Program (ODP) cores taken from the eastern Pacific Ocean. These cores have yielded detailed foraminiferal (Kennett and Venz, 1995; Poore et al., 2000), radiolarian and diatom (Pisias et al., 2001), pollen (Heusser, 1995; Heusser et al., 2000) and alkenone (Kreitz et al., 2000; Lyle et al., 2000, 2001; Mangelsdorf et al. 2000; Poore et al., 2000; Herbert et al., 2001; Seki et al., 2002) records of the last interglacial–glacial cycle, including isotope substage 5a. In particular, alkenones hold considerable promise for estimating marine paleotemperatures. However, alkenone paleotemperature reconstructions, like those of other proxy paleoclimate indicators from deep-sea cores, are based on assumptions about chronology. None of the cores off North America is dated directly or independently for the last interglacial complex. The core chronology is based upon the “orbital tuning” method, which necessarily has assumptions about climate forcing (Martinson et al., 1987). In addition, a recent study suggests that alkenones may be up to 7000 yr older than coexisting foraminifera from the same depth (Ohkouchi et al., 2002).

Herein, we present new high-precision thermal ionization mass-spectrometric (TIMS) U-series ages of solitary corals (*Balanophyllia elegans*) from several marine terrace localities from southern Oregon to southern California (Fig. 1). The corals date to the final high sea stand (marine isotope substage 5a) of the last interglacial complex. In addition, we report new TIMS

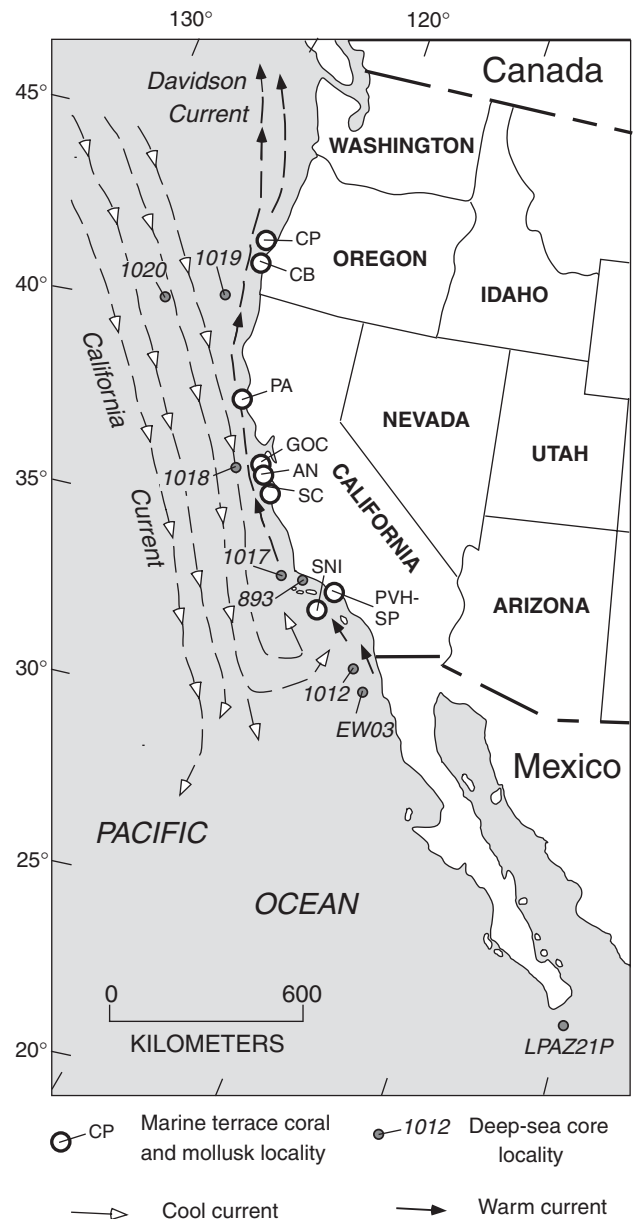


Fig. 1. Map of part of the Pacific Coast of North America showing marine terrace localities, deep-sea core locations, and ocean currents. Locality abbreviations: CP, Coquille Point; CB, Cape Blanco; PA, Point Arena; GOC, Green Oaks Creek; AN, Point Año Nuevo; SC, Santa Cruz; PVH-SP, Palos Verdes Hills-San Pedro area; SNI, San Nicolas Island.

U-series ages of corals from terraces that are slightly higher (i.e., relatively older) at localities on the Palos Verdes Hills and San Nicolas Island. We also present compilations of new and published fossil fauna data, chiefly mollusks, from these localities. These compilations, with modern zoogeography, allow inferences about marine paleotemperatures and can be compared with eastern Pacific Ocean ODP paleoclimatic data.

2. Uranium-series methods

The most common coral in marine terrace deposits along the marginal eastern Pacific Ocean is a solitary species, *B. elegans* Verrill, 1884, and all corals dated for this study belong to this species. Corals analyzed here were all collected by the authors, with three exceptions. Two *B. elegans* individuals were collected by Hoskins (1957), one each at Point Año Nuevo (USGS loc. M5925) and Point Santa Cruz (USGS loc. M5924), and a third was collected by Chace and Chace (1919) from their “Chiton bed” locality at Point Fermin in San Pedro, California (SDSNH 08193 from SDSNH loc. 0625). All specimens were cleaned 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 were all well preserved and composed of 95–100% aragonite as determined by X-ray diffractometry. Two corals, from Point Santa Cruz and Point Fermin, were too small to X-ray, but neither showed any signs of recrystallization under magnification. Uranium concentrations and isotope abundances were determined by isotope dilution using ^{229}Th – ^{233}U – ^{236}U spikes and thermal ionization mass spectrometry. Details of the analytical methods are given in Ludwig et al. (1992). All errors given herein, whether from new TIMS analyses or previous alpha-spectrometric analyses, are 2-sigma.

Consistent with previous studies on the Pacific Coast of North America (Stein et al., 1991; Muhs et al., 1994, 2002a), all fossil corals analyzed have U contents that are higher than that found in living specimens (Table 1). However, Muhs et al. (2002a) showed that although U concentrations in modern, dead-collected corals are higher than those in modern, live-collected ones, both have $^{234}\text{U}/^{238}\text{U}$ values that are indistinguishable from those in modern seawater. Thus, in addition to U uptake during growth, post-mortem U uptake in *Balanophyllia* apparently takes place in the marine environment after death, but before emergence.

The primary criteria for reliability of U-series ages of corals are: (1) absence of recrystallization to calcite, (2) $^{230}\text{Th}/^{232}\text{Th}$ values that are high enough to ensure that there is no evidence of significant “inherited” ^{230}Th from detrital minerals, and (3) $^{234}\text{U}/^{238}\text{U}$ values that, when combined with the $^{230}\text{Th}/^{234}\text{U}$ ages, yield back-calculated initial $^{234}\text{U}/^{238}\text{U}$ values that are indistinguishable from those of modern seawater. Modern seawater is often stated to have a $^{234}\text{U}/^{238}\text{U}$ activity ratio of 1.149 (e.g., Stirling et al., 1998; Potter et al., 2004). However, direct measurements indicate that modern seawater actually has a range of $^{234}\text{U}/^{238}\text{U}$ values, from 1.140 to 1.150 (Chen et al., 1986). The living corals analyzed here, plus other living corals from southern California, (Muhs et al., 2002a), also show a range of $^{234}\text{U}/^{238}\text{U}$ values, from 1.142 to 1.150, in

agreement with the reported values of modern seawater. Isotopic evolution curves show the theoretical sympathetic variation in $^{230}\text{Th}/^{238}\text{U}$ and $^{234}\text{U}/^{238}\text{U}$ activity ratios over time in fossil corals without initial ^{230}Th and with various initial $^{234}\text{U}/^{238}\text{U}$ activity ratios (Fig. 2).

Many fossil corals do not plot precisely on a theoretical seawater evolution curve, and the usual observation is one of higher-than-expected $^{234}\text{U}/^{238}\text{U}$ values (Gallup et al., 1994; Edwards et al., 1997; Muhs et al., 2002a; Scholz et al., 2004). The choice of an “acceptable” range for higher initial $^{234}\text{U}/^{238}\text{U}$ activity ratios is somewhat arbitrary, although Edwards et al. (1997) demonstrated that corals with initial $^{234}\text{U}/^{238}\text{U}$ activity ratios as high as 1.16–1.19 showed concordant $^{230}\text{Th}/^{234}\text{U}$ and $^{231}\text{Pa}/^{235}\text{U}$ ages. On the other hand, Cutler et al. (2003) showed that some corals with initial $^{234}\text{U}/^{238}\text{U}$ activity ratios identical with, or close to that of modern seawater did not exhibit concordant $^{230}\text{Th}/^{234}\text{U}$ and $^{231}\text{Pa}/^{235}\text{U}$ ages. Less commonly, fossil corals exhibit initial $^{234}\text{U}/^{238}\text{U}$ activity ratios that are lower than that of modern seawater. The precise mechanism for the cause of either higher or lower initial $^{234}\text{U}/^{238}\text{U}$ values is still not clearly understood. Variation of the $^{234}\text{U}/^{238}\text{U}$ value in seawater over time is a possibility, although a recent study by Henderson (2002) casts doubt on this hypothesis. Gallup et al. (1994) and Scholz et al. (2004) have presented plausible models for ^{230}Th and ^{234}U additions that result in higher-than-expected values. Such open-system conditions tend to bias corals to older apparent ages. We are uncertain as to how lower-than-expected $^{234}\text{U}/^{238}\text{U}$ values may bias apparent ages. Furthermore, given the range of measured $^{234}\text{U}/^{238}\text{U}$ values we find in living corals, the choice of a single value (1.149) for modern seawater, as used by other workers, seems somewhat misleading. Nevertheless, for the purposes of comparability, corals whose values (within analytical uncertainty) plot on an isotopic evolution curve for modern seawater (assuming an initial $^{234}\text{U}/^{238}\text{U}$ activity ratio of 1.149), within an uncertainty of ± 0.008 , are considered to have the most reliable ages. This criterion is identical to that used by Potter et al. (2004).

3. Geologic setting and uranium-series ages of North American Pacific Coast corals

3.1. Southern Oregon

In coastal Oregon, marine terraces are common landforms, but few fossils have been found in terrace deposits. However, two late Quaternary fossil localities are known from Coquille Point, in Bandon, Coos County, and at Cape Blanco, Curry County (Fig. 3). In the Coquille Point area, the lowest marine terrace is called the Whisky Run terrace (Griggs, 1945; McNelly

Table 1

U and Th concentrations, isotopic activity ratios, U-series ages and calculated initial U activity ratios (AR) in solitary corals (*Balanophyllia elegans*) from Oregon and California

Locality and laboratory #	U (ppm)	±	²³² Th (ppm)	²³⁴ U/ ²³⁸ U	±	²³⁰ Th/ ²³⁸ U	±	²³⁰ Th/ ²³² Th	²³⁰ Th/ ²³⁸ U age (ka) ^a	±	²³⁴ U/ ²³⁸ U init AR ^a	±
<i>Modern (live-collected) corals, Point Piedras Blancas, California</i>												
PPB-2-A	3.59	0.13	0.0088	1.1436	0.0019	0.0007	0.0006	1.67	0.06	0.06	1.1436	0.0019
PPB-2-A dup #1	3.59	0.12	0.0095	1.1460	0.0017	0.0034	0.0005	4.68	0.32	0.05	1.1461	0.0017
PPB-2-B	3.46	0.12	0.0100	1.1478	0.0018	0.0009	0.0005	1.76	0.08	0.05	1.1479	0.0018
PPB-2-C	2.96	0.11	0.0087	1.1458	0.0018	0.0155	0.0013	16.8	1.48	0.13	1.1465	0.0018
<i>Coquille Point, Coos County Oregon</i>												
<i>Whisky Run terrace (LACMIP loc. 2636)</i>												
Coq-Pt.-A	4.91	0.12	0.0168	1.1143	0.0015	0.5801	0.0024	515	78.6	0.5	1.1427	0.0018
Coq-Pt.-A dup #1	4.85	0.16	0.0232	1.1147	0.0032	0.5952	0.0026	378	81.5	0.6	1.1444	0.0039
Coq-Pt.-A dup #2	4.90	0.11	0.0169	1.1165	0.0016	0.5779	0.0013	508	77.9	0.3	1.1452	0.0019
<i>Point Arena, Mendocino County, California</i>												
<i>First terrace, or Q₁ mapping unit (USGS loc. M7824)</i>												
Pt. Arena-1-A	4.37	0.14	0.0129	1.0906	0.0034	0.5876	0.0032	606	82.8	0.8	1.1145	0.0041
<i>Green Oaks Creek area, San Mateo County, California</i>												
<i>Davenport terrace (LACMIP loc. 5019)</i>												
AN-1	4.32	0.13	0.0846	1.1169	0.0032	0.5674	0.0036	88	75.8	0.8	1.1499	0.0038
AN-2	4.52	0.13	0.0926	1.1204	0.0017	0.6111	0.0027	91	84.0	0.6	1.1527	0.0021
AN-3	5.30	0.17	0.0498	1.1161	0.0025	0.6008	0.0018	194	82.5	0.5	1.1465	0.0030
AN-4	5.49	0.11	0.0738	1.1181	0.0021	0.5959	0.0035	135	81.2	0.7	1.1486	0.0025
AN-5	5.18	0.11	0.0242	1.1212	0.0015	0.5853	0.0036	381	78.8	0.7	1.1515	0.0018
AN-6	4.48	0.12	0.0343	1.1177	0.0026	0.5842	0.0021	232	79.0	0.5	1.1471	0.0031
AN-8	4.34	0.12	0.0877	1.1214	0.0017	0.5827	0.0033	88	78.3	0.7	1.1515	0.0021
AN-9	4.66	0.12	0.0252	1.1196	0.0017	0.5766	0.0015	323	77.3	0.3	1.1488	0.0020
AN-9 dup #1	4.67	0.11	0.0262	1.1172	0.0019	0.5775	0.0022	313	77.7	0.5	1.1460	0.0023
AN-10	5.26	0.12	0.0258	1.1185	0.0021	0.5798	0.0017	359	78.0	0.4	1.1478	0.0026
AN-10 dup #1	5.27	0.12	0.0270	1.1188	0.0024	0.5809	0.0035	345	78.2	0.7	1.1482	0.0028
AN-11	4.47	0.11	0.0473	1.1195	0.0017	0.5883	0.0021	169	79.6	0.5	1.1496	0.0021
AN-12	4.10	0.11	0.0578	1.1231	0.0024	0.5920	0.0029	128	79.9	0.6	1.1542	0.0029
<i>Point Año Nuevo, San Mateo County, California</i>												
<i>Davenport terrace (USGS loc. M5925)</i>												
H56-32	3.94	0.11	0.0120	1.1123	0.0019	0.5623	0.0019	561	75.8	0.4	1.1391	0.0023
<i>Point Santa Cruz, Santa Cruz County, California</i>												
<i>Davenport terrace (USGS loc. M5924)</i>												
H56-31	4.37	0.11	0.0366	1.1235	0.0018	0.5454	0.0021	198	71.5	0.4	1.1511	0.0022
<i>Palos Verdes Hills, Los Angeles County, California</i>												
<i>Paseo del Mar terrace (Golden Cove locality)</i>												
PVH-GC-A	4.62	0.11	0.0262	1.1257	0.0015	0.6124	0.0018	328	84.2	0.4	1.1594	0.0018
PVH-GC-B	4.37	0.11	0.0463	1.1252	0.0017	0.6130	0.0023	176	84.3	0.5	1.1589	0.0021
PVH-GC-C	4.57	0.12	0.0292	1.1220	0.0015	0.6030	0.0046	287	82.7	0.9	1.1541	0.0018
PVH-GC-D	4.05	0.11	0.0281	1.1281	0.0017	0.6249	0.0019	274	86.4	0.4	1.1635	0.0021
<i>Palos Verdes Hills-San Pedro, Los Angeles County, California</i>												
<i>Paseo del Mar terrace ("Chiton bed" locality; SDSNH loc. 0625)</i>												
Chiton bed-1	3.90	0.12	0.0141	1.1151	0.0022	0.5777	0.0022	483	78.5	0.5	1.1437	0.0027
<i>Palos Verdes Hills, Los Angeles County, California</i>												
<i>Paseo del Mar terrace (LACMIP loc. 12575)</i>												
PVH-12575-A	4.36	0.11	0.0227	1.0926	0.0019	0.5624	0.0020	328	77.5	0.4	1.1152	0.0023
PVH-12575-B	3.91	0.11	0.0080	1.1041	0.0018	0.5759	0.0016	859	78.9	0.4	1.1301	0.0021
PVH-12575-C	5.52	0.12	0.0164	1.0864	0.0020	0.5491	0.0020	561	75.6	0.4	1.1070	0.0024
PVH-12575-D	4.51	0.20	0.0166	1.0972	0.0026	0.5597	0.0043	462	76.4	0.9	1.1206	0.0032
PVH-12575-E	4.20	0.12	0.0060	1.0960	0.0019	0.5510	0.0019	1,179	74.9	0.4	1.1186	0.0022
GK-90-1-A	4.46	0.11	0.0181	1.0989	0.0017	0.5679	0.0055	424	77.9	1.1	1.1233	0.0020
GK-90-1-B	4.11	0.11	0.0181	1.1059	0.0018	0.5771	0.0026	397	78.9	0.6	1.1323	0.0022
GK-90-1-C	3.99	0.11	0.0251	1.1017	0.0014	0.5678	0.0018	274	77.5	0.4	1.1266	0.0017

Table 1 (continued)

Locality and laboratory #	U (ppm)	±	²³² Th (ppm)	²³⁴ U/ ²³⁸ U	±	²³⁰ Th/ ²³⁸ U	±	²³⁰ Th/ ²³² Th	²³⁰ Th/ ²³⁸ U age (ka) ^a	±	²³⁴ U/ ²³⁸ U init AR ^a	±
<i>Palos Verdes Hills, Los Angeles County, California</i>												
<i>Gaffey terrace (LACMIP loc. 12608)</i>												
GK-101-1-A	4.47	0.11	0.0035	1.1073	0.0020	0.7476	0.0020	2,919	119.5	0.7	1.1504	0.0026
GK-101-1-A dup	4.43	0.12	0.0035	1.1090	0.0019	0.7454	0.0020	2,837	118.5	0.7	1.1524	0.0025
GK-101-1-B	4.34	0.11	0.0049	1.1064	0.0023	0.7247	0.0027	1,959	113.3	0.9	1.1466	0.0030
GK-101-1-C	4.22	0.13	0.0581	1.1041	0.0020	0.7421	0.0027	164	118.6	0.9	1.1456	0.0027
<i>San Nicolas Island, Ventura County, California</i>												
<i>First terrace, Cormorant Point (LACMIP loc. 12005)</i>												
GK-89-14-A	4.04	0.11	0.0160	1.1367	0.0022	0.6158	0.0026	472	83.0	0.6	1.1728	0.0026
GK-89-14-B	3.34	0.11	0.0126	1.1240	0.0014	0.5832	0.0012	470	78.1	0.3	1.1546	0.0016
GK-89-14-C	3.60	0.11	0.0238	1.1227	0.0020	0.5719	0.0021	263	76.1	0.5	1.1522	0.0024
GK-89-14-D	3.82	0.13	0.0325	1.1232	0.0015	0.6059	0.0049	216	82.6	1.0	1.1556	0.0019
GK-89-14-E	3.56	0.11	0.0077	1.1197	0.0031	0.5839	0.0019	817	78.7	0.5	1.1495	0.0038
GK-89-14-F	3.53	0.12	0.0698	1.1465	0.0018	0.6777	0.0050	104	94.6	1.1	1.1913	0.0022
GK-89-14-G	4.69	0.11	0.0117	1.1181	0.0022	0.5676	0.0013	691	75.7	0.3	1.1463	0.0027
GK-89-14-H	3.55	0.11	0.0154	1.1358	0.0018	0.6137	0.0028	430	82.7	0.6	1.1715	0.0022
GK-89-14-I	4.42	0.11	0.0141	1.1151	0.0019	0.5676	0.0019	540	76.1	0.4	1.1427	0.0023
GK-89-14-J	3.13	0.13	0.0189	1.1414	0.0021	0.6257	0.0019	314	84.4	0.5	1.1795	0.0025
GK-89-14-K	3.94	0.11	0.0273	1.1175	0.0021	0.6218	0.0038	272	86.6	0.8	1.1501	0.0026
GK-89-14-L	3.60	0.12	0.0505	1.1294	0.0021	0.6138	0.0045	133	83.5	0.9	1.1638	0.0026
GK-89-14-M	4.44	0.12	0.0102	1.1241	0.0015	0.5934	0.0016	786	80.1	0.3	1.1556	0.0018
<i>San Nicolas Island, Ventura County, California</i>												
<i>First terrace, Vizcaino Point (LACMIP loc. 11009)</i>												
GK-89-13-A	3.40	0.11	0.036	1.1386	0.0017	0.6110	0.0032	178	82.4	0.7	1.1749	0.0021
GK-89-13-B	3.80	0.11	0.028	1.1268	0.0013	0.5925	0.0016	243	80.1	0.3	1.1589	0.0015
GK-89-13-C	3.46	0.11	0.009	1.1401	0.0015	0.6176	0.0021	687	83.5	0.4	1.1774	0.0018
GK-89-13-E	4.14	0.11	0.047	1.1233	0.0018	0.5746	0.0023	155	77.0	0.5	1.1533	0.0022
GK-89-13-F	3.86	0.10	0.093	1.1240	0.0025	0.5836	0.0037	74	78.6	0.8	1.1548	0.0030
<i>San Nicolas Island, Ventura County, California</i>												
<i>Second terrace, south of Vizcaino Point (LACMIP loc. 10622)</i>												
SNI-VIZ-Pt.-A	3.80	0.12	0.0143	1.1314	0.0020	0.8014	0.0019	645	128.7	0.8	1.1890	0.0027
SNI-VIZ-Pt.-B	4.19	0.12	0.0113	1.1101	0.0024	0.7495	0.0025	840	118.6	0.9	1.1539	0.0032
SNI-VIZ-Pt.-C	4.17	0.11	0.0354	1.1117	0.0027	0.7538	0.0039	270	119.4	1.2	1.1566	0.0035
SNI-VIZ-Pt.-D	4.50	0.11	0.0116	1.1069	0.0024	0.7456	0.0017	876	118.2	0.7	1.1493	0.0032
SNI-VIZ-Pt.-E	3.12	0.11	0.0164	1.1149	0.0017	0.7531	0.0028	436	118.5	0.9	1.1607	0.0022
SNI-VIZ-Pt.-F	4.39	0.12	0.0174	1.1100	0.0023	0.7507	0.0024	574	118.9	0.8	1.1539	0.0031
SNI-VIZ-Pt.-G	3.34	0.11	0.0048	1.1210	0.0020	0.7650	0.0046	1,626	120.5	1.4	1.1701	0.0027
SNI-VIZ-Pt.-H	4.61	0.12	0.0071	1.1084	0.0021	0.7562	0.0038	1,492	120.8	1.2	1.1526	0.0028
SNI-VIZ-Pt.-I	3.40	0.11	0.0100	1.1139	0.0018	0.7584	0.0080	786	120.2	2.3	1.1600	0.0025
SNI-VIZ-Pt.-J	3.93	0.14	0.0073	1.1137	0.0032	0.7588	0.0049	1,237	120.4	1.6	1.1598	0.0043
SNI-VIZ-Pt.-K	4.11	0.12	0.0130	1.1090	0.0021	0.7472	0.0021	719	118.1	0.7	1.1522	0.0028
SNI-VIZ-Pt.-L	4.45	0.11	0.0246	1.1082	0.0020	0.7472	0.0022	410	118.3	0.8	1.1511	0.0026
SNI-VIZ-Pt.-M	3.87	0.11	0.0157	1.1085	0.0028	0.7462	0.0024	559	118.0	0.9	1.1515	0.0036
SNI-VIZ-Pt.-N	4.23	0.12	0.0145	1.1114	0.0017	0.7431	0.0022	658	116.5	0.7	1.1549	0.0022
SNI-VIZ-Pt.-O	3.86	0.12	0.0123	1.1111	0.0018	0.7505	0.0028	714	118.6	0.9	1.1553	0.0024
SNI-VIZ-Pt.-P	3.93	0.13	0.0078	1.1140	0.0019	0.7569	0.0023	1,153	119.8	0.8	1.1599	0.0025
GK-91-14-A #1	4.11	0.11	0.0180	1.1175	0.0010	0.7607	0.0043	526	120.1	1.2	1.1650	0.0015
GK-91-14-A #2	4.13	0.11	0.0184	1.1186	0.0016	0.7581	0.0021	515	119.2	0.7	1.1660	0.0021
GK-91-14-B #1	4.09	0.11	0.0321	1.1151	0.0017	0.7555	0.0033	292	119.2	1.0	1.1612	0.0022
GK-91-14-B #2	4.08	0.11	0.0862	1.1146	0.0017	0.7630	0.0036	110	121.4	1.1	1.1615	0.0023
GK-91-14-C	3.99	0.12	0.0235	1.1248	0.0019	0.7721	0.0020	398	121.7	0.7	1.1761	0.0025
GK-91-14-E	3.78	0.11	0.0141	1.1146	0.0028	0.7569	0.0063	616	119.7	1.9	1.1607	0.0037
GK-91-14-F	3.36	0.11	0.0135	1.1295	0.0019	0.7747	0.0026	585	121.4	0.8	1.1825	0.0025
GK-91-14-G	4.04	0.12	0.0208	1.1184	0.0016	0.7614	0.0026	449	120.1	0.8	1.1663	0.0021
GK-91-14-H	4.62	0.11	0.0164	1.1137	0.0019	0.7534	0.0017	645	118.9	0.6	1.1591	0.0025
GK-91-14-I	3.93	0.11	0.0163	1.1227	0.0017	0.7581	0.0029	556	118.3	0.9	1.1715	0.0022

^aAges and calculated initial ²³⁴U/²³⁸U activity ratios (AR) based on half-lives given in Cheng et al. (2000). Samples with ages and initial ²³⁴U/²³⁸U ratios in bold have the highest degree of reliability.

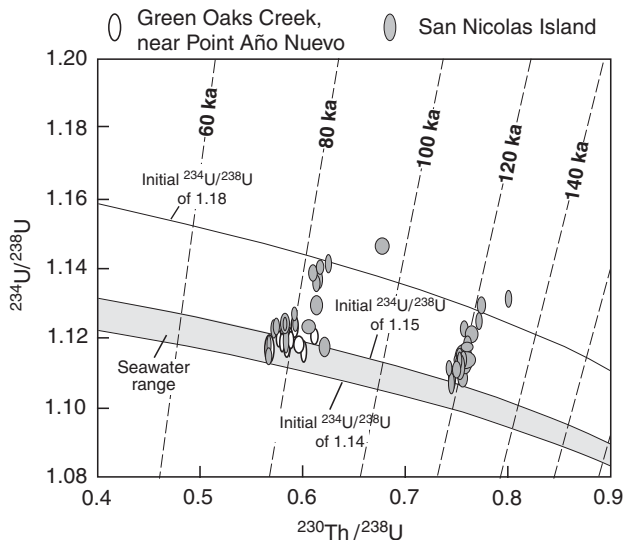


Fig. 2. Isotopic evolution curves (solid lines) showing sympathetic variation in $^{230}\text{Th}/^{238}\text{U}$ and $^{234}\text{U}/^{238}\text{U}$ activity ratios over time in materials with no initial ^{230}Th and with various initial $^{234}\text{U}/^{238}\text{U}$ activity ratios. Age in thousands of years (ka) is shown by isochrons (dashed lines). Shaded band is expected range, within the measured range of variation of modern corals, of $^{234}\text{U}/^{238}\text{U}$ values of fossil corals that took up U from seawater and remained as closed isotopic systems throughout their subsequent history. Superimposed on the theoretical plots are measured values of the solitary coral *B. elegans* from the Davenport terrace at Green Oaks Creek (open ellipses) and the 1st ($\sim 80,000$) and 2nd ($\sim 120,000$) terraces on San Nicolas Island. Ellipses define the measured values and 2-sigma uncertainties, as calculated using Isoplot/Ex software (Ludwig, 2001).

and Kelsey, 1990). The lowest surface at Cape Blanco is called the Cape Blanco terrace (Kelsey, 1990). Addicott (1964, 1966), Zullo (1969), and Kennedy (1978) studied fossils from the Whisky Run and Cape Blanco terraces. In a previous study, a coral from the Whisky Run terrace at Coquille Point yielded an alpha-spectrometric U-series age of $\sim 80,000$ yr BP (Muhs et al., 1990). Amino acid ratios in the bivalve *Saxidomus* reported by Kennedy et al. (1982) suggested that the Cape Blanco terrace could be younger than the Whisky Run terrace at Coquille Point. Later amino acid and oxygen isotope studies, also on *Saxidomus* valves, suggested that the two terraces could be correlative (Muhs et al., 1990). Correlation of the Cape Blanco and Whisky Run terraces is also supported by soils data (Bockheim et al., 1992; Kelsey and Bockheim, 1994).

A single *B. elegans* from the Whisky Run terrace at Coquille Point was large enough to yield three U-series analyses on separate fragments of the same individual. Two fragments gave concordant ages of $\sim 78,000$ – $79,000$ yr BP, whereas a third gave an older age of $81,000$ – $82,000$ yr BP (Table 1). All three fragments yielded similar U contents and calculated initial $^{234}\text{U}/^{238}\text{U}$ values that are indistinguishable from that of modern seawater, so we are uncertain about the cause

of the age difference. In any case, the three analyses support the original age estimate, based on alpha-spectrometric U-series dating and amino acid data, that the Whisky Run terrace at Coquille Point is $\sim 80,000$ yr old.

3.2. Northern California: Point Arena

Well-preserved marine terraces are present in several areas along the coast of northern California. Prentice (1989) and Muhs et al. (2003) mapped marine terraces in the vicinity of Point Arena, Mendocino County, ~ 175 km north of San Francisco (Fig. 4). The three lowest terraces, informally designated Qt_1 , Qt_2 and Qt_3 in Fig. 4, have shoreline angle elevations of ~ 20 – 25 , ~ 40 – 45 and ~ 60 – 65 m, respectively. The Qt_1 terrace is well-expressed geomorphically and the terrace platform, cut on bedrock, has a sharp contact with the overlying marine sediments. On sea cliff exposures, the platform is typically riddled with pholad-bored holes and has a variable elevation, ranging from ~ 5 to ~ 17 m. Terrace deposits are well stratified, horizontal beds of sand and gravel and vary in thickness from less than 1 m to as much as ~ 7 m. A morphologically well-expressed soil with an A/E/Bw/C or A/E/Bs/C profile is developed in the upper part of the marine terrace deposits. Kennedy (1978, 1981) studied fossils from the lowest terrace deposits (our mapping unit Qt_1) at Point Arena. Kennedy et al. (1982) and Muhs et al. (1990, 1994) presented amino acid and U-series data correlating this terrace with that at Coquille Point, Oregon. Alpha-spectrometric U-series analyses of marine terrace corals from Point Arena are $\sim 76,000$ yr BP and $\sim 88,000$ yr BP. Uranium-series analyses presented here are new data derived from previous collections, as field work conducted in 2001 and 2003 revealed that the fossil localities are either covered or eroded away.

A new TIMS analysis of a single *Balanophyllia* from the first terrace at Point Arena yielded an apparent age of $83,000 \pm 800$ yr BP (Table 1) and is therefore broadly consistent with the ages reported earlier. Unexpectedly, however, the calculated initial $^{234}\text{U}/^{238}\text{U}$ value is significantly lower than that of modern seawater. As discussed above, we are uncertain as to how lower-than-expected $^{234}\text{U}/^{238}\text{U}$ values should be interpreted in terms of a potential age bias. Nevertheless, our inference is that the terrace at Point Arena correlates with the $\sim 80,000$ yr high stand of sea, though its precise age is uncertain.

3.3. Central California: Green Oaks Creek, Point Año Nuevo, and Point Santa Cruz

In central California, Bradley and Griggs (1976) mapped six prominent terraces in the Santa Cruz-Point Año Nuevo area (Fig. 5). The lowest marine terrace in

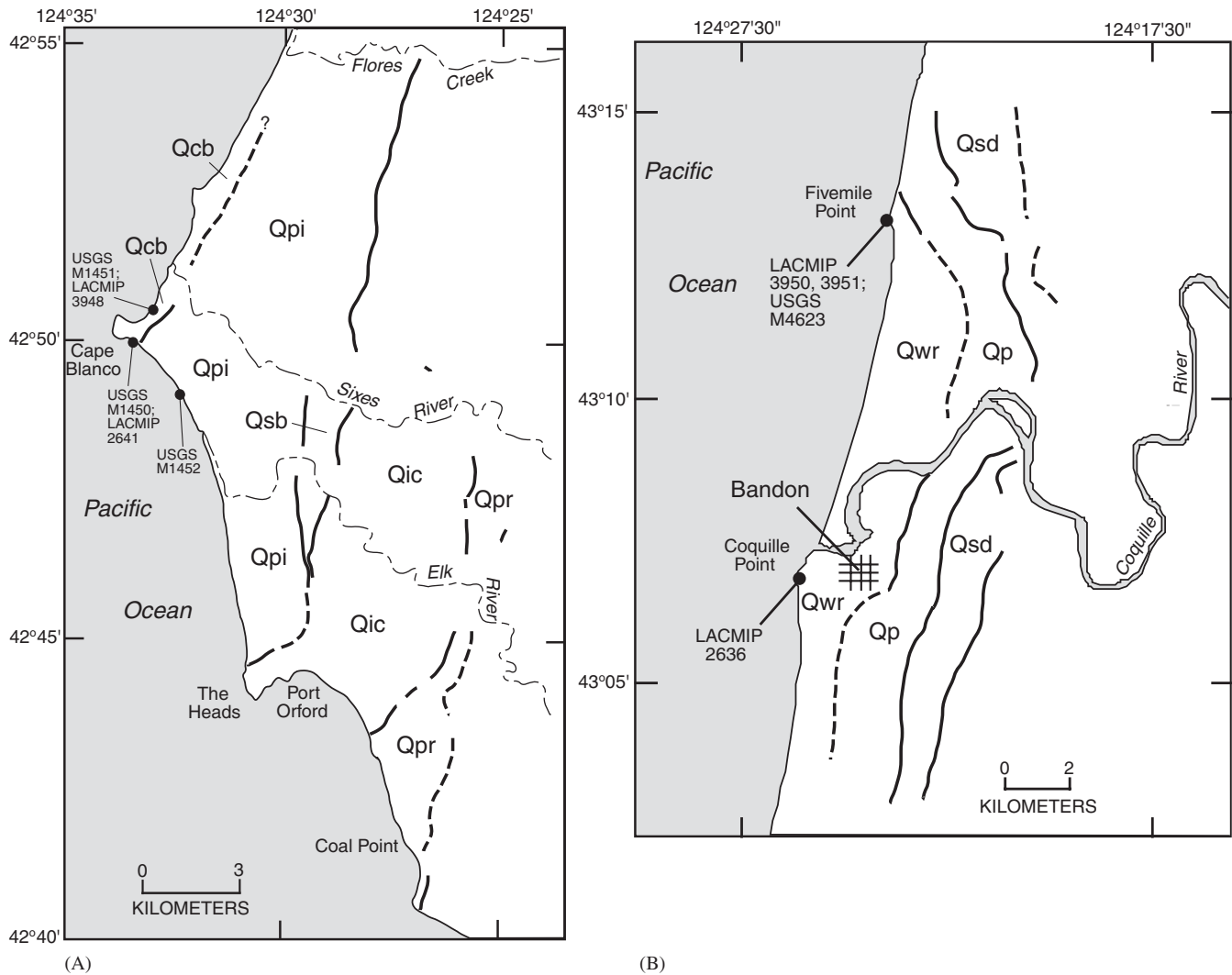


Fig. 3. Map showing marine terrace inner edges and fossil localities in the (A) Cape Blanco and (B) Coquille Point-Bandon areas, southern Oregon. Marine terrace inner edges redrawn from Kelsey (1990) and McNelly and Kelsey (1990). Terrace abbreviations for Cape Blanco: Qcb, Cape Blanco terrace; Qpi, Pioneer terrace; Qsb, Silver Butte terrace; Qic, Indian Creek terrace; Qpr, Poverty Ridge terrace. Terrace abbreviations for Coquille Point-Bandon: Qwr, Whisky Run terrace; Qp, Pioneer terrace; Qsd, Seven Devils terrace.

central California between Santa Cruz and Point Año Nuevo is called the Santa Cruz terrace. The Santa Cruz terrace appears to be a single, uplifted marine terrace. However, detailed seismic profiling and examination of outcrops by Bradley and Griggs (1976) show that it consists of three distinct platforms cut on bedrock, but covered with marine and non-marine deposits that have “smoothed” the subaerial surface topographically into a single, broad landform. Bradley and Griggs (1976) referred to the uppermost of the three buried platforms as the Greyhound platform. The Greyhound platform has a maximum shoreline angle elevation of ~50 m, but is closer to ~44 m elsewhere. Bradley and Griggs (1976) showed that the variability of shoreline angle elevations of this and other platforms is a function of tectonic deformation over local structures. The next-lowest

surface, the Highway 1 platform, is found extensively along the coast. The Highway 1 platform is up to 530 m wide and has a shoreline angle elevation that ranges from 26 to 39 m. The lowest surface, called the Davenport platform, has a width of at least 200–300 m and a shoreline angle elevation that ranges from 12 to 23 m. Too few exposures allow for these terraces to be mapped separately, but isolated exposures where the Davenport platform can be identified are present along the coast between Santa Cruz and north of Point Año Nuevo (Fig. 5).

We studied three exposures of fossiliferous marine sediments overlying the Davenport platform, at Green Oaks Creek and Point Año Nuevo (San Mateo County) and Point Santa Cruz (Santa Cruz County). In sea cliff exposures, the Davenport platform is ~5 m above sea

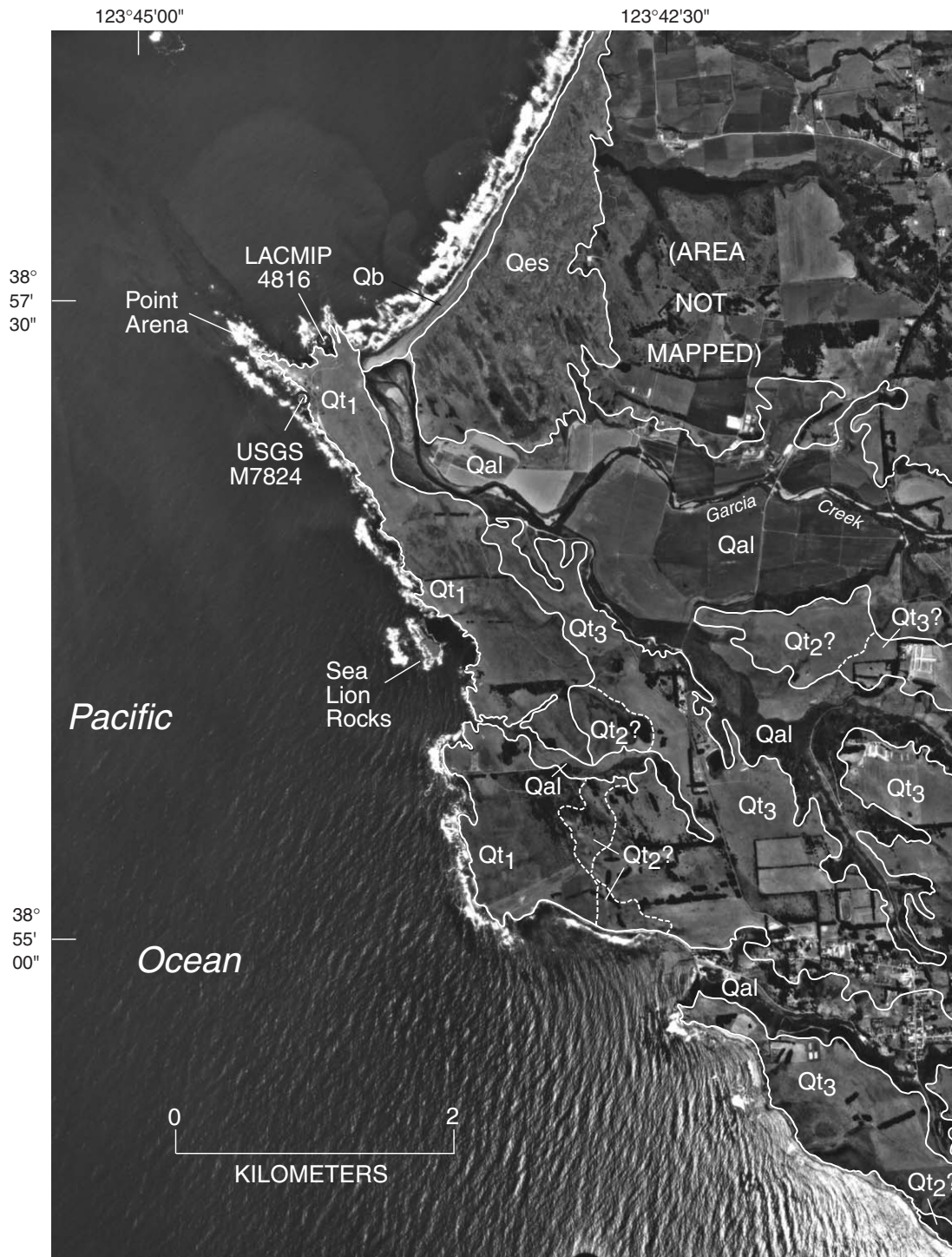


Fig. 4. Aerial photograph and Quaternary geologic map of the area around Point Arena, California and fossil localities studied. White lines are contacts; dashed where uncertain. Units: Qb, beach deposits; Qal, alluvium; Qes, eolian sand; Qt₁, Qt₂, Qt₃, deposits of the 1st, 2nd, and 3rd marine terraces, respectively. Geologic mapping by D.R. Muhs based on interpretation of aerial photographs and reconnaissance field checking (see also Muhs et al., 2003).

level around Green Oaks Creek, north of Point Año Nuevo, and has a fossiliferous basal, marine gravel ~0.5 m thick, overlain by ~4 m of marine (?) sand, capped by ~2 m of eolian sand. A paleosol separates the

eolian sand from the underlying marine (?) sediments. The Davenport platform is extensively bored by pholadid bivalves, notably *Penitella turnerae* (Kennedy, 1978). Near Point Año Nuevo proper, Davenport

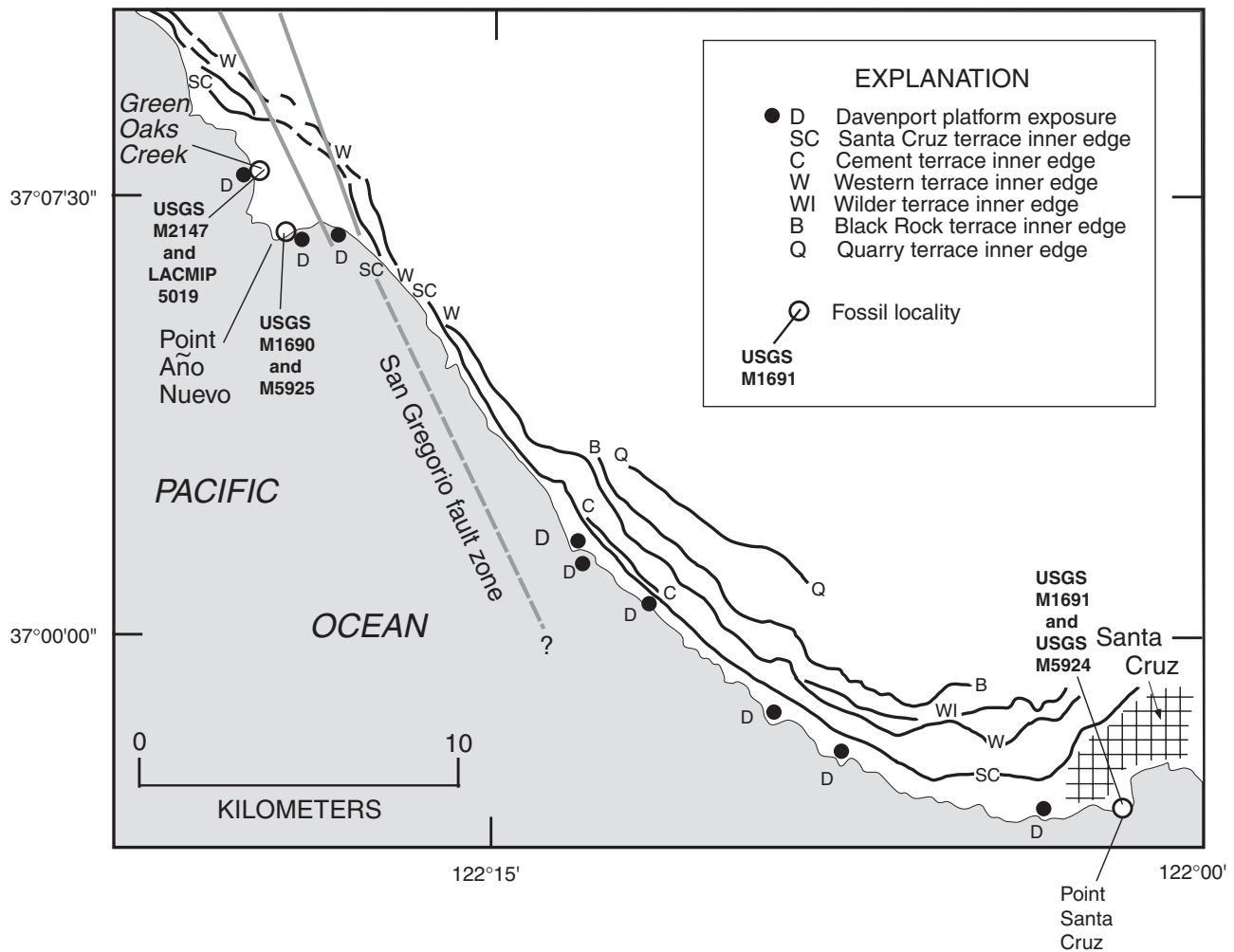


Fig. 5. Map of a portion of the central coast of California, from Santa Cruz to just north of Point Año Nuevo, showing marine terrace inner edges (solid black lines, dashed where uncertain), fossil localities, and location of the San Gregorio fault zone (solid gray lines; dashed where uncertain). Marine terrace inner edges redrawn from Bradley and Griggs (1976) and Weber et al. (1979); location of the San Gregorio fault zone from Weber et al. (1979) and Weber (1990).

platform deposits are also exposed in the modern sea cliff and are highly fossiliferous (Addicott, 1966). Marine deposits here are ~0.5 m thick and are overlain by ~10 m of alluvium. The platform in this area is displaced vertically by at least two northwesterly striking faults that are part of the San Gregorio fault zone (Fig. 5, after Weber, 1990). On the uplifted crustal block between these two faults, the Davenport platform is ~10 m above sea level where it is exposed in sea cliffs. Additional exposures of the Davenport platform are present near Point Santa Cruz. Here, the platform exposed in the sea cliff is ~6 m above sea level and is cut into sandstone bedrock. The platform is overlain by thin (~20 cm), fossiliferous marine deposits, containing paired specimens of the bivalves *Saxidomus gigantea* and *Protothaca staminea*. About 25 m inland of the sea-cliff exposure, the platform is covered with ~3.5 m of eolian (?) sand, with a well-developed (A/Bt/C profile, with Fe-pisolites) soil in its upper part.

Ages of 11 corals from the Green Oaks Creek locality range from $84,000 \pm 600$ to $75,800 \pm 800$ yr BP. Duplicate analyses of corals AN-9 and -10 from this locality do not show any difference in ages, within analytical uncertainty. With three exceptions (AN-1, -2 and -8), all corals analyzed have high (> 100) $^{230}\text{Th}/^{232}\text{Th}$ activity ratios, indicating little or no contamination with detrital, non-carbonate grains and therefore minimal “inherited” ^{230}Th . The somewhat higher ^{232}Th contents (i.e., lower $^{230}\text{Th}/^{232}\text{Th}$ values) in AN-1, -2 and -8 may bias these samples to slightly older ages. All fossil corals analyzed from Green Oaks Creek have back-calculated initial $^{234}\text{U}/^{238}\text{U}$ values that are within ± 0.008 of the quoted average seawater value of ~1.149 (Table 1; Fig. 2). At the Point Año Nuevo locality (USGS loc. M5925), a single *B. elegans* yielded an age of $75,800 \pm 400$ yr, although the back-calculated initial $^{234}\text{U}/^{238}\text{U}$ value (1.139) is lower than that of modern seawater. At Point Santa Cruz (USGS loc. M5924), a

single *Balanophyllia* gave a surprisingly young age of $71,500 \pm 400$ yr, about 4000 yr younger than any coral from the localities already discussed, but with an acceptable initial $^{234}\text{U}/^{238}\text{U}$ value.

3.4. Southern California: Palos Verdes Hills-San Pedro area

The Palos Verdes Hills-San Pedro area of Los Angeles County is an uplifted crustal block bounded on its landward side by the Palos Verdes fault and displaced on its southeastern side by the Cabrillo fault (Fig. 6). As many as 13 marine terraces have been mapped in the Palos Verdes Hills-San Pedro area (Woodring et al., 1946). New mapping and interpretation of the lowest marine terraces in the Palos Verdes Hills-San Pedro

area, presented here (Fig. 6), combined with previous aminostratigraphic and oxygen isotope data (Lajoie et al., 1991; Muhs et al., 1992) show that the terrace nomenclature of Woodring et al. (1946) needs modification. For example, Muhs et al. (1992) showed that what has been mapped as the “First Terrace” in San Pedro contains deposits that are probably of two different ages, depending on locality. Hence, in remapping the lowest terraces of the area, we have chosen to use local place names to designate terraces as morphostratigraphic units (Fig. 6), rather than use the terrace numbering system of Woodring et al. (1946). Because the area has been developed extensively in the past 50 years, we used 1:20,000-scale aerial photographs from 1953 as a mapping base. West of Point Fermin, on the upthrown side of the Cabrillo fault, we refer to the

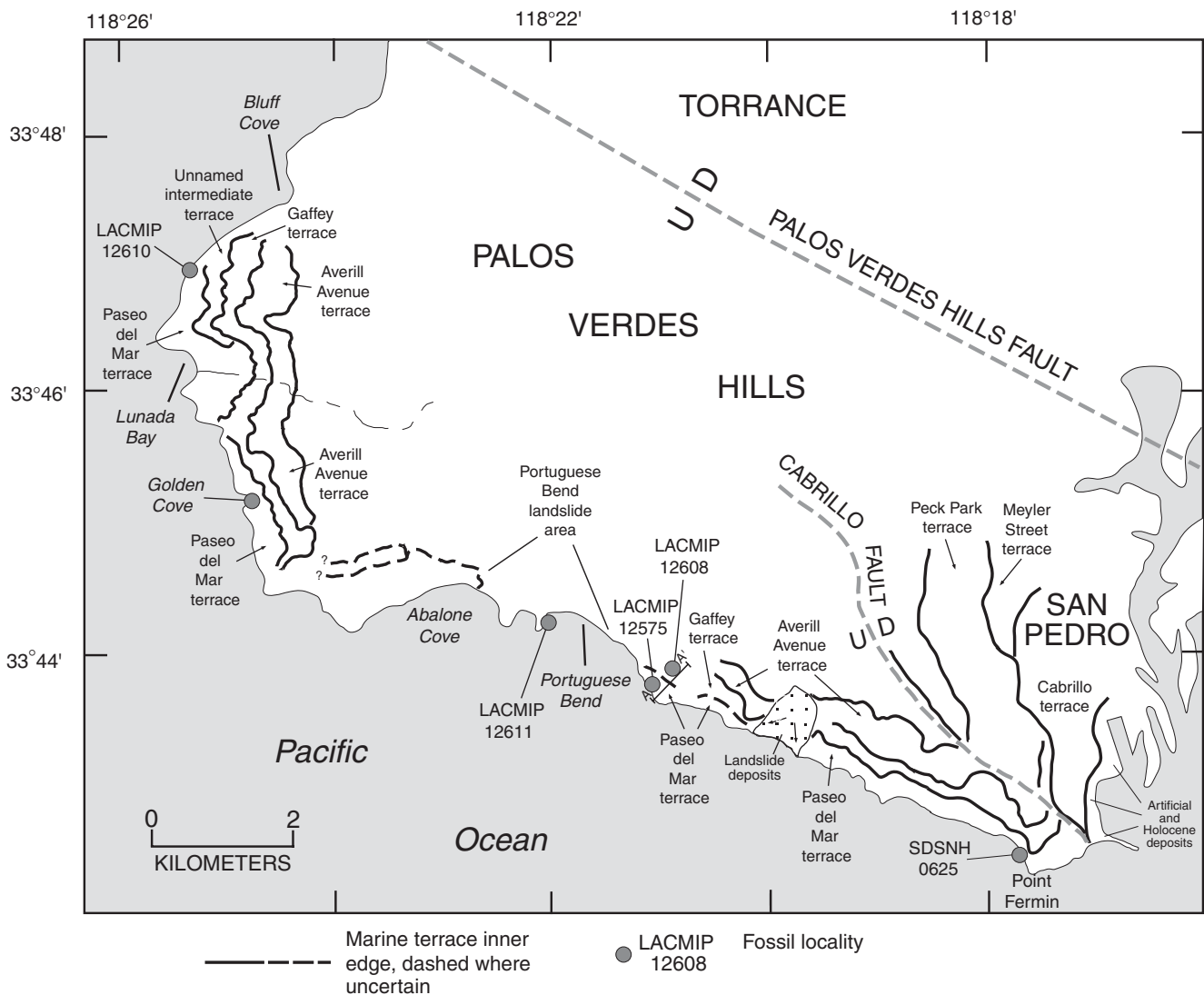


Fig. 6. Map showing marine terrace inner edges (solid black lines, dashed where uncertain, lower terraces only) in the Palos Verdes Hills-San Pedro area, fossil localities, location of cross section A-A' (Fig. 7), and location of the Palos Verdes Hills and Cabrillo faults. Geologic mapping by D.R. Muhs based on interpretation of aerial photographs and field checking; fault locations generalized from Woodring et al. (1946).

lowest surface that has horizontal continuity as the Paseo del Mar terrace (the “Second Terrace” of Woodring et al., 1946). We did not observe exposures of the shoreline angle of this terrace. However, based on platform elevations in sea cliff and arroyo exposures and the elevation of the topographically defined terrace inner edge (seen in plan view), we estimate the shoreline angle elevation to be ~45–47 m (Fig. 7). This estimate is supported by the observation of chiton homing scars in the bedrock of the wave-cut platform near LACMIP loc. 12575 at an elevation of ~43 m. In the coastal segment southwest of the Cabrillo fault between Point Fermin and Portuguese Bend (Fig. 6), the surface immediately above the Paseo del Mar terrace is designated here as the Gaffey terrace (the “Fourth Terrace” of Woodring et al., 1946). Shoreline angle exposures of this terrace could not be found either, but in arroyo exposures, platform elevations are as high as ~67 m and we infer a shoreline angle elevation between 70 and 80 m. The next highest terrace, designated here as

the Averill Avenue terrace (the “Fifth Terrace” of Woodring et al., 1946), has an inferred shoreline angle elevation that could not be determined with any precision, but may range somewhere between 110 and 140 m. We also remapped the lowest terraces on the west side of the Palos Verdes Hills in the coastal segment between Abalone Cove and Bluff Cove (Fig. 6). The Paseo del Mar, Gaffey and Averill Avenue terraces are correlative with the three lowest terraces in most of this coastal segment and are present at approximately the same elevations. Around Lunada Bay, however, there is a terrace intermediate between the Paseo del Mar and Gaffey terraces and has an estimated shoreline angle elevation between ~60 and ~70 m. Woodring et al. (1946) also recognized this terrace, which they designated as their “Third Terrace.”

In the Palos Verdes Hills, U-series ages of *Balanophyllia* specimens from these low terraces indicate that at least two high sea stands of the last interglacial complex are represented. The Gaffey terrace corals date to the

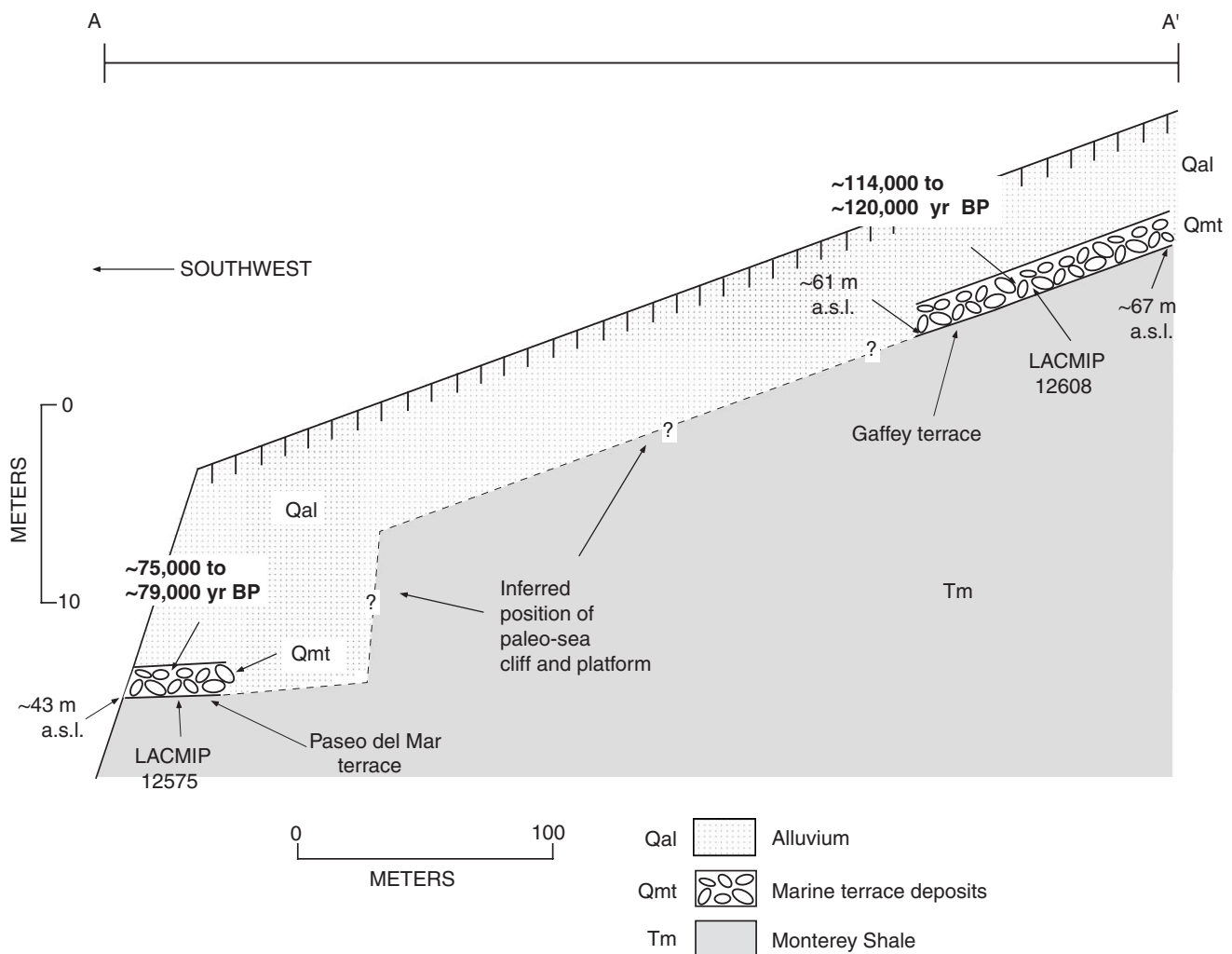


Fig. 7. Cross section A-A' showing marine terrace platforms, overlying deposits, fossil localities, and U-series ages (this study) in the Palos Verdes Hills area. Location of cross section shown in Fig. 6.

latter part of oxygen isotope substage 5e of the last interglacial complex (Table 1). Three of the four corals gave ages ranging from $119,500 \pm 700$ to $118,500 \pm 700$ yr BP, with one significantly younger coral dating to $113,300 \pm 900$ yr BP. Calculated initial $^{234}\text{U}/^{238}\text{U}$ values of all four corals are indistinguishable from values in modern seawater. Specimens of *Balanophyllia* from three localities on the lower-elevation Paseo del Mar terrace date to the $\sim 80,000$ yr high sea stand and oxygen isotope substage 5a (Table 1). At the Golden Cove locality (Fig. 6), four corals yielded reasonably high $^{230}\text{Th}/^{232}\text{Th}$ values, but only one has a calculated initial $^{234}\text{U}/^{238}\text{U}$ value within ± 0.008 of modern seawater. This coral gave an age of $82,700 \pm 900$ yr BP; the other three have initial $^{234}\text{U}/^{238}\text{U}$ values higher than that of modern seawater, and older ages. At the “Chiton bed” locality (SDSNH loc. 0625) near Point Fermin, a single *Balanophyllia* from the Paseo del Mar terrace gave an age of $78,500 \pm 500$ yr, with acceptable $^{230}\text{Th}/^{232}\text{Th}$ and initial $^{234}\text{U}/^{238}\text{U}$ values. At LACMIP loc. 12575, corals are much more abundant than at the other two localities. Unfortunately, although we analyzed eight individuals and all have acceptable $^{230}\text{Th}/^{232}\text{Th}$ values, none has a calculated initial

$^{234}\text{U}/^{238}\text{U}$ value within ± 0.008 of that in modern seawater. As with the single coral analyzed in this study from Point Arena, all corals from LACMIP loc. 12575 have initial $^{234}\text{U}/^{238}\text{U}$ values that are lower than those found in modern seawater. Calculated ages of the corals from LACMIP loc. 12575 range from $74,900 \pm 400$ to $78,900 \pm 400$ yr BP, which nevertheless overlap the range of ages found at Coquille Point, Green Oaks Creek, and the “Chiton bed” locality.

3.5. Southern California: San Nicolas Island

San Nicolas Island, Ventura County, has one of the best preserved, longest and most fossiliferous sequences of Quaternary marine terraces on the Pacific Coast of North America. Vedder and Norris (1963) mapped 14 marine terraces on this island (Fig. 8) and reported richly fossiliferous marine deposits on many terraces. They also presented faunal data and discussed the marine paleoclimatic implications of the fossil assemblages. Uranium-series dating by alpha spectrometry has shown that the two lowest terraces on San Nicolas Island record high sea stands of the last interglacial complex (Muhs et al., 1994). The first terrace has a

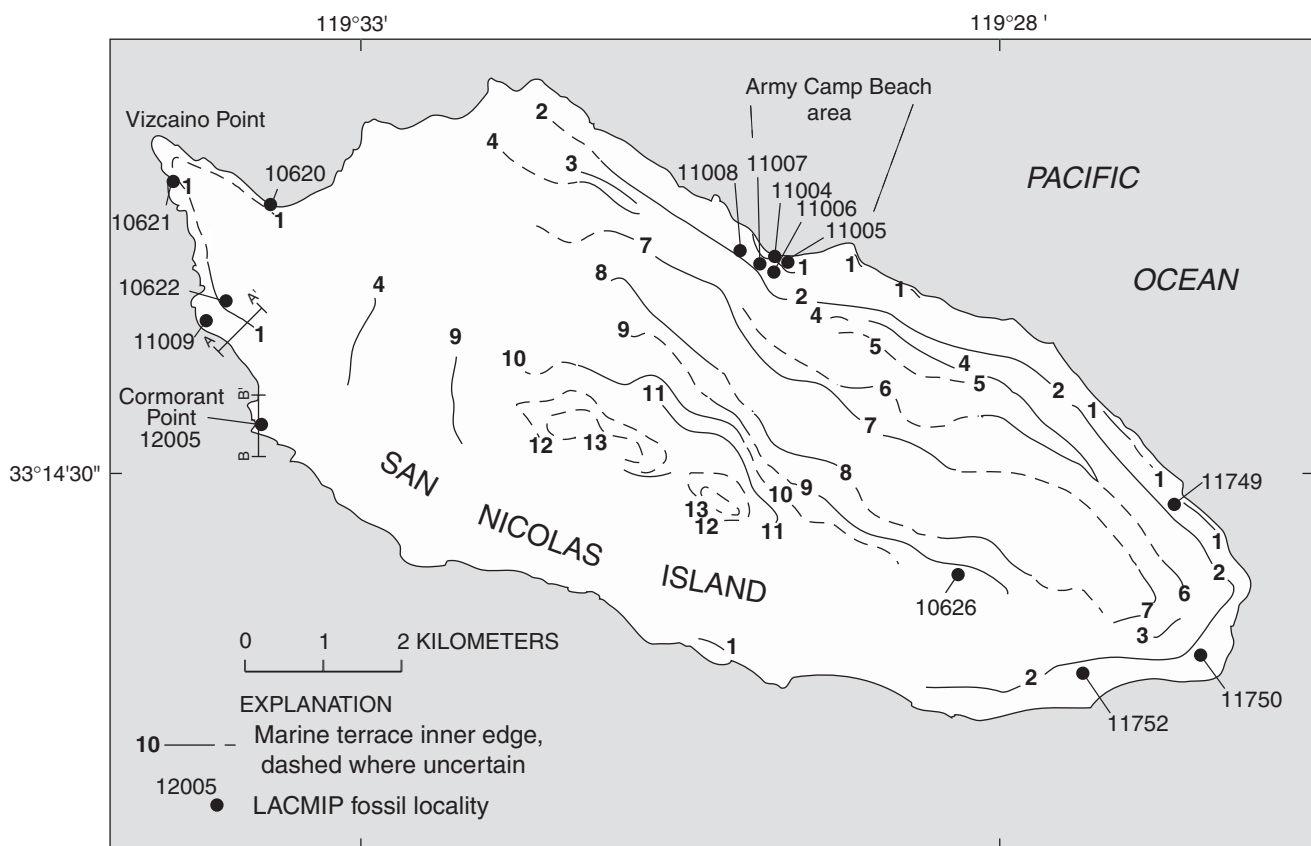


Fig. 8. Map of San Nicolas Island showing marine terrace inner edges (solid black lines; dashed where uncertain), fossil localities, and location of cross sections A-A' and B-B'. Terrace inner edges are from Vedder and Norris (1963) except for the 1st terrace, which was mapped by Muhs et al. (1994).

shoreline angle elevation of ~ 11 m near Army Camp Beach and elsewhere along the northern coast, but the shoreline angle is at ~ 22 m near Vizcaino Point (Fig. 8). Muhs et al. (1994) reported alpha-spectrometric U-series ages of $\sim 80,000$ yr BP from the first terrace at Army Camp Beach and Vizcaino Point. We collected corals on the first terrace from a new locality (LACMIP loc. 12005) at Cormorant Point, a short distance south of Vizcaino Point and recollected corals from the previously studied LACMIP loc. 11009 (Figs. 8 and 9). The second terrace is the best-preserved landform on San

Nicolas Island. Around the northern, northeastern and eastern sides of the island, it has a shoreline angle elevation of ~ 33 m. Near Vizcaino Point, deposits of the second terrace crop out above the first terrace, but owing to a cover of eolian sand, the shoreline angle is not exposed (Fig. 9). In fact, the second terrace in this part of the island may have been simply a nearshore shoal at the time of terrace formation. The second terrace here has been uplifted higher than at Army Camp Beach, however, as the wave-cut platform has an exposed elevation of ~ 36 m. From LACMIP loc. 10622

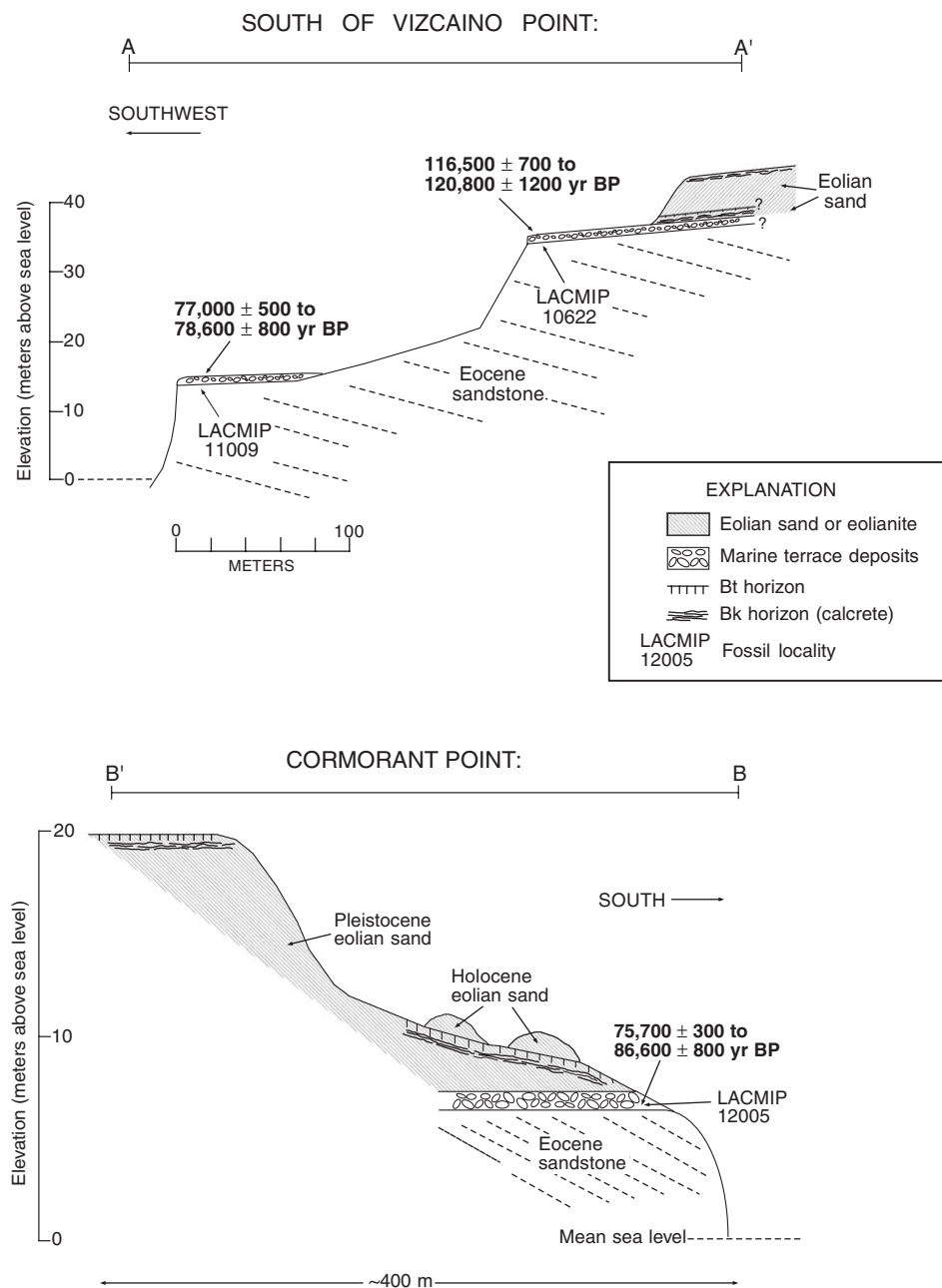


Fig. 9. Cross sections showing Quaternary stratigraphy and U-series ages south of Vizcaino Point (LACMIP locs. 11009 and 10622; cross section A-A' on Fig. 8) and near Cormorant Point (LACMIP loc. 12005; cross-section B-B' on Fig. 8), San Nicolas Island, California. All U-series ages are from this study, except for that from the 1st terrace south of Vizcaino Point, which is from Muhs et al. (1994).

on this terrace, we recollected corals for individual TIMS U-series dating.

Of 26 corals analyzed from the second terrace near Vizcaino Point (LACMIP loc. 10622), ten showed both acceptable $^{230}\text{Th}/^{232}\text{Th}$ values and initial $^{234}\text{U}/^{238}\text{U}$ values that are within 0.008 of modern seawater (Table 1; Fig. 2). Ages of the acceptable corals range from $120,800 \pm 1200$ to $116,500 \pm 700$ yr BP, a range similar to that for the Gaffey terrace on the Palos Verdes Hills. The ages are also in broad agreement with alpha-spectrometric U-series ages reported previously by Muhs et al. (1994). Deposits of the first terrace at Cormorant Point on San Nicolas Island yielded thirteen unrecrystallized *Balanophyllia*. Of these, eight had acceptable $^{230}\text{Th}/^{232}\text{Th}$ values and calculated initial $^{234}\text{U}/^{238}\text{U}$ values within ± 0.008 of modern seawater (Table 1; Fig. 2). The ages of these eight corals range from $86,600 \pm 800$ to $75,700 \pm 300$ yr BP. From LACMIP loc. 11009 on the first terrace, five unrecrystallized corals were analyzed; three of these had acceptable initial $^{234}\text{U}/^{238}\text{U}$ values. The ages of these three corals range from $80,100 \pm 300$ yr to $77,000 \pm 500$ yr BP, in good agreement with the coral ages from Cormorant Point.

4. Zoogeographic aspects of terrace faunas

Marine terrace faunas, particularly those rich in mollusks, provide valuable information in reconstructing marine paleoclimates of the Quaternary (e.g., Valentine, 1961, 1989; Addicott, 1964, 1966; Kennedy, 1978, 2000; Kennedy et al., 1982, 1992; Spencer and Campbell, 1987; Roy et al., 1995; Muhs et al., 2002a,b). Species that are most important in paleoclimatic interpretation of marine terrace faunas are those whose modern geographic distributions extend only to the south (“extralimital southern”) or only to the north (“extralimital northern”), respectively, of any fossil locality (Kennedy, 2000). Paleoclimatic inferences can also be made from species that are not strictly extralimital, but whose range endpoints are at or near a given fossil locality. These are referred to herein as “northward ranging” or “southward ranging” species, and when combined with the extralimital data, can aid in marine paleoclimatic interpretations. Fossils with modern ranges that extend to both the north and south of a locality are referred to herein as thermally “neutral” species.

It is important to note that what constitutes a “modern” geographic range of a species is a dynamic concept. For example, Barry et al. (1995) showed that ocean warming in the period between the 1930s and the 1990s resulted in a northward shift in geographic ranges of numerous species of marine invertebrates, including many mollusks. In the present study, modern geo-

graphic ranges are taken from the following sources: Abbott (1974), Kennedy (1978), McLean (1978), Abbott and Haderlie (1980), Haderlie and Abbott (1980), Newman and Abbott (1980), Kennedy and Armentrout (1989), McLean and Gosliner (1996), O’Clair and O’Clair (1998), Clark (1999), Coan et al. (2000), and collections of the Natural History Museum of Los Angeles County, Malacology Section (LACM; see <http://ip.nhm.org/nhmsearch/findlots.php>) and the Santa Barbara Museum of Natural History (SBMNH).

4.1. Southern Oregon

Addicott (1966), Zullo (1969) and Kennedy (1978) studied marine fossils from deposits of the Whisky Run terrace at Coquille Point and nearby localities. Extralimital southern species are absent from these deposits. However, the Whisky Run terrace deposits contain eleven extralimital northern species and one northward-ranging species (the gastropod *Littorina sitkana*) whose southern range endpoint today is in the vicinity of Coquille Point, Oregon (Fig. 10). Five species (the echinoid *Strongylocentrotus droebachiensis*; the bivalves *Mya truncata* and *Macoma obliqua* and the gastropods *Cryptobranchia concentrica* and *Puncturella noachina*) today range no farther south than Puget Sound, Washington ($\sim 47^\circ\text{N}$) and live as far north as Barrow, Alaska ($\sim 70^\circ\text{N}$). South of Coquille Point, at Cape Blanco, Oregon, the lowest emergent marine terrace is also fossiliferous (Addicott, 1964; Kennedy, 1978). Our interpretation is that the first terrace at Cape Blanco is correlative with the Whisky Run terrace at Coquille Point, based on similar amino acid ratios and oxygen isotope ratios in mollusks, reported by Muhs et al. (1990). The Cape Blanco terrace fauna includes nine extralimital northern species, including seven that are also found at Coquille Point (Kennedy, 1978; Fig. 10). We interpret the faunal data from Coquille Point and Cape Blanco to indicate marine paleotemperatures cooler than modern at $\sim 80,000$ yr BP along the southern Oregon coast.

4.2. Northern and central California: Point Arena, Green Oaks Creek, Point Año Nuevo, and Point Santa Cruz

In northern California, the marine terrace faunas at Point Arena (LACMIP loc. 4816; USGS loc. M7824) contain extralimital northern species and lack any extralimital southern or southward-ranging species (Fig. 11). Nine extralimital northern species of mollusks, barnacles and bryozoans have been identified (the bivalves *Mya truncata*, *Netastoma japonicum*, and *Penitella hopkinsi*; the gastropods *Cranopsis multistriata*, *Cryptobranchia concentrica*, *Puncturella noachina* and *Trichotropis cancellata*; the barnacle *Balanus rostratus*; and the bryozoan *Heteropora alaskensis*) (Kennedy,

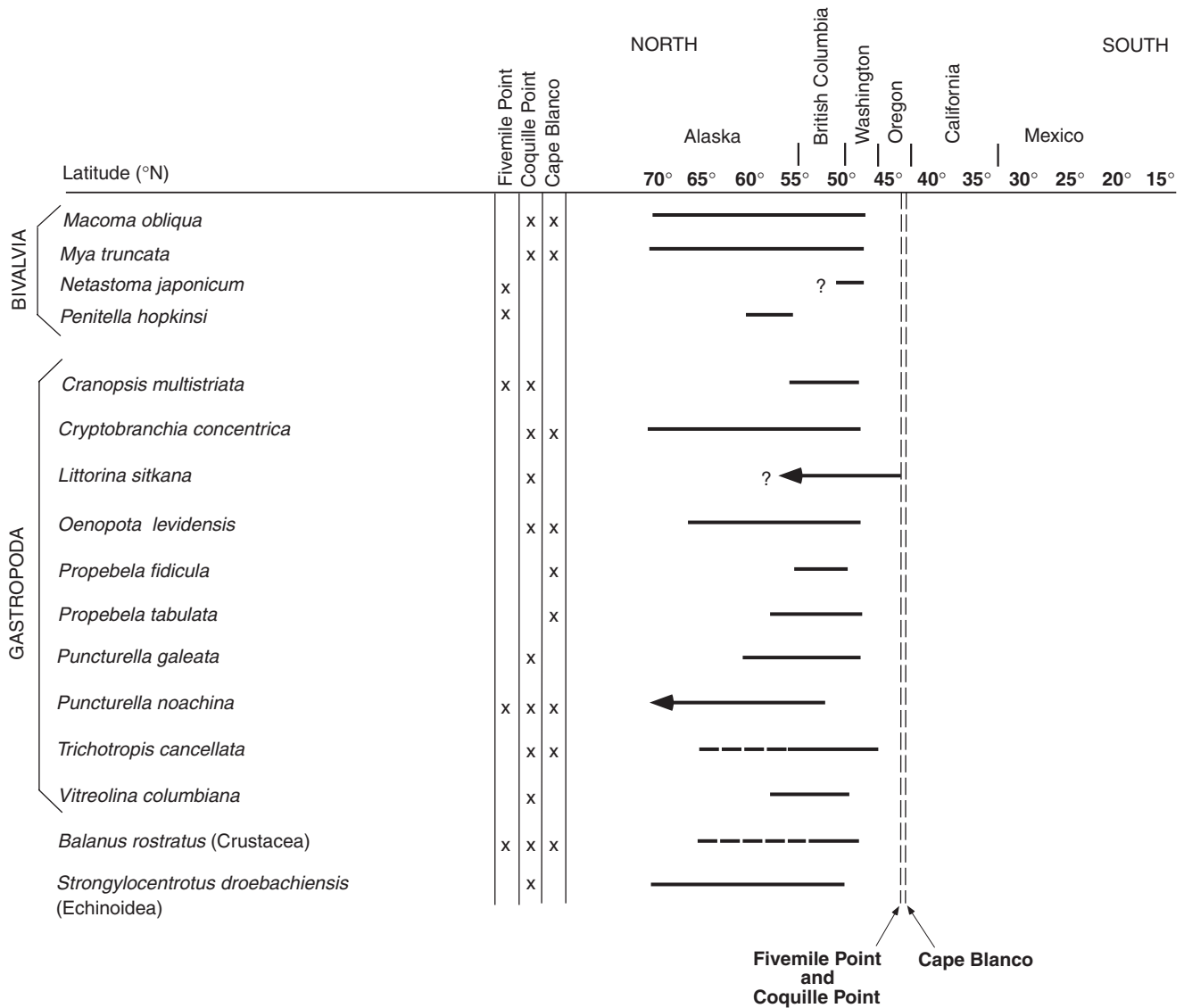


Fig. 10. Modern geographic ranges of extralimital northern and northward-ranging fossil mollusks, barnacles and echinoids found in ~80,000 yr BP marine terrace deposits at Coquille Point and Cape Blanco, Oregon; lines are dashed where range endpoints are uncertain. Fossil data from Addicott (1964, 1966), Zullo (1969), Kennedy (1978), and Kennedy and Armentrout (1989).

1978, 1981; Kennedy and Armentrout, 1989). Thus, as with southern Oregon, we interpret the faunal data to indicate cooler-than-modern marine paleotemperatures off the northern California coast at ~80,000 yr BP.

Our discussion of the faunas at Green Oaks Creek, Point Año Nuevo, and Point Santa Cruz, all localities in central California, is based on the faunal lists given in Addicott (1966) and Kennedy (1978), updated with current information on modern zoogeographic ranges. Deposits of the Davenport terrace at Green Oaks Creek contain four extralimital northern species (*M. truncata*, *C. concentrica*, *Nucella lima*, and *T. cancellata*) including three that are also found at Point Arena (Fig. 11). In addition, the fauna at Green Oaks Creek has three other species that are not strictly extralimital, but whose

modern southern range endpoints are at or near Point Año Nuevo, just south of Green Oaks Creek.

At Point Año Nuevo (USGS loc. M1690), Addicott (1966) recognized the cool-water aspect of the terrace fauna, although current information about zoogeographic ranges has modified the number of species that we would now interpret as cool-water forms. In the extensive fauna at Point Año Nuevo reported by Addicott (1966) and Kennedy (1978), there are numerous extralimital northern species but no extralimital southern or southward-ranging species (Fig. 11). The extralimital northern species in the fauna are *M. truncata*, *C. concentrica*, *N. lima*, *Propebela fidicula*, *P. tabulata*, *T. cancellata*, and *B. rostratus*, as well as three northward-ranging species. The Davenport terrace

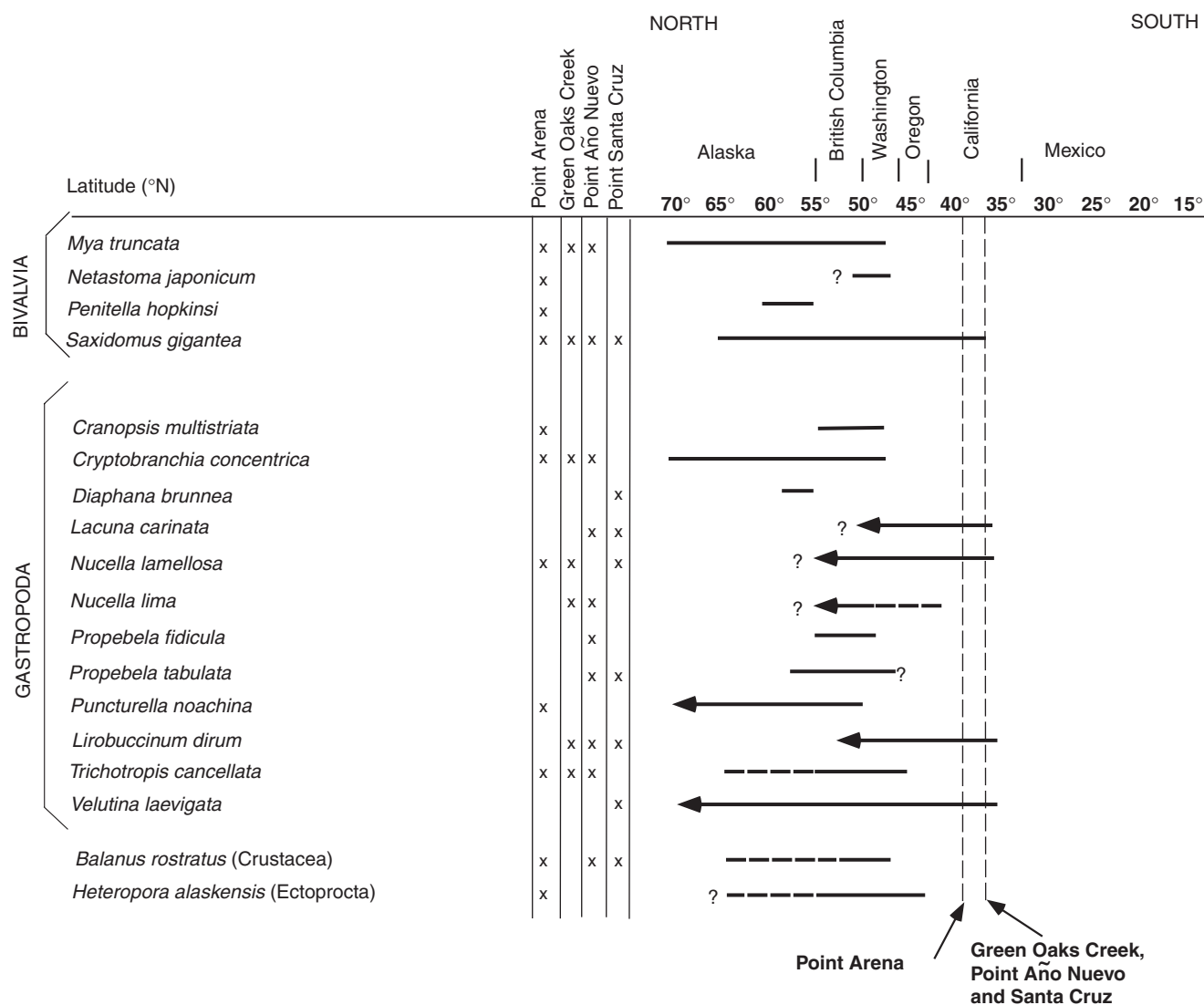


Fig. 11. Modern geographic ranges of extralimital northern and northward-ranging fossil mollusks, barnacles, and bryozoans found in ~80,000 yr BP marine terrace deposits at Point Arena, Green Oaks Creek (north of Point Año Nuevo), Point Año Nuevo and Santa Cruz, California; lines are dashed where range endpoints are uncertain. Fossil data from Addicott (1966), Kennedy (1978), and Kennedy and Armentrout (1989).

fauna from Point Santa Cruz (USGS loc. M1691; see Addicott, 1966) contains three extralimital northern species (*Diaphana brunnea*, *P. tabulata* and *B. rostratus*) and five northward-ranging species (Fig. 11). As with the other central California localities, the fauna lacks any extralimital southern or southward-ranging species. Based on the combined data from Green Oaks Creek, Point Año Nuevo, and Point Santa Cruz, we conclude that central California had cooler-than-modern waters at ~80,000 yr BP.

4.3. Southern California: Palos Verdes Hills-San Pedro area

In the Palos Verdes Hills-San Pedro area, faunas from the ~120,000-yr-old Gaffey and ~80,000-yr-old Paseo

del Mar terraces illustrate the differences in marine paleotemperatures during these two sea-level high stands. The ~120,000-yr-old fauna from the Gaffey terrace deposits at LACMIP loc. 12608 has only zoogeographically neutral species, as is typical in exposed coast habitats (Kennedy, 2000). Taxa identified to the species level are mostly typical rocky-shore forms (see Appendix Table in the online version of this article), and all have modern geographic distributions that extend well to the north and south of the Palos Verdes Hills. The observation of “thermally neutral” species in this deposit suggests a marine temperature at ~120,000 yr BP that was little different from that of today on this rocky shore.

In contrast, the faunas from localities on the 80,000-yr-old Paseo del Mar terrace have a cool-water aspect.

The fauna from LACMIP loc. 12575 is also dominated by rocky-shore forms and includes a large number of zoogeographically neutral species (see Appendix Table in the online version of this article). No extralimital southern species or southward-ranging species are present, with one possible exception. *Mangelia hooveri* has a reported modern range of San Pedro to San Diego (Abbott, 1974), which in principle would make it a southward-ranging species. Nevertheless, the taxonomic status of this species is uncertain at this point (J.H. McLean, personal communication, 2005), so we prefer not to make any paleoclimatic interpretations on the basis of this specimen. In addition to the abundant neutral species at LACMIP 12575, however, two extralimital northern species are present in the collections from this locality. These northern species are the bivalve *Penitella turnerae* and the barnacle *Semibalanus cariosus* (Fig. 12). *P. turnerae* ranges from the Queen

Charlotte Islands, British Columbia (Kennedy, 1989, p. 318) to Point Sal, Santa Barbara County, California (LACM 77-32.22; see Coan et al., 2000, p. 727). The barnacle *S. cariosus* has a modern range from the Bering Sea only as far south as Morro Bay, California (Newman and Abbott, 1980). Two northward ranging gastropods (*Tegula brunnea* and *T. montereyi*) are present in this deposit as well. *T. brunnea* ranges from Cape Arago, Oregon to Santa Barbara Island, California (Abbott and Haderlie, 1980) and possibly to San Pedro (LACM 57937 and SBMNH 8700) or Corona del Mar (SBMNH 43249). *Tegula montereyi* ranges from Bolinas Bay (Marin County), California to Santa Barbara Island (Abbott and Haderlie, 1980), but possibly also to San Pedro (LACM 57941) and San Nicolas Island (LACM 147862). Nevertheless, both *T. brunnea* and *T. montereyi* are only rarely found south of Point Conception.

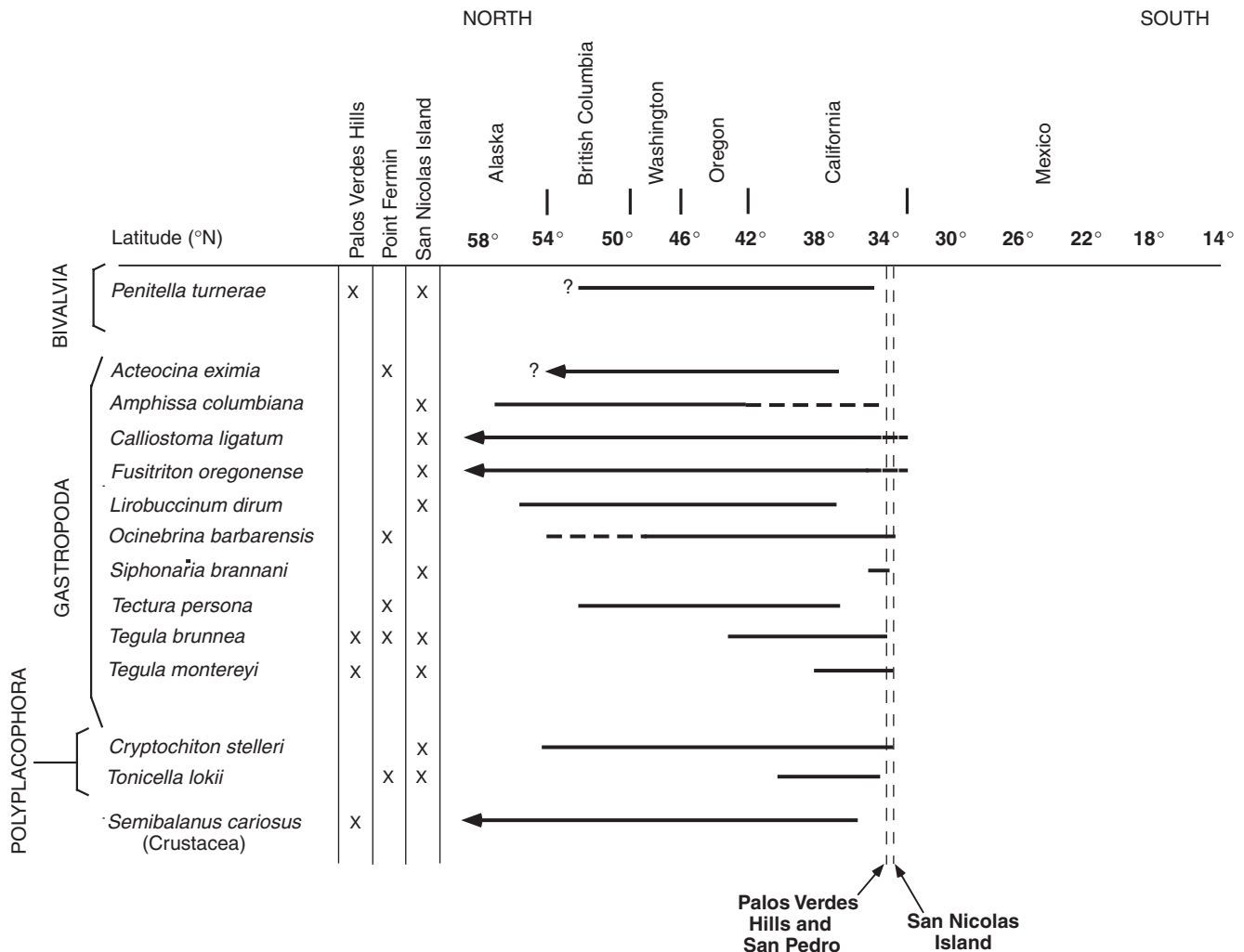


Fig. 12. Modern geographic ranges of extralimital northern and northward-ranging fossil mollusks found in deposits of the ~80,000-yr-old 1st terrace on San Nicolas Island and the Paseo del Mar terrace in the Palos Verdes Hills-San Pedro area; lines are dashed where range endpoints are uncertain. Fossil data are from the present study (see Appendix Table in the online version of this article), except those for the Point Fermin locality, which are updated from Chace and Chace (1919).

The fauna from the “Chiton bed” locality on the Paseo del Mar terrace near Point Fermin contains several cool-water species (Chace and Chace, 1919). Unfortunately, the exposure has been mostly lost by both park construction and modern sea-cliff retreat; the only species we could recover from the remnant exposure were fragments of *Haliotis* sp. and *Tegula funebris*. However, updating of the geographic ranges of (unconfirmed) species reported by Chace and Chace (1919) indicates that the fauna may contain several extralimital northern or northward ranging gastropods, including *Tectura persona* and *Acteocina eximia*, as well as the northward-ranging *T. brunnea* and *Ocenebrina barbarensis* (Fig. 12). In addition, Clark (1999) reported the extralimital northern chiton *Tonicella lokii* from this locality. We interpret the fauna at the ~80,000-yr-old “Chiton bed” locality to indicate cooler-than-modern marine waters.

4.4. Southern California: San Nicolas Island

The fauna from the ~120,000-yr-old second terrace at Vizcaino Point on the northwest end of San Nicolas Island (LACMIP loc. 10622), like that from the Gaffey terrace in the Palos Verdes Hills, consists of zoogeographically neutral species. The fauna here includes many common rocky-shore forms (see Appendix Table in the online version of this article). With the exception of *Tegula brunnea*, which ranges only as far south as Santa Barbara Island or possibly San Pedro (see discussion above), all of these rocky-shore species have modern ranges that extend well to the north and south of San Nicolas Island. We interpret these data to indicate that surface water temperatures off this part of San Nicolas Island at ~120,000 yr were about the same as those of today.

The ~80,000 yr BP locality on the first terrace at Cormorant Point on San Nicolas Island has a fauna that contrasts with the nearby ~120,000-yr-old locality at Vizcaino Point (Fig. 12). The ~80,000-yr-old fauna is more diverse than the older one and although it consists mostly of zoogeographically neutral species, no extralimital southern or southward-ranging species are present. However, several extralimital northern or northward-ranging species are found at Cormorant Point, including the extralimital northern bivalve *Penitella turnerae* and four species of gastropods. *Amphissa columbiana* ranges from Kodiak Island, Alaska (O’Clair and O’Clair, 1998) to San Pedro, California (Abbott and Haderlie, 1980), but is most common from Alaska to southernmost Oregon. *Lirabuccinum dirum* ranges from Chirikof Island, Alaska only to Monterey, California (Abbott and Haderlie, 1980). Two species of gastropods, *T. brunnea* and *T. montereyi* are not common in southern California, as discussed above. There is a single, modern specimen of

T. montereyi from San Nicolas Island in collections at the Los Angeles County Museum of Natural History (LACM 147862). It is not likely a common species around the island, however, as Kanter (1980), Russell (1991) and Seapy and Littler (1993) did not report either *T. brunnea* or *T. montereyi* from modern intertidal environments on San Nicolas Island. Two other species of gastropods, *Fusitriton oregonense* and *Calliostoma ligatum*, are found from Alaska to San Diego (Abbott and Haderlie, 1980; O’Clair and O’Clair, 1998), but are rare (*C. ligatum*), or found only in deeper water (>148 m) (*F. oregonense*) off southern California. One other gastropod found at Cormorant Point, *Siphonaria brannani*, is found only in southern California, from San Miguel Island to Santa Barbara Island (Seapy and Littler, 1993) or possibly to Santa Catalina Island (Abbott, 1974). However, it has not been reported from either San Nicolas Island (Kanter, 1980; Russell, 1991; Seapy and Littler, 1993) or nearby San Clemente Island (Seapy and Littler, 1993; LACM, Malacology Section records). Two other cool-water species found in ~80,000 yr BP terrace deposits on San Nicolas Island are both chitons. One is *Tonicella lokii*, which Clark (1999) reported from the first terrace at Army Camp Beach on San Nicolas Island (LACMIP loc. 11004; see Fig. 8). Muhs et al. (1994) dated *B. elegans* (using alpha spectrometry) at this locality also to ~80,000 yr BP. *T. lokii* has a modern range from Shelter Cove, Humboldt County, California, to San Miguel Island, California. The other cool-water chiton at Cormorant Point is *Cryptochiton stelleri*, which presently ranges from the Aleutian Islands to San Nicolas Island, but is rare south of Monterey Bay (Haderlie and Abbott, 1980). Kanter (1980), Russell (1991), and Seapy and Littler (1993) did not report *C. stelleri* in modern surveys of intertidal invertebrates on San Nicolas Island. Berry and Hubbs (1954) note, however, that *C. stelleri* is known from some Holocene shell middens in southern California and northern Baja California and Vedder and Norris (1963) report it in middens on San Nicolas Island. Collectively, the assemblage of extralimital northern and northward-ranging species gives a cool-water aspect to this 80,000-yr-old fauna.

5. Discussion

5.1. Uranium-series ages of terrace corals

The Gaffey terrace on the Palos Verdes Hills and the second terrace on San Nicolas Island have corals with U-series ages that correlate these deposits with some part of deep-sea oxygen isotope substage 5e, considered to be the peak of the last interglacial complex. Those corals from the Palos Verdes Hills and San Nicolas Island with initial $^{234}\text{U}/^{238}\text{U}$ activity ratios within

± 0.008 of the modern seawater value of 1.149 yield ages ranging from $120,800 \pm 1200$ to $116,500 \pm 700$ yr BP, with one younger coral dated to $113,300 \pm 900$ yr BP. Corals from uplifting Barbados (Gallup et al., 1994; Edwards et al., 1997; Speed and Cheng, 2004), slowly uplifting Oahu, Hawaii (Muhs et al., 2002b) and the tectonically stable Bahamas (Chen et al., 1991) and Australia (Stirling et al., 1998) have yielded U-series ages for emergent reefs that are thought to mark this same high stand of sea. The U-series ages for these tropical localities overlap the range of ages reported here, but also include many ages that are older (see summary in Muhs, 2002). Muhs et al. (2002a, 2004), using concepts presented by Bradley and Griggs (1976), have pointed out that corals from sediments on midlatitude, erosional marine terraces probably represent the latter phases of interglacial high sea stands; the early parts of interglacial periods are characterized by terrace cutting. Therefore, coral ages from erosional terraces should not be expected to range as old as those for constructional reefs on tropical coastlines. The age range reported here, from $\sim 120,000$ to $\sim 113,000$ yr BP, is close to that reported by Muhs et al. (2002a) for corals from erosional marine terraces on San Clemente Island, California and at Punta Banda, Baja California ($\sim 123,000$ to $\sim 114,000$ yr BP), which supports this model.

There has probably been no greater speculation about the age of a coastal landform in California than that of the Davenport platform between Point Año Nuevo and Santa Cruz. Anderson and Menking (1994) reviewed many of the previous age estimates made for this terrace. Bradley and Addicott (1968) reported U-series ages of mollusks of $\sim 60,000$ – $100,000$ yr BP, but Bradley and Griggs (1976) pointed out that U-series ages of mollusks are unreliable. The latter workers suggested instead that the Highway 1 platform, present just above the Davenport platform, was cut during the $\sim 120,000$ -yr-BP high stand of sea. They interpreted the Davenport platform, although at a lower elevation, to have been cut during a hypothesized (Bloom et al., 1974), lower, $\sim 140,000$ -yr-BP sea stand. Based on amino acid ratios in fossil mollusks and the faunal zoogeographic aspect, Kennedy et al. (1982) concluded that the fossil localities on the Davenport platform dated to the $\sim 80,000$ yr BP high stand of sea. Assuming an age of $\sim 120,000$ yr BP for the Highway 1 terrace, Lajoie et al. (1991) estimated an age of $\sim 100,000$ yr BP for the Davenport terrace. Perg et al. (2001) used cosmogenic isotopes to estimate an age of $65,000 \pm 3000$ yr BP for the Highway 1 terrace where it is found just northwest of Santa Cruz, implying an even younger age for the Davenport terrace.

The coral ages reported here, from Green Oaks Creek, Point Año Nuevo, and, with a lesser degree of certainty, Point Santa Cruz, all indicate that the Davenport platform dates to the $\sim 80,000$ yr BP high stand of sea.

Ages for the Davenport platform in central California reported here do not agree with an implied age estimate for this terrace using cosmogenic isotopes (Perg et al., 2001). The data of Perg et al. (2001) suggest a significantly younger terrace age than those that all previous investigators have inferred for any platform within the Santa Cruz terrace complex. Although Perg et al. (2001) did not date the Davenport platform directly, their data imply that this terrace should correlate with one of the interstadial high stands of sea, recorded as uplifted, coral-reef terraces on New Guinea. These terraces date to $\sim 50,000$, $\sim 40,000$ or $\sim 30,000$ yr BP (Chappell et al., 1996; Cutler et al., 2003). Based on the data presented here, we feel that the cosmogenic ages for the older Santa Cruz terraces are probably underestimates. It is possible that ages reported by Perg et al. (2001) reflect the ages of alluvium that overlies the marine deposits. Our own observations suggest that the terrestrial sedimentary cover in this area is typically much thicker than the marine cover; marine sediments are rarely, if ever, exposed at the ground surface. Alternatively, if marine deposits at their sampling locality are indeed exposed at the surface, younger-than-expected ages could result if the deposits are eroded.

Uranium-series ages of *B. elegans* from the California terraces permit an independent estimate of the possible duration of the high sea stand recorded by marine isotope substage 5a. Our multiple ages from the Green Oaks Creek locality give the highest degree of confidence (Fig. 2), and suggest a sea-level high-stand duration from $\sim 84,000$ to at least $\sim 76,000$ yr BP. All of the corals from the Davenport platform at Green Oaks Creek have initial $^{234}\text{U}/^{238}\text{U}$ activity ratios identical to that of modern seawater, within the ± 0.008 uncertainty range. The age range implied for the first terrace on San Nicolas Island (again using only those corals that have acceptable initial $^{234}\text{U}/^{238}\text{U}$ activity ratios) is $\sim 86,000$ to $\sim 76,000$ yr BP, in good agreement with the range of ages for the Davenport platform. If we choose to use a narrower range of “acceptable” initial $^{234}\text{U}/^{238}\text{U}$ activity ratios, e.g., 1.149 ± 0.004 , the age ranges for the Davenport platform and the first terrace on San Nicolas Island are unchanged. A conservative estimate is $\sim 8,000$ yr, based on the overlapping spread of ages ($\sim 84,000$ to $\sim 76,000$ yr BP) from Green Oaks Creek and the first terrace on San Nicolas Island. This range of ages agrees closely with the range of coral ages from the Southampton Formation on Bermuda, $\sim 84,000$ to $\sim 77,000$ yr BP, reported by Ludwig et al. (1996) and Muhs et al. (2002b).

In southern Barbados, Potter et al. (2004) reported a range of ages for the lowest terraces (their “T-1a” terrace complex) from $\sim 87,000$ to $\sim 74,000$ yr BP. However, their corals came from two different localities, one with ages ranging from $\sim 87,000$ to $\sim 81,000$ yr BP,

and the other with ages ranging from $\sim 79,000$ to $\sim 74,000$ yr BP. They interpreted these data to mean that there were two distinct high stands of sea during oxygen isotope substage 5a, one centering on $\sim 84,000$ yr BP and the other centering on $\sim 77,000$ yr BP. Although this intriguing hypothesis deserves further testing in other localities, we have not found any persuasive evidence of two separate high sea stands during substage 5a on the Pacific Coast of North America. The only possibility we can identify is that the terrace platform at Point Santa Cruz, which yielded a relatively young age of $\sim 71,000$ yr BP, could represent a younger event. More than a single U-series age is required to ascertain if this age estimate is representative of a truly younger terrace, however. If the interpretation of Potter et al. (2004) is correct, it is surprising that such a record has not been reported from the coast of western Barbados. In that part of the island, the local uplift rate is higher, and multiple high sea stands ought to be even better resolved (cf. Mesolella et al., 1969; Edwards et al., 1997; Speed and Cheng, 2004).

Summer insolation at high latitudes in the Northern Hemisphere reached a peak around 82,000 yr BP (Berger and Loutre, 1991), which is thought to have resulted in a major loss of high-latitude glacial ice (Fig. 13). The $\sim 80,000$ -yr-old terraces on many coastlines of the world, cited above, record this loss of glacial ice as a sea-level high stand, as does the oxygen isotope record in deep-sea cores (Martinson et al., 1987). Interestingly, however, the timing of this high sea stand has some significant differences with the present interglacial high sea stand. The summer insolation maximum that ushered in the modern relatively high sea level reached its Northern Hemisphere peak around 11,000 yr BP (Berger and Loutre, 1991). However, sea level did not reach near-present elevations until about 7000–5,000 yr BP (see compilation in Fig. 3 of Lambeck and Chappell, 2001), a sea-level lag of 6000–4,000 yr. In contrast, U-series ages of corals from several localities studied here, as well as on Bermuda (Muhs et al., 2002b) and Barbados (Gallup et al., 1994; Edwards et al., 1997; Potter et al., 2004), indicate that sea level must have been relatively high at the time of the 82,000 yr BP Northern Hemisphere summer insolation peak, or even prior to it. A higher-than-present sea level also occurred by $\sim 130,000$ yr BP, before the high-latitude summer insolation peak of $\sim 127,000$ yr BP (see review in Muhs, 2002). These findings suggest that loss of high-latitude glacial ice during some warm periods may occur well before summer insolation has reached maximum values, although this apparently did not occur during the Holocene.

5.2. Paleoclimatic implications of terrace faunas

From the two $\sim 120,000$ -yr-old fossil localities on the Palos Verdes Hills and San Nicolas Island, we infer

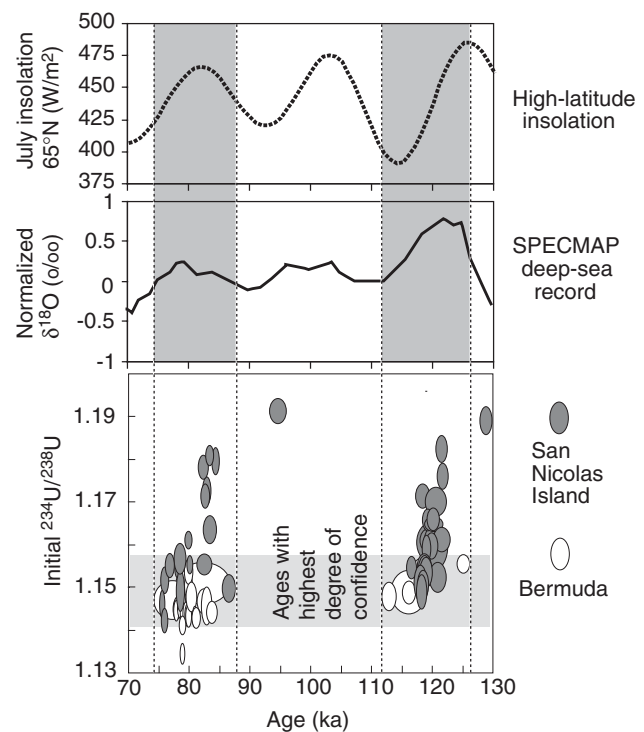


Fig. 13. Plot showing U-series ages and initial $^{234}\text{U}/^{238}\text{U}$ activity values of solitary corals from the 1st and 2nd terraces on San Nicolas Island, California compared to similar data for colonial corals from the Southampton and Rocky Bay Formations on Bermuda (Bermuda data from Ludwig et al., 1996; Muhs et al., 2002b). Ellipses define 2-sigma errors as calculated using Isoplot/Ex (Ludwig, 2001). "Acceptable range" is defined as the range of initial $^{234}\text{U}/^{238}\text{U}$ activity values that would indicate probable closed-system conditions with respect to U-series isotopes over the history of the fossil (see text for discussion). Also shown are normalized oxygen isotope values from the deep-sea record of SPECMAP (Martinson et al., 1987) and July insolation at the top of the atmosphere at 65°N (data from Berger and Loutre, 1991) for the same time period.

water temperatures little different from those of today, at least in exposed coastal habitats. Other localities on the Pacific Coast, with the same kind of exposed, rocky-shore environments, also have either thermally neutral fossil assemblages, or have a limited number of extralimital southern species, implying slightly warmer temperatures at $\sim 120,000$ yr BP (see examples in Kennedy et al., 1992; Muhs et al., 2002a). However, fossil localities preserved in estuarine or protected shore environments of the Pacific Coast, such as paleo-embayments, often contain large numbers of extralimital southern species (e.g., Valentine, 1961; Johnson, 1962; Emerson et al., 1981; Kennedy, 2002). Many of these localities have been inferred to date to the $\sim 120,000$ yr high sea stand, based on amino acid geochronology, and they are found from Oregon to southern Baja California Sur. Thus, water temperatures along much or all of the Pacific Coast of North America were as warm as, or warmer than present at $\sim 120,000$ yr BP.

In contrast, the marine terrace faunal data presented here suggest that at ~80,000 yr BP, water temperatures off the Pacific Coast of North America were cooler than at present. It is difficult, however, to estimate just how much cooler eastern Pacific waters were in quantitative terms using an aggregate of marine mollusks (for an example of the difficulties of such a procedure, see discussion in Lindberg et al., 1980). Nevertheless, some broad comparisons are possible. For example, Coquille Point and Cape Blanco, Oregon and Point Arena, California are all within the present Mendocinian subprovince of the Oregonian molluscan faunal province (Valentine, 1966). This subprovince includes northern California, Oregon and Washington. However, the ~80,000 yr BP faunas at these localities have an overall aspect that is equivalent to most of the Columbian faunal subprovince of the Oregonian province. The Columbian subprovince ranges from Puget Sound to Dixon Entrance, British Columbia. Thus, marine paleotemperatures off southern Oregon and northern California at ~80,000 yr BP were probably similar to those off British Columbia today.

It is also possible to make comparisons with similar data from other time periods in the late Quaternary. As discussed above, temperatures during the main high sea stand of the last interglacial complex, at ~120,000 yr BP, were at least as warm as present in exposed coastal habitats, and, based on some estuarine or protected-shore localities, may have been significantly warmer than present. In contrast, a submerged, fossiliferous, marine deposit in Monterey Bay, California has a radiocarbon age of ~20,000 cal yr BP, and thus dates to the last glacial period (Powell, 1994). This deposit has a molluscan assemblage that includes at least ten and perhaps as many as thirteen extralimital northern species and a half-dozen or more northward-ranging species. Compared to the number of extralimital northern species in ~80,000-yr-old deposits at nearby localities (Green Oaks Creek, Point Año Nuevo, and Point Santa Cruz) the ~20,000-yr-old fauna indicates, therefore, water temperatures during the last glacial period that were significantly colder than during the ~80,000 yr BP high sea stand. Thus, the fossil assemblages of the ~80,000-yr-old deposits suggest water temperatures that were not as warm as full interglacials (isotope stage 1 or substage 5e), but also not as cool as full-glacial conditions, such as at ~20,000 yr BP (isotope stage 2).

There have been several studies of the causes of changes in marine molluscan diversity, along both spatial and temporal scales, on the Pacific Coast (Lindberg et al., 1980; Valentine, 1989; Roy et al., 1995, 1998; Lindberg and Lipps, 1996). Several conclusions have emerged from these studies: (1) modern marine molluscan diversity changes as a function of

latitude, on both the Pacific and Atlantic coasts, and diminishes sharply north of about 30–35°; (2) diversity is correlated strongly and positively with sea surface temperature; (3) the Pleistocene molluscan record of California represents much of the modern molluscan diversity; and (4) molluscan provincial boundaries provide a greater barrier to southern species migrating north than to northern species migrating south. Roy et al. (1995) point out that for southern species migrating north during the Pleistocene, warmer waters found to the north were likely to be those at shallow depths, whereas during cooler periods, northern species migrating south could find cooler waters in both shallow and deep environments, as well as in zones of upwelling. Our studies provide support for this model. Rocky coasts at ~120,000 yr BP, such as on the Palos Verdes Hills and San Nicolas Island, would not provide shallow-water environments favorable for migration of southern species northward. Thus, no extralimital southern species were found in marine terrace deposits of this age at these localities, and only a few have been reported for other ~120,000-yr-old rocky-shore localities, such as San Clemente Island, California and Punta Banda, Baja California (Muhs et al., 2002a). In contrast, rocky-shore environments with deep waters provide many opportunities for northern species migrating south. About equal numbers of extralimital northern or northward ranging species are found in southern Oregon, northern and central California, and southern California, which supports the model of Roy et al. (1995).

Changes in relative marine paleotemperatures, based on terrace faunas, can be compared with paleotemperature estimates from deep-sea cores. Sediments from cores off of the Pacific Coast of North America span the last interglacial–glacial cycle, including substage 5a (~80,000 yr BP) and substage 5e (~120,000 yr BP). Paleoclimate studies by Kreitz et al. (2000), Mangelsdorf et al. (2000), Herbert et al. (2001) and Seki et al. (2002) are based on analysis of alkenones in phytoplankton from cores taken off the Pacific Coast. Alkenone-based marine paleotemperatures indicate that the eastern Pacific Ocean was as warm or warmer than present at ~120,000 yr BP. Faunal studies from our two new ~120,000-yr-old localities (Palos Verdes Hills and San Nicolas Island) agree with these conclusions, as do the faunas from other open-coast marine terrace localities that date to ~120,000 yr, reported by Muhs et al. (2002a).

In general, faunal aspects of ~80,000-yr-old terraces also agree with the alkenone record. Alkenone-derived paleotemperature estimates from *most* cores (ODP hole 1020, off northern California, ODP hole 1018A, off Santa Cruz, ODP holes 1017 and 1016, off Point Conception, and ODP hole LPAZ21P, off the southern tip of Baja California Sur) suggest that water

temperatures were cooler than present at ~80,000 yr BP. However, other cores (ODP hole 893A, off Santa Barbara, and ODP holes 1012 and EW03, off northern Baja California) have alkenone data that suggest water temperatures at ~80,000 yr BP were as about as warm as present (893 and EW03) or even warmer than present (1012). Our data, combined with those presented by Kennedy (1978), Emerson et al. (1981), Rockwell et al. (1989), Kennedy et al. (1992), and Muhs et al. (2002a), suggest that at ~80,000 yr BP, waters were cooler than present off the Pacific Coast, from at least southern Oregon to northern Baja California Sur, in agreement with an earlier summary by Kennedy et al. (1982). The reason for the discrepancy between the terrace faunal record and the alkenone record for some ODP localities (893, EW03, and 1012) is not understood. Paleoclimate proxies from other marine organisms indicate that water temperatures off the Pacific Coast of North America were cooler than present at ~80,000 yr BP. Foraminiferal data from ODP hole 893A, near Santa Barbara, indicate water temperatures much cooler than present at ~80,000 yr BP (Kennett and Venz, 1995). Radiolarian data from a core (EW9504-17PC) off southern Oregon show sea surface temperatures 2–3 °C cooler than present at ~80,000 yr BP (Pisias et al., 2001).

Vegetation communities in coastal Oregon and California strongly reflect marginal eastern Pacific Ocean surface water temperatures. Detailed pollen studies of cores from offshore southern Oregon and northern and southern California provide evidence for terrestrial vegetation at ~80,000 yr BP (Heusser, 2000; Heusser et al., 2000; Herbert et al., 2001; Pisias et al., 2001). In northern California, *Sequoia* (redwood) and *Quercus* (oak) are warm-climate indicators. Pollen data from ODP hole 1020, off northern California (Fig. 1), as well as from hole EW9504-17, off southern Oregon, show that *Sequoia* and *Quercus* were not as abundant during substage 5a as during substage 5e or the present interglacial period (isotope stage 1). Nevertheless, these taxa were more abundant during substage 5a than during the last glacial period (isotope stages 2–4). In contrast, *Pinus* (pine), a cool-climate indicator, was more abundant during substage 5a than during substage 5e or stage 1, but was not as abundant as during stages 2 or 3. In southern California, pollen data from ODP hole 893 (Santa Barbara Basin) show that *Quercus*, a warm-climate indicator in this region, was not as abundant in substage 5a as it is at present, nor as abundant as it was during substage 5e. Thus, the pollen data are in excellent agreement with the faunal data presented here in that they indicate eastern Pacific Ocean water temperatures at ~80,000 yr BP that are intermediate between full-interglacial (e.g., substage 5e or stage 1) and full-glacial (stage 2) conditions in both northern and southern California.

5.3. Causes of cooler water temperatures off western North America at ~80,000 yr BP

The eastern Pacific Ocean off North America has, as its most prominent feature, the California Current System (CCS). The CCS is an eastern boundary current (Fig. 1) that is part of the larger North Pacific gyre, driven by the subtropical, or Hawaiian, high-pressure cell. The CCS has inputs from cold subarctic Pacific water, warm central North Pacific water, cold coastal upwelled water, and warm subsurface equatorial Pacific water (Lynn and Simpson, 1987; Hickey, 1998). For the most part, the CCS is a broad, diffuse, equatorward flow whose core is offshore. Along the continental shelf and slope there is another current, called the Inshore Countercurrent or Davidson Current (Fig. 1). The main direction of flow of the Davidson Current is poleward during the winter; however, during the spring inshore surface flow is equatorward and is part of the overall flow of the CCS (Lynn and Simpson, 1987). Our localities at Coquille Point, Cape Blanco, Point Arena, Green Oaks Creek, Point Año Nuevo, and Point Santa Cruz are all affected, to one degree or another, by the California Current. South of Point Conception, part of the California Current turns southeastward and then shoreward (Hickey, 1992). This water mass becomes entrained in a counterclockwise flow called the Southern California Eddy, and affects the region south of Point Conception, including most of mainland southern California. Because of mixing with water derived from the south, waters in the Southern California Eddy, which affect the Palos Verdes Hills, are warmer than those of the offshore portion of the California Current, at the same latitude. Because it is farther offshore, San Nicolas Island, as with our localities farther north, is affected directly by the California Current during much of the year. Thus, modern intertidal and nearshore marine environments on San Nicolas Island have a greater number of mollusks with northern affinities than do the modern intertidal and nearshore marine environments around the Palos Verdes Hills (Littler, 1980; Seapy and Littler, 1980, 1993). The differing positions of the Palos Verdes Hills and San Nicolas Island with respect to the CCS and the Southern California Eddy may explain why a greater number of extralimital northern species are found in ~80,000-yr-old deposits on San Nicolas Island compared to Point Fermin and the Palos Verdes Hills (Fig. 12). Despite this minor difference, our compilations, combined with those of previous studies (Kern, 1977; Kennedy, 1978; Emerson et al., 1981; Kennedy et al., 1982, 1992; Rockwell et al., 1989; Muhs et al., 2002a) indicate that cooler-than-modern waters were present at ~80,000 yr BP on the Pacific Coast from southern Oregon to northern Baja California Sur. We propose that such an extensive cooling of the eastern Pacific Ocean must be a function

of a regional-scale process, such as changes in the inputs of the CCS or the amount of coastal upwelling. Alternatively, an external mechanism, such as insolation forcing, could have affected the entire region.

Doose et al. (1997) proposed a heat balance model for the California Current. In this model, the temperature of the water flowing out at the southern end of the CCS is a function of (1) the flux and temperature of water entering the CCS from the north, (2) the flux and temperature of upwelling water, and (3) heat added by insolation. At ~80,000 yr BP, insolation at 30°N was actually higher than present in summer (~511 vs. ~474 W/m²) and slightly lower than present in winter (~212 vs. ~227 W/m²), based on calculations of Berger and Loutre (1991). Relative seasonal differences in insolation were similar at higher latitudes as well. Thus, we suspect that changes in insolation do not explain the overall cooler temperatures at ~80,000 yr BP, although the slight shifts in insolation could have caused a somewhat greater seasonal range in water temperatures. Off northern California, the amount of coastal upwelling at ~80,000 yr BP can be assessed by abundances of the diatom *Chaetoceros*, a known indicator of coastal upwelling (Barron et al., 2003), in cores that include both Holocene (ODP hole 1019) and substage 5a (ODP hole 1020) records. Diatom data suggest that the amount of coastal upwelling was no greater than present, and may have been less than present at ~80,000 yr BP (Poore et al., 2000). Off southern California, the amount of upwelling can be assessed by the presence of the planktonic foraminifer *Globigerina bulloides* (Kennett and Venz, 1995). Relative abundances of this species in ODP hole 893A, from Santa Barbara Basin, indicate that during substage 5a, upwelling was less prevalent than during most of the Holocene. We therefore conclude that increased upwelling along the Pacific Coast is not responsible for cooler-than-modern water temperatures during the ~80,000 yr BP high stand.

Other workers studying paleoceanographic records off the Pacific coast of North America have interpreted cooler-than-modern temperatures to be the result of a stronger California Current, or at least a larger component of cool, subarctic water in the CCS (Kennett and Venz, 1995; Pisias et al., 2001). Conversely, warmer-than-modern temperatures are interpreted to be the result of a weaker California Current and greater poleward migration of warm, lower-latitude waters. For example, Kennett and Venz (1995), studying planktonic foraminifera in ODP hole 893A, concluded that over the past ~160,000 yr, times of cool sea-surface temperatures were associated with an increased influence of the CCS and weakened northward flow of the relatively warm Davidson Countercurrent. Pisias et al. (2001) concluded that warmer-than-modern temperatures off southern Oregon and northern California (such

as during isotope substage 5e at ~120,000 yr BP) are due to reduced equatorward advection of cool waters in the CCS. We hypothesize that cooler-than-modern waters along the Pacific Coast during the ~80,000 yr BP stand of sea are due to greater equatorward advection of cool, subarctic-Pacific-derived waters in the CCS.

5.4. Comparison with the Atlantic coast of North America at ~120,000 and ~80,000 yr BP

We can compare marine paleotemperatures at ~120,000 yr BP and ~80,000 yr BP from the Pacific Coast with reconstructed paleotemperatures on the Atlantic Coast of North America and islands near it. In a recent review of substage 5e-equivalent marine fossil localities, Muhs et al. (2002b) concluded that waters in the Caribbean were at least as warm as present and western Atlantic waters, from Bermuda to Arctic Canada, were probably warmer than present at ~120,000 yr BP. Faunal data presented here and in previous studies also show that marginal eastern Pacific waters were as warm or warmer than present at ~120,000 yr BP.

In contrast, at ~80,000 yr BP, Pacific and Atlantic waters had large differences in paleotemperatures, relative to present. Fossil localities with ~85,000–70,000 yr BP ages on corals occur in emergent marine deposits in Virginia, North Carolina, South Carolina and Georgia (Oaks et al., 1974; Mixon et al., 1982; Szabo, 1985; Wehmiller et al., 2004). Molluscan faunas from the Womack, New Light and Toy Avenue localities (around Virginia Beach, Virginia), dated to ~80,000 yr BP, all contain large numbers of extralimital southern or southward-ranging species, lack any extralimital northern species, and have few or no northward-ranging species (Spencer and Campbell, 1987). Interpretations of marine ostracode faunas from these and other localities are consistent with those based on the molluscan faunas (Cronin et al., 1981). Localities with ostracode data that indicate waters warmer than those of the present have been reported from ~80,000 yr BP deposits at New Light, Womack, and Mears, Virginia; Moyock, North Carolina; and Scanawah Island, South Carolina (Cronin et al., 1981). Farther south, off the Florida Keys, Ludwig et al. (1996) and Toscano and Lundberg (1999) dated a submerged reef to ~80,000 yr BP. The coral fauna in this reef includes *Acropora palmata* and *Colpophyllia natans*. *A. palmata* and *C. natans* presently live throughout the Caribbean Sea and as far south as Venezuela, but no farther north than the Florida Keys (Chiappone et al., 1996). Both corals are, therefore, at or near their modern northern distributional limits in the Florida Keys, which suggests water temperatures at least as warm as those of today. Because water temperatures along the Atlantic Coastal Plain and Florida are determined, to a great degree, by

the presence of the Gulf Stream, a western boundary current, the faunal data presented here suggest a Gulf Stream at least as strong as that of the present during substage 5a.

As discussed above, during the peak of the last interglacial period 120,000 yr BP, marine paleotemperatures off both eastern and western North America (as well as at high latitudes) were as warm as, or warmer than present. In contrast, there appear to have been strong regional differences in marine paleotemperatures around North America at ~80,000 yr BP. It seems likely that the Gulf Stream at ~80,000 yr BP was at least as strong as it is now and delivered relatively warm waters to the US Atlantic Coastal Plain and Florida (Fig. 14). Water temperatures off the Pacific Coast of North America, however, were cooler than present at ~80,000 yr BP, from southern Oregon to at least northern Baja California Sur, possibly due to a stronger California Current.

6. Conclusions

High-precision TIMS U-series dating of solitary corals (*Balanophyllia elegans*) shows that the second emergent terraces of the Palos Verdes Hills and San Nicolas Island date to the ~120,000 yr BP high sea stand of the last interglacial complex. This high sea stand is recorded on Barbados, Bermuda and New Guinea, as well as other localities on the Pacific Coast of North America, and correlates with marine isotope substage 5e. New U-series analyses of corals indicate that localities near Coquille Point, Oregon, and Point Arena, Green Oaks Creek, Point Año Nuevo, Santa Cruz, the Palos Verdes Hills, San Pedro and San Nicolas Island (all in California) record the ~80,000 yr BP high stand of sea. This high sea stand is also recorded on Barbados, Bermuda and New Guinea and is correlative with marine isotope substage 5a. In the Holocene, sea level rise to its present elevation lagged the ~11,000 yr BP

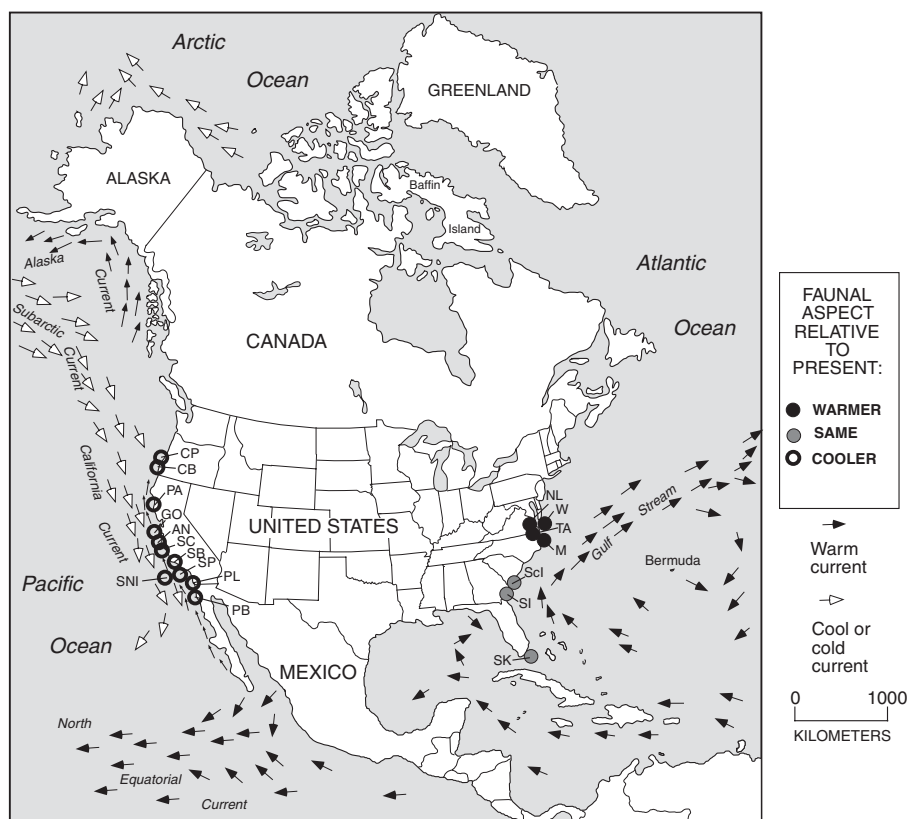


Fig. 14. Map of North America showing fossil localities thought to date from the ~80,000 yr BP sea-level high stand, thermal aspects of fossil faunas relative to present and major ocean current systems. CP, Coquille Point; CB, Cape Blanco; PA, Point Arena; GO, Green Oaks Creek; AN, Point Año Nuevo; SC, Santa Cruz; SP, San Pedro-Palos Verdes Hills; SNI, San Nicolas Island; fossil data from Addicott (1964, 1966), Zullo (1969), Kennedy (1978), Chace and Chace (1919), and Appendix Table in the online version of this article. Age data are from the present study. Other fossil and age data on the Pacific Coast of North America: SB, Santa Barbara (Kennedy et al., 1992); PB, Punta Banda (Rockwell et al., 1989, and Muhs et al., 1994, 2002a); PL, Point Loma (Kern, 1977, and Muhs et al., 1994, 2002a); TB, Turtle Bay (Emerson et al., 1981). Abbreviations of ~80,000-yr-old localities from the Atlantic coast of North America: NL, New Light, Virginia; W, Womack, Virginia; TA, Toy Avenue, Virginia; M, Moyock, North Carolina; ScI, Scanawah Island, South Carolina; SI, Skidaway Island, Georgia; SK, Sand Key, Florida. Age data from Oaks et al. (1974), Mixon et al. (1982), Szabo (1985), Wehmiller et al. (2004), Ludwig et al. (1996), and Toscano and Lundberg (1999); fossil data from Cronin et al. (1981), Spencer and Campbell (1987), Hulbert and Pratt (1998) and Toscano and Lundberg (1999).

Northern Hemisphere summer insolation high. In contrast, the 84,000–76,000 yr high sea stand on the Pacific Coast may have coincided with, or even preceded the summer insolation high at ~82,000 yr BP. Furthermore, U-series ages from both Green Oaks Creek and San Nicolas Island (herein) and Bermuda (Muhs et al., 2002b) suggest that the high sea stand at ~80,000 yr BP could have had a duration of 8000 yr.

Marine terrace faunas provide valuable information about nearshore water temperatures during sea level high stands of the past. Fossils from terraces dated to the ~120,000 yr BP high sea stand in southern California lack extralimital species in exposed coastal locales and suggest that water temperatures were similar to those of the present. However, at all of our ~80,000 yr BP localities, from southern Oregon to southern California, terrace faunas at exposed coastal locales are characterized by numerous extralimital northern species and a lack of extralimital southern species. These assemblages are interpreted to indicate that during this high sea stand, nearshore waters were cooler than at present. Because neither insolation nor upwelling appear to have been responsible for this cooling, lower-than-present water temperatures at ~80,000 yr BP may have been due to a stronger California Current with a greater component of cool, subarctic waters.

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Appendix A. Electronic Supplementary Material

The online version of this article contains additional supplementary data. Please visit [doi:10.1016/j.quascirrev.2005.03.014](https://doi.org/10.1016/j.quascirrev.2005.03.014).

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