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Sea-level history during the Last Interglacial complex on San Nicolas Island, California: implications for glacial isostatic adjustment processes, paleozoogeography and tectonics

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ABSTRACT

San Nicolas Island, California has one of the best records of fossiliferous Quaternary marine terraces in North America, with at least fourteen terraces rising to an elevation of ∼270 m above present-day sea level. In our studies of the lowest terraces, we identified platforms at 38–36 m (terrace 2a), 33–28 m (terrace 2b), and 13–8 m (terrace 1). Uranium-series dating of solitary corals from these terraces yields three clusters of ages: ∼120 ka on terrace 2a (marine isotope stage [MIS] 5.5), ∼120 and ∼100 ka on terrace 2b (MIS 5.5 and 5.3), and ∼80 ka (MIS 5.1) on terrace 1. We conclude that corals on terrace 2b that date to ∼120 ka were reworked from a formerly broader terrace 2a during the ∼100 ka sea stand. Fossil faunas differ on the three terraces. Isolated fragments of terrace 2a have a fauna similar to that of modern waters surrounding San Nicolas Island. A mix of extralimital southern and extralimital northern species is found on terrace 2b, and extralimital northern species are on terrace 1. On terrace 2b, with its mixed faunas, extralimital southern species, indicating warmer than present waters, are interpreted to be from the ∼120 ka high sea stand, reworked from terrace 2a. The extralimital northern species on terrace 2b, indicating cooler than present waters, are interpreted to be from the ∼100 ka sea stand. The abundant extralimital northern species on terrace 1 indicate cooler than present waters at ∼80 ka.

Using the highest elevations of the ∼120 ka platform of terrace 2a, and assuming a paleo-sea level of +6 m based on previous studies, San Nicolas Island has experienced late Quaternary uplift rates of ∼0.25–0.27 m/ka. These uplift rates, along with shoreline angle elevations and ages of terrace 2b (∼100 ka) and terrace 1 (∼80 ka) yield relative (local) paleo-sea level elevations of +2 to +6 m for the ∼100 ka sea stand and −11 to −12 m for the ∼80 ka sea stand. These estimates are significantly higher than those reported for the ∼100 ka and ∼80 ka sea stands on New Guinea and Barbados. Numerical models of the glacial isostatic adjustment (GIA) process presented here demonstrate that these differences in the high stands are expected, given the variable geographic distances between the sites and the former Laurentide and Cordilleran ice sheets. Moreover, the numerical results show that the absolute and differential elevations of the observed high stands provide a potentially important constraint on ice volumes during this time interval and on Earth structure.

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1. Introduction

Generation of a eustatic sea level curve that tracks glacial–interglacial cycles has been a goal of Quaternary stratigraphers and paleoclimatologists for decades. Emergent marine terraces have long been studied as a means of reconstructing sea level history, whether they are erosional, wave-cut platforms on high-energy coasts, or constructional, coral reef tracts on tropical coasts. Early studies were conducted on both tectonically stable coasts (e.g., Veeh, 1966) and uplifting coasts (Broecker et al., 1968; Veeh and Chappell, 1970) in the tropics, capitalizing on the unique suitability of coral, among marine invertebrates, for uranium-series dating. Study of emergent coral reefs on tectonically stable coasts gives information only on sea levels that were higher than present.

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For sea levels lower than present, tectonically active coasts, where uplift is in progress, can yield past sea level estimates for times when global ice volume was higher than present. In the present study, we address two issues related to Quaternary sea level history on the California coast.

One unresolved issue is the magnitude of sea level rise during relatively high sea stands that post-date the peak of the Last Interglacial complex at ~120 ka. The first studies on the uplifting coast of Barbados (Broecker et al., 1968; Matthews, 1973) showed that the ~80 ka sea stand was −13 to −18 m below present and the ~100 ka sea stand was −10 to −18 m below present, indicating global ice volumes significantly higher than those of today. Elevations and ages of uplifted reefs on other tropical islands in general support the early Barbados studies (Veeh and Chappell, 1970; Bloom et al., 1974; Chappell, 1974; Chappell and Veeh, 1978; Dodge et al., 1983). Later studies on Barbados (Potter et al., 2004; Schellmann et al., 2004; Thompson and Goldstein, 2005) indicate that sea level could have been as much as −18 to −20 m during the ~80 ka sea stand and perhaps −13 to −25 m during the ~100 ka sea stand. Moreover, some of these later studies indicate that there were multiple sea stands during MIS 5.1 (~80 ka) and MIS 5.3 (~100 ka).

Studies on other coastlines have yielded paleo-sea level estimates that differ significantly from those on Barbados. For example, Harmon et al. (1983), working on tectonically stable Bermuda, report coral-bearing marine deposits *above* modern sea level that date to ~100 ka and ~80 ka. Subsequent, higher-precision dating of emergent marine deposits on Bermuda by Muhs et al. (2002a) confirms the presence of marine deposits above present sea level at ~80 ka. On the tectonically stable Atlantic Coastal Plain of the eastern United States, Wehmiller et al. (2004) report marine deposits dating to ~80 ka a few meters above present sea level over a coastal distance of more than 700 km, from Virginia to Georgia. On the Japanese islands of Hateruma-shima and Kikai-jima, Ota and Omura (1992) report ages and elevations of marine terraces that indicate sea levels near present at ~80 ka and ~100 ka on Hateruma-shima or well above present at these times on Kikai-jima. Radtke et al. (1996) point out, however, that reworking of corals, at least on Hateruma-shima, makes paleo-sea level estimates from this island uncertain.

Australia, although tectonically stable like the U.S. Atlantic Coastal Plain and Bermuda, appears to have had a sea-level history in the period ~100–80 ka more akin to Barbados. In particular, while there are good records of the ~120 ka high sea stand along the Australian coastline, there is no evidence of sea levels above present at ~80 ka or ~100 ka based on extensive field surveys around the entire continent (Murray-Wallace and Belperio, 1991; Stirling et al., 1995, 1998; Murray-Wallace, 2002).

The geographic variability in the high sea stands may represent departures from eustasy due to the glacial isostatic adjustment (GIA) process, where GIA is the general term for perturbations in the Earth's gravitational, deformational and rotational state, associated with ice-ocean mass transfer during the Quaternary ice ages (Lambeck and Nakada, 1992; Potter and Lambeck, 2003; Milne and Mitrovica, 2008; Kopp et al., 2009; Tamisiea and Mitrovica, 2011). Indeed, Potter and Lambeck (2003) used a numerical model of GIA to explain divergent estimates of sea level at ~80 ka on the U.S. Atlantic Coastal Plain and Bermuda compared to those on Barbados. GIA provides a global-scale imprint on local sea-level histories. In the near field of the ancient ice complexes, the GIA-induced departure from eustasy is dominated by vertical crustal motions, while in the far-field it is largely governed by meltwater redistribution of smaller amplitude (we return to these issues below). In this regard, the Atlantic Coastal Plain and Bermuda are closer to the Laurentide ice sheet of North America during both of the two most recent major glacial periods (~160–140 ka [MIS 6] and ~25–12 ka [MIS 2]) than Barbados, New Guinea or Australia were to any major ice sheet.

It is important to validate and refine the idea that GIA processes produce different late Quaternary sea level records by examining other mid-latitude coastlines, particularly in the Northern Hemisphere. On the Pacific Coast of North America (Fig. 1), marine terraces form stair-step-like flights that resemble the uplifted reef terraces of Barbados and New Guinea. Unlike those islands, however, the terraces are not constructional reefs, but erosional landforms. Since the pioneering study of Alexander (1953), these flights of marine terraces have been interpreted to be the result of sea level fluctuations superimposed on steady tectonic uplift (Lajoie et al., 1991; Muhs et al., 1994, 2004). Although Pacific Coast marine terraces are erosional landforms that develop in the high-energy surf zone, after uplift they usually retain a veneer of marine sand and gravel, often including fossil marine invertebrates. Among these fossils, mollusks are by far the most common, but solitary corals are also found. Solitary corals contain U derived from seawater, like their hermatypic colonial counterparts (Muhs et al.,

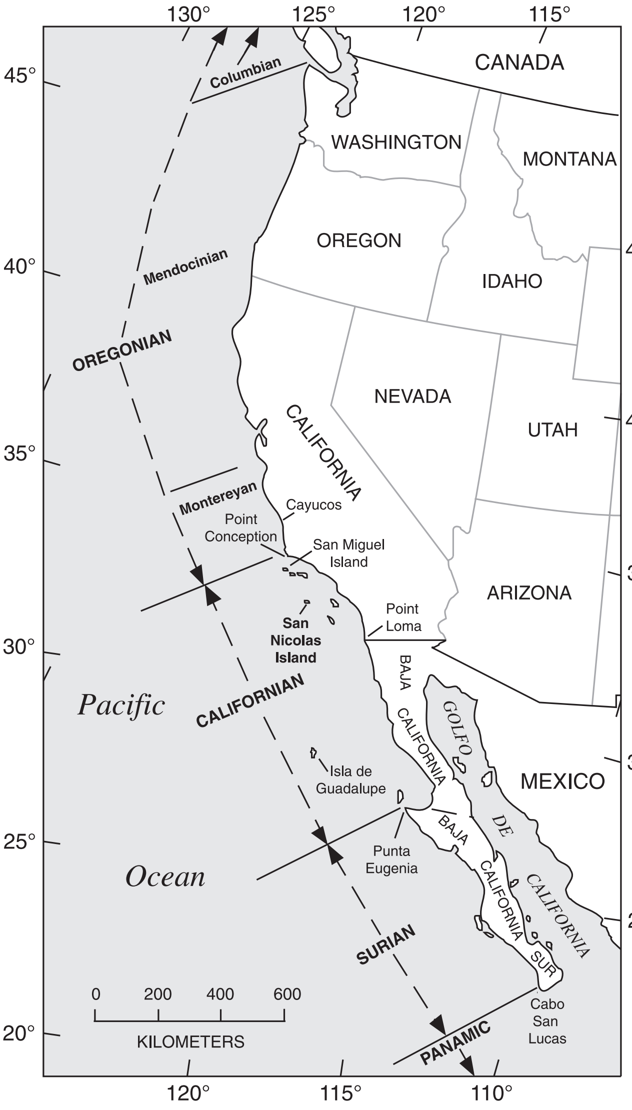


Fig. 1. Map of a portion of the Pacific Coast of North America, showing location of San Nicolas Island, marine invertebrate faunal zones (Valentine, 1966) and other localities referred to in the text.

2002b) and therefore the potential exists for dating erosional marine terraces.

A second problem we address in the present study is the issue of what has been called "thermally anomalous" faunas in Pacific Coast marine terrace deposits. For more than a century, invertebrate paleontologists working with California marine terrace deposits have recognized faunal assemblages that are inconsistent with present zoogeography (Arnold, 1903; Woodring, 1935, 1957; Woodring et al., 1946; Valentine, 1955, 1961; Emerson, 1956; Kanakoff and Emerson, 1959; Valentine and Meade, 1961; Vedder and Norris, 1963; Kern, 1971, 1977; Zinsmeister, 1974). Thermally anomalous faunas include extant species, but the assemblage is also characterized by mixtures of extralimital southern and extralimital northern species of marine invertebrate fossils. A number of explanations have been invoked to explain such mixtures, including transportation of cool-water forms from greater depths by storm waves, reworking of fossils from older units, changes in depth or temperature tolerances, and greater seasonality. Some of the apparent thermal anomalies were explained with the advent of aminostratigraphy, when it was recognized that because of differing uplift rates, the lowest terrace on a given reach of coastline was not necessarily the same age as the lowest terrace on a nearby reach of coastline (Wehmiller et al., 1977; Kennedy et al., 1982). Commonly, where a low-elevation terrace is dated to the ~80 ka sea stand, the fauna contains extralimital northern species or at least a significant number of northward-ranging species (Kennedy et al., 1982; Muhs et al., 2006). At other localities where a low-elevation terrace is dated to the ~120 ka high sea stand, the fauna usually has either a zoogeographically "neutral" assemblage (i.e., neither extralimital northern or southern species) or a number of extralimital southern species.

Nevertheless, not all thermally anomalous faunas on the California coast are explained by shore-parallel variations in terrace ages. In places, mixtures of extralimital northern and southern forms are found at a *single* fossil locality or where direct lateral tracing indicates that two or more closely spaced fossil localities must be on the same terrace surface. Kennedy (2000) hypothesized that a greater temperature range, perhaps from greater seasonality, characterized some parts of the Last Interglacial period and could explain the mixture of northern and southern forms. Muhs et al. (2002b) analyzed individual corals from terraces near Cayucos and Point Loma (Fig. 1), where such faunal mixtures have been reported (Valentine, 1958; Kern, 1977). Results show that terrace deposits at both localities contain corals of two age groups, one dating to the ~120 ka high sea stand and the other dating to the ~100 ka sea stand. Muhs et al. (2002b) hypothesized that in areas where the uplift rate is low, at least the outer (seaward) portion of the terrace formed by the ~120 ka high sea stand may have been reoccupied by the ~100 ka sea stand. The resultant mixture of fossils could therefore contain corals that date to both sea stands and molluscan faunas that include both southern forms (from the ~120 ka sea stand) and northern forms (from the ~100 ka sea stand). Such an explanation would require, however, that the ~100 ka sea stand was close to or above present sea level, which is inconsistent with the New Guinea and Barbados records of paleo-sea level at this time.

Testing competing hypotheses about relative sea level during the ~80 and ~100 ka sea stands, as well as the extralimital mollusk conundrum, requires study of a locality where certain key requirements can be met. A suitable study area must have terraces that can be mapped and elevations measured precisely, corals are present for uranium-series dating and fossil mollusks are abundant. An appropriate locality is San Nicolas Island, California (Fig. 1) where marine terraces are well expressed geomorphologically (Figs. 2 and 3) and where a long-term presence by the U.S. Navy has allowed the island to escape urban development that has covered

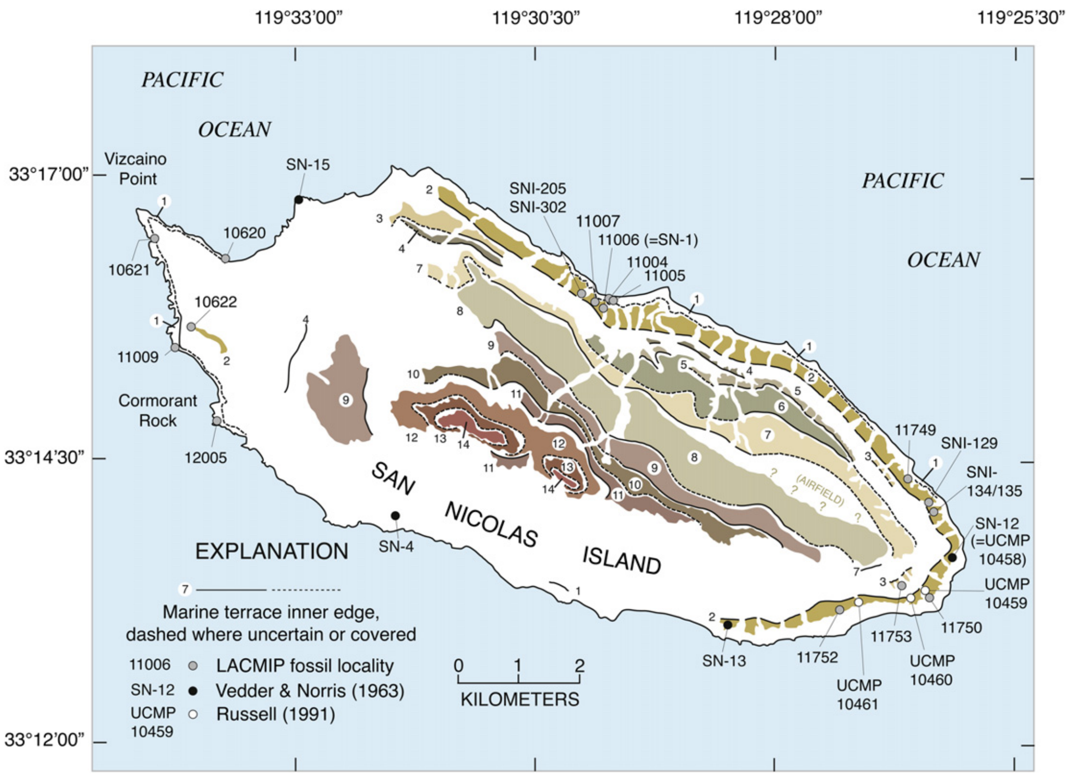


Fig. 2. Map of San Nicolas Island, California, showing marine terrace inner edges (Vedder and Norris, 1963; Muhs et al., 2006) and seaward extent of marine terrace deposits (this study). Also shown are fossil localities from this study (LACMIP and SNI designations), Vedder and Norris (1963) and Russell (1991).

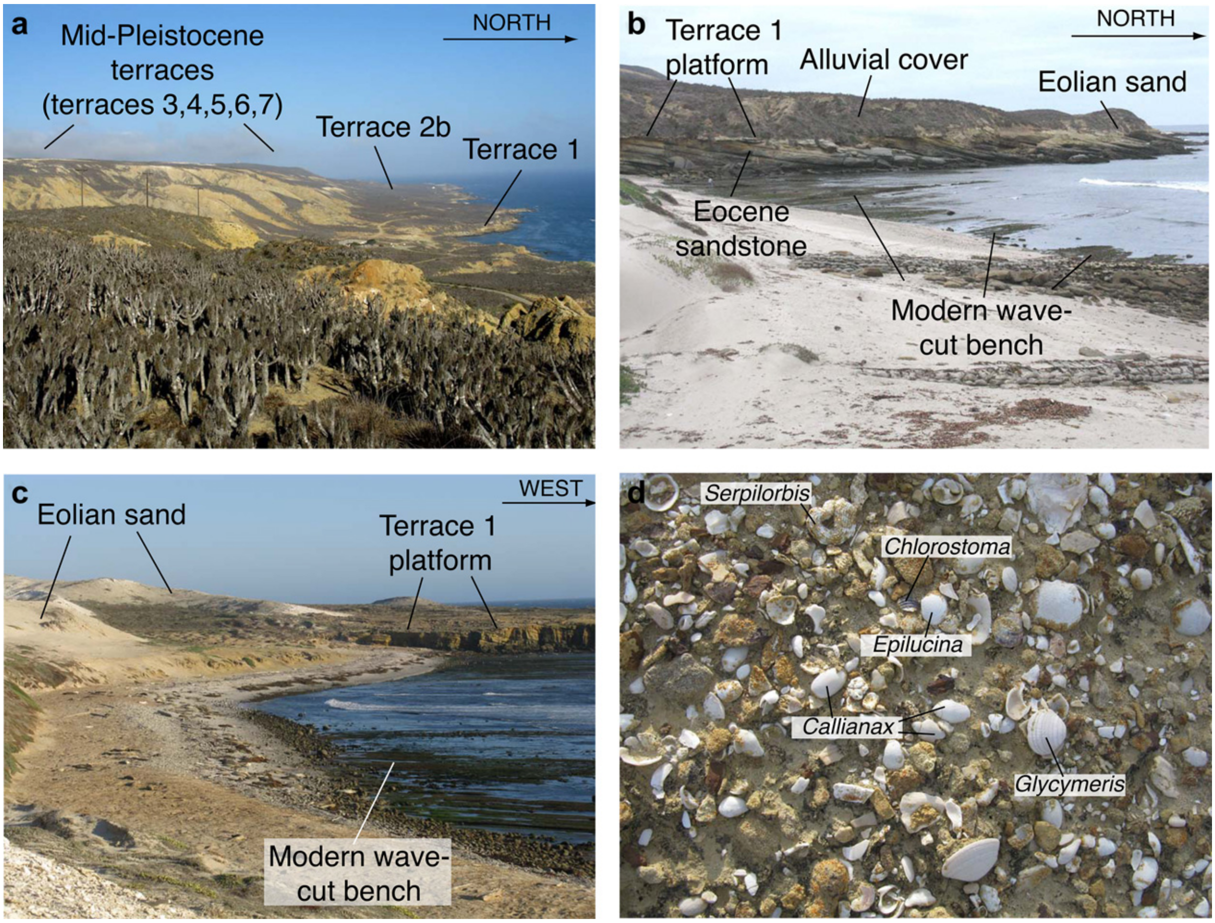


Fig. 3. Marine terraces, deposits and fossils on San Nicolas Island: (a) view to the northwest from the north-central part of San Nicolas Island, showing terraces 1 and 2, and higher terraces, near Celery Canyon and NAVFAC Canyon (Fig. 4); (b) closeup of terrace 1 area in (a), showing marine platform and overlying deposits; (c) view of terrace 1 and overlying eolian sand near Cormorant Rock (Fig. 2); (d) closeup of marine terrace fossils on terrace 2, near LACMIP loc. 11750 (Fig. 2).

or destroyed marine terraces in much of the rest of southern California. Previous studies on San Nicolas Island show that that corals are abundant in marine terraces of the Last Interglacial complex (Muhs et al., 1994, 2006) and paleontological work indicates there is a rich fossil marine invertebrate record (Vedder and Norris, 1963; Russell, 1991; Muhs et al., 2006).

2. Methods

2.1. Marine terrace mapping and GPS methods

Vedder and Norris (1963) mapped marine terrace inner edges on San Nicolas Island and Muhs (1985) and Muhs et al. (2006) provided additional minor mapping, primarily of the lowest terraces. In the present study, we reexamined and confirmed most of the terrace inner edge mapping by Vedder and Norris (1963) and made slight modifications in a few areas based on new observations. In addition, we also mapped what we estimate to be the seaward extent of the marine terrace deposits, based on a combination of topographic expression and field observations (Figs. 2 and 4). Critical to our studies is accurate and precise determination of the elevations of past sea level indicators. For California marine terraces, the best estimates of the positions of past sea levels come from what is referred to as the shoreline angle, the junction between the wave-cut bench and the paleo-sea cliff. In theory, shoreline angles ought to be well exposed in canyons that dissect marine terraces in a shore-normal direction. In practice, however, alluvial, colluvial or eolian deposits often obscure observation of shoreline angles. Under such conditions, it is still possible to estimate shoreline angle elevations by measuring elevations of several points on the wave-cut bench and several points on the paleo-sea cliff. The elevation of the intersection of an extrapolated bench-elevation line and an extrapolated paleo-sea cliff-elevation line can yield an approximate shoreline angle elevation.

Elevations of all localities we studied on San Nicolas Island were determined using differential Global Positioning System (GPS) measurements. Latitude-longitude data and elevations were determined using a Trimble Pathfinder Pro XH GPS instrument connected to a PDA, running Trimble TerraSync software (use of trade names is for descriptive purposes only and does not constitute endorsement or recommendation by the U.S. Government). At each location, data were collected from at least four, and usually six to eight, satellites for at least 500 s in order to obtain consistent 3-D geometry. The data were post-processed using Trimble Pathfinder Office software, in which GPS field data were differentially corrected against five to eight base stations in the Continuously Operating Reference Station (CORS; Strange and Weston, 1997) and Scripps Orbit and Permanent Array Center (SOPAC; Bock et al., 1997) networks, located within 200 km of the field locations. Differentially correcting the GPS elevations generally resulted in horizontal uncertainties of 10 cm or less and vertical uncertainties in the range of 10–30 cm. Comparison of GPS-derived elevations with benchmarks and taped elevations on San Nicolas Island shows good agreement, within the limits of instrumental uncertainty.

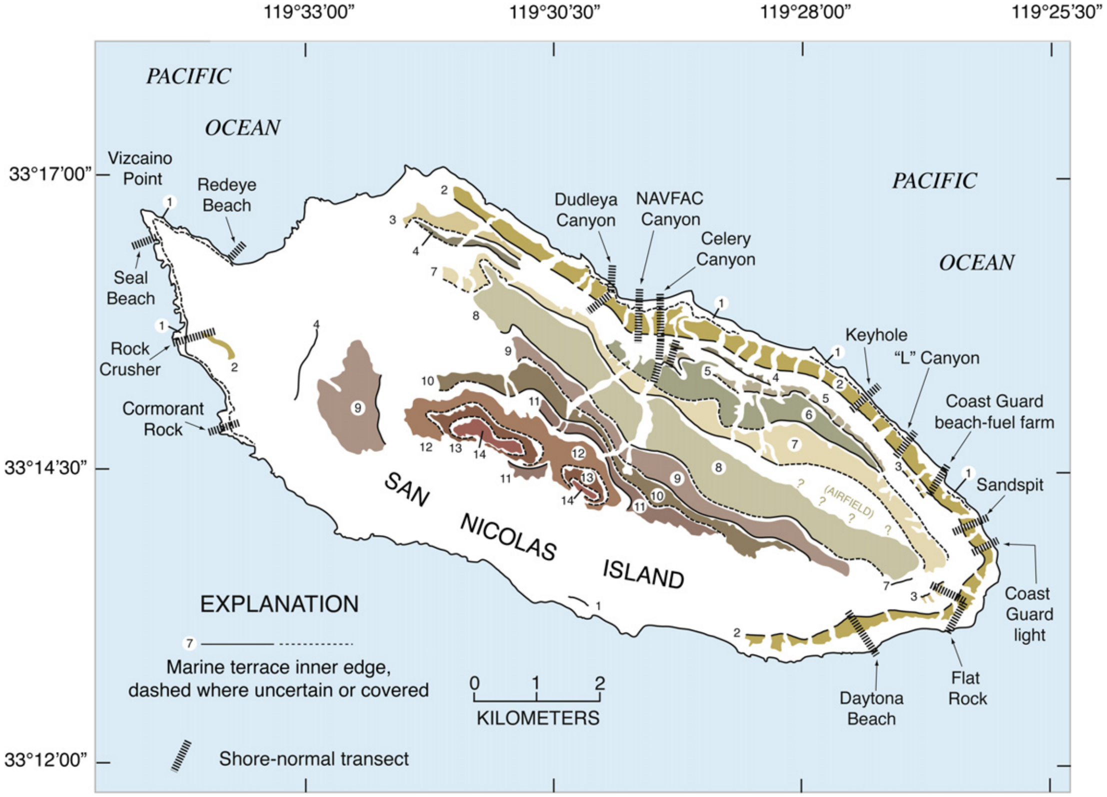


Fig. 4. Map of San Nicolas Island, California, showing marine terrace inner edges (Vedder and Norris, 1963; Muhs et al., 2006) and seaward extent of marine terrace deposits (this study). Also shown are marine terrace elevation transect locations.

2.2. Uranium-series dating methods

All corals, whether colonial or solitary, take up U in isotopic equilibrium with seawater and, under favorable circumstances, behave as closed systems with respect to ^{238}U and its long-lived daughter products, ^{234}U and ^{230}Th, after death and emergence. The solitary coral *Balanophyllia elegans* presently lives along the Pacific Coast of North America from southeastern Alaska to central Baja California (Gerrodette, 1979; O'Clair and O'Clair, 1998). This species is the most common coral occurring as a fossil in marine terrace deposits on the Pacific Coast of North America. It is potentially suitable for U-series dating because living specimens incorporate measurable U in isotopic equilibrium with seawater (Stein et al., 1991; Muhs et al., 1994, 2002b, 2006).

All *Balanophyllia* specimens in this study were prepared by hand removal of detrital mineral grains and careful scraping of secondary carbonates under magnification, followed by multiple ultrasonic baths in distilled water. The cleaned corals are all well-preserved and 95–100% aragonite, as determined by X-ray diffractometry. After cleaning, sample preparation followed methods outlined by Ludwig et al. (1992). Cleaned corals were dissolved in HNO_3, spiked with ^{229}Th, ^{233}U, and ^{236}U and purified with ion exchange methods. Purified U and Th were loaded with colloidal graphite on separate Re filaments; isotopic abundances were determined by thermal ionization mass spectrometry (TIMS). Ages were calculated using a half-life of 75,690 yr for ^{230}Th and a half-life of 245,250 yr for ^{234}U (Cheng et al., 2000).

There are three important criteria for evidence of reliable ages in U-series dating of fossil corals. The first is no indication of bulk U loss or gain. Living specimens of *B. elegans* from San Nicolas Island and other localities off the California coast have U concentrations ranging from 2.9 to 3.7 ppm (Muhs et al., 2002b, 2006), similar to colonial corals, and ^{234}U/^{238}U values that fall within the range reported for modern seawater (Chen et al., 1986). Dead corals collected from modern beaches on San Nicolas Island have ages that range from 100 ± 100 to 800 ± 100 yr and ^{234}U/^{238}U values that also fall within the range of modern seawater, but have U concentrations that range from 3.2 to 4.7 ppm (Muhs et al., 2002b), higher than most colonial corals. Omura (1983) reports that fossil solitary corals from marine terraces in Japan also have U concentrations that are higher than what is observed in colonial corals. These observations led Muhs et al. (2002b) to conclude that secondary U uptake occurs in *B. elegans* after death, but that the source of this U is seawater. The inference of secondary addition of U from seawater (as opposed to local U-bearing terrestrial waters) for dead San Nicolas Island corals is supported by detailed analyses of bulk marine terrace sediments on San Nicolas Island that show ^{234}U/^{238}U values that are much higher than seawater values or in modern corals (Muhs et al., 1989). Thus, if secondary U additions in dead corals occur while they are still submerged, *Balanophyllia* still has the potential for accurate age determination of marine terrace deposits. Nevertheless, U concentrations in fossil corals that are lower than those in live-collected specimens of the same genus are a clear indication of bulk U loss.

A second important criterion for reliable ages is no evidence of inherited ^{230}Th. This problem typically occurs when detrital silicate minerals are not completely removed during the cleaning process. Inherited ^{230}Th can be evaluated by examination of the bulk ^{232}Th concentrations, which should be low, and the ^{230}Th/^{232}Th value, which should be high if there are no problems of detrital mineral contamination.

As with hermatypic colonial corals from the tropics, the best criterion for determining closed-system conditions during the post-emergence history of a fossil is concordance between

^{230}Th/^{234}U and ^{231}Pa/^{235}U ages. We did not determine ^{231}Pa/^{235}U ages for our samples. However, a third criterion for closed-system history is whether the calculated initial ^{234}U/^{238}U value is within the range of modern seawater. Edwards et al. (1997) show that corals with initial ^{234}U/^{238}U activity values as high as 1.166 show concordance between ^{230}Th/^{234}U and ^{231}Pa/^{235}U ages.

3. Results

3.1. Marine terrace geomorphology

Much of the geomorphology of San Nicolas Island has been shaped by marine terrace formation and tectonic uplift (Fig. 4). Marine terrace platforms and cliffs are cut primarily on Eocene sandstone and siltstone and terrace deposits consist largely of well-rounded pebbles, cobbles and boulders of this lithology, usually with a well-sorted sandy matrix. Pholad borings are common in many of the terrace clasts and fossils are almost always present. Terrace deposits are typically 0.5 m to as much as 1.5 m thick and only rarely thicker, with an alluvial, colluvial or eolian cover that is often several meters thick (Fig. 3). The highest terrace mapped by Vedder and Norris (1963) is terrace 14 (Figs. 2 and 4), which consists of two isolated, mesa-like summits on the island. Marine fossils, sometimes with little or no terrace sediment, are found on the wave-cut platform of this terrace at elevations of 270–272 m. The broadest high terrace below the island's summit is terrace 10, where fossils are abundant and extraordinarily well-preserved, at marine platform elevations of 222–228 m. At intermediate elevations, the broadest well-preserved surface is that of terrace 8, which is several hundred meters wide and has a shoreline angle elevation between ∼187 m and ∼184 m. Like terraces 14 and 10, it is also highly fossiliferous, though fossils on this terrace are not as diverse as those on terrace 10. Terraces at successively lower elevations tend to have increasingly thicker deposits of alluvium and/or colluvium covering the marine terrace deposits. In addition, variable terrace preservation is apparent in our findings and in the mapping of Vedder and Norris (1963). For example, in the Flat Rock area in the southeastern part of the island, terraces 2 and 3 are preserved, but terrace 1 is missing (Fig. 4). In contrast, in the Dudleya Canyon area, terraces 1 and 2 are preserved, but terraces 3 and 4 are missing. Terraces 5 and 6, although well expressed on the northeastern coast of the island, are entirely missing from the western half of the island. Carbonate-rich eolian sands cover much of western San Nicolas Island (Vedder and Norris, 1963; Muhs et al., 2009) and marine terrace deposits are only well exposed around the modern sea cliffs on the northwest coast of the island (Fig. 2).

The best expressed and preserved low terrace is what is mapped as terrace 2 by Vedder and Norris (1963), which Muhs et al. (1994) dated (using alpha-spectrometric U-series on corals) to the Last Interglacial period (Figs. 2–4). At many localities, terrace 2, though broad (∼200 m to ∼400 m) and well exposed, consists of a single wave-cut platform with a shoreline angle elevation of ∼31–33 m. At five other localities, however, we observed that terrace 2 consists of a broad (∼200–400 m) wave-cut platform with a shoreline angle at ∼28 to ∼33 m, but in addition there is a separate, higher and very narrow (∼5–10 m) terrace fragment with a shoreline angle of ∼36 to ∼38 m (Fig. 5). These higher, narrow and isolated terrace fragments are too small to be obvious

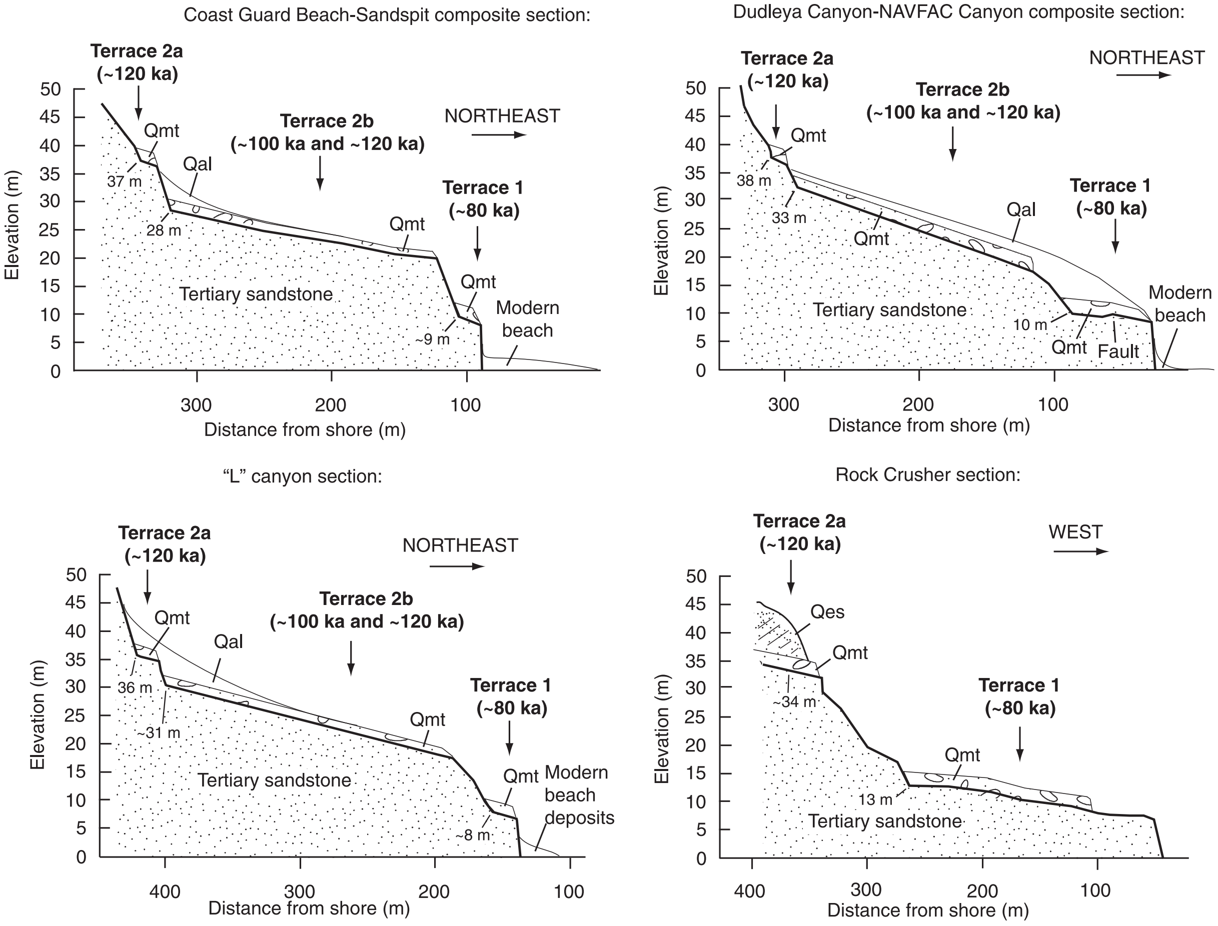


Fig. 5. Marine terrace cross sections from four transects across terraces 2a, 2b and 1 (see Fig. 4 for locations). Qmt: marine terrace deposits; Qal: alluvium; Qes: eolian sand.

on aerial photographs and were not recognized as separate from the broader, lower 2nd terrace by Vedder and Norris (1963) or Muhs et al. (1994). Informally, we refer to the higher, narrow terrace fragments as "terrace 2a" and the lower, broader terrace as "terrace 2b" (Fig. 5).

Terrace 1, where it is found, is present as a narrow bench cut into the outer part of terrace 2b. On the north side of the island, shoreline angles of this terrace are exposed in several canyons, at elevations of ~8–10 m (Fig. 5). On the western side of the island, the outer edge of the terrace marine platform is exposed, but the inner platform and shoreline angles usually are not. Because much of this part of the island is covered by eolian sand, many of our elevations of terrace 1 on this part of the island are minima. However, at one site, near a locality designated as "Rock Crusher" by the U.S. Navy, the shoreline angle of terrace 1 is exposed at an elevation of ~13 m. Muhs et al. (2006) had previously estimated the shoreline angle elevation of terrace 1 at this locality to be on the order of ~22 m, but this higher estimate was based on a broad bedrock step on the sea cliff that was misinterpreted as a shoreline angle (Fig. 5). A fragment of marine platform from terrace 2a, overlain by a rich fossil assemblage, occurs above the sea cliff that backs terrace 1 at Rock Crusher (Fig. 5). The highest elevation we measured on the terrace 2a marine platform here is ~34 m, in broad agreement with previous transit and stadia measurements reported by Muhs et al. (2006). No shoreline angle of terrace 2a is exposed and indeed, at the time of platform cutting, terrace 2a here was probably a shoal, at least a kilometer or more offshore.

Terrace shoreline angle elevations can be plotted in a shore-parallel sense in order to gain a sense of terrace continuity and possible tectonic deformation due to the presence of local structures. Where we lacked direct observations of shoreline angles, we plotted bracketing elevations, using the highest measured elevation on the wave-cut platform and the lowest measured elevation on the sea cliff backing the terrace platform in question. The resultant plots define a series of shore-parallel terrace elevation envelopes (Fig. 6). These data show that across the east-west extent of the island, terrace shoreline angle elevations are consistent within a couple of meters or so, indicating little in the way of differential uplift on the island.

3.2. Uranium-series dating of marine terrace corals

Valentine and Veeh (1969) reported the first U-series ages on corals from San Nicolas Island more than four decades ago. Although analytical uncertainties are understandably large in this pioneering study, their data indicate that terrace 2 is likely of Last Interglacial age. A later study (Muhs et al., 1994) also showed that terraces 1 and 2 on San Nicolas Island date to parts of the Last Interglacial complex, or MIS 5. These authors reported alpha-spectrometric U-series ages of ~111 ka to ~133 ka for multiple-individual coral analyses from terrace 2 at LACMIP localities 10622, 11006, 11007, 11008, 11749 and 11750 (Fig. 2). The same study, however, also yielded an alpha-spectrometric U-series age of ~104 ka for corals from LACMIP loc. 11752, also on terrace 2. From terrace 1, Muhs et al. (1994) reported alpha-spectrometric U-series ages of ~80 ka to ~87 ka for multiple-individual coral analyses at LACMIP localities 10620, 10621, 11004, 11005, and 11009.

More recently, Muhs et al. (2006) presented new TIMS U-series ages of individual corals from both terraces 1 and 2, but only from localities on the western part of the island. At LACMIP loc. 10622, corals showing closed-system conditions gave U-series ages ranging from ~116 ka to ~121 ka. At Cormorant Rock (LACMIP loc. 12005; Fig. 2), terrace 1 corals gave closed-system TIMS U-series ages ranging from ~76 to ~87 ka.

Here we report 65 new U-series ages of corals from terrace 1 (LACMIP loc. 11004), terrace 2b (LACMIP locs. 11006, 11749, 11752) and terrace 2a (SNI-302). All corals have, with one exception, U concentrations of 3.0–4.8 ppm, within the range of living and modern dead *B. elegans*, indicating no losses of U (Table 1). All ^{230}Th/^{232}Th values are greater than 100 and most are greater than 200. These values, along with Th concentrations of 0.1 ppm or less, indicate no significant additions of "inherited" ^{230}Th from detrital mineral grains. Although these criteria are necessary requirements to be passed for interpreting corals to have experienced a closed-system history, another requirement is that back-calculated initial ^{234}U/^{238}U values (based on apparent ^{230}Th/^{238}U ages and measured ^{234}U/^{238}U values) should fall within the range of modern seawater and modern, living corals. Modern seawater has ^{234}U/^{238}U activity ratios of 1.14–1.15 (Chen et al., 1986) and live-collected specimens

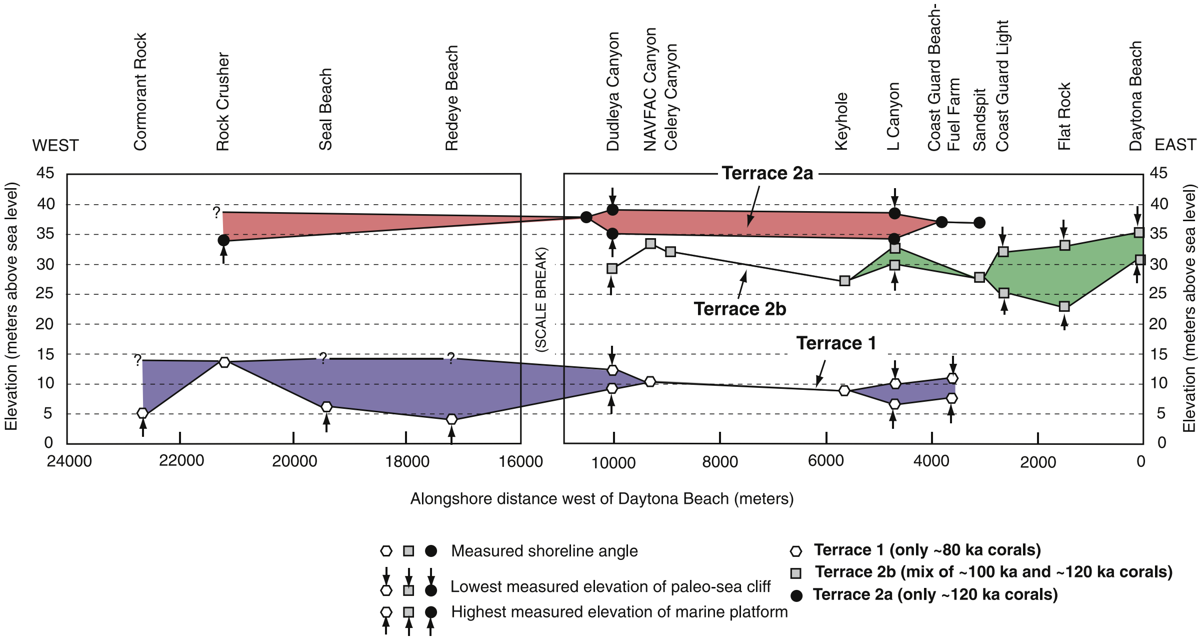


Fig. 6. Shore-parallel profiles of the lowest three marine terraces (2a, 2b and 1), showing shoreline angle elevations (or upper and lower limits of their elevations). See Fig. 4 for locations.

Table 1
U and Th concentrations, isotopic activity ratios (AR), U-series ages, and initial $^{234}U/^{238}U$ activity ratios of San Nicolas Island marine terrace corals.

Marine terrace, LACMIP loc., and samples	U (ppm)	Error %	Th (ppm)	$^{234}U/^{238}U$ AR	+/−	$^{230}Th/^{238}U$ AR	+/−	$^{230}Th/^{232}Th$ AR	$^{230}Th/^{238}U$ age (ka)	+/−	$^{234}U/^{238}U$ initial AR	+/−
Terrace 1												
LACMIP loc. 11004												
A	3.89	0.12	0.0191	1.1541	0.0021	0.6132	0.0025	379	80.5	0.5	1.1934	0.0025
B #1	4.28	0.11	0.0079	1.1551	0.0017	0.6249	0.0015	1021	82.7	0.3	1.1959	0.0021
B #2	4.29	0.12	0.0102	1.1538	0.0027	0.6205	0.0014	793	82.0	0.4	1.1939	0.0032
C	4.64	0.12	0.0326	1.1356	0.0019	0.5945	0.0020	258	79.0	0.4	1.1695	0.0023
D	5.19	0.11	0.0372	1.1530	0.0018	0.6024	0.0029	255	78.6	0.6	1.1910	0.0021
F	3.65	0.14	0.0216	1.1463	0.0024	0.6187	0.0039	317	82.5	0.8	1.1847	0.0029
Terrace 2b												
LACMIP loc. 11006												
A	4.21	0.11	0.0144	1.1239	0.0020	0.6936	0.0017	616	101.6	0.5	1.1651	0.0026
B	3.90	0.12	0.0177	1.1575	0.0029	0.8212	0.0027	550	128.3	1.0	1.2263	0.0038
C	3.97	0.11	0.0336	1.1385	0.0015	0.8008	0.0023	287	126.8	0.8	1.1982	0.0020
D	4.36	0.11	0.0852	1.1486	0.0019	0.8047	0.0028	125	125.6	0.9	1.2119	0.0024
E	4.32	0.11	0.0205	1.1266	0.0016	0.7783	0.0040	498	123.1	1.2	1.1792	0.0022
F #1	3.80	0.11	0.0153	1.1401	0.0017	0.7088	0.0020	537	102.6	0.5	1.1872	0.0022
F #2	3.80	0.13	0.0140	1.1435	0.0017	0.7111	0.0017	584	102.6	0.5	1.1917	0.0022
G	3.87	0.11	0.0120	1.1373	0.0019	0.6967	0.0041	683	100.2	1.0	1.1823	0.0025
H	4.15	0.11	0.0243	1.1900	0.0019	0.8285	0.0036	431	123.2	1.0	1.2691	0.0025
I	4.76	0.11	0.0174	1.1257	0.0024	0.7718	0.0026	642	121.4	0.9	1.1772	0.0031
J	4.15	0.11	0.0249	1.1713	0.0022	0.8295	0.0044	419	127.5	1.3	1.2456	0.0030
K	4.03	0.11	0.0177	1.1280	0.0019	0.7105	0.0020	491	105.0	0.6	1.1722	0.0024
L	4.42	0.11	0.0102	1.1218	0.0020	0.6743	0.0022	889	97.5	0.6	1.1604	0.0025
Terrace 2b												
50 m south of LACMIP loc. 11006												
A	3.93	0.11	0.0259	1.1652	0.0025	0.8294	0.0026	381	128.9	0.9	1.2378	0.0032
B	4.27	0.11	0.0159	1.1168	0.0019	0.7394	0.0017	603	114.4	0.6	1.1614	0.0025
C	4.25	0.11	0.0201	1.1171	0.0018	0.6694	0.0016	430	97.1	0.5	1.1541	0.0022
D	3.71	0.11	0.0110	1.1320	0.0016	0.7007	0.0016	714	102.0	0.5	1.1761	0.0020
E	3.53	0.11	0.0174	1.1247	0.0025	0.6842	0.0031	422	99.3	0.8	1.1650	0.0031
G	3.83	0.12	0.0101	1.1441	0.0023	0.8088	0.0022	934	127.9	0.8	1.2068	0.0030
H	3.30	0.11	0.0408	1.1317	0.0020	0.6919	0.0022	170	100.0	0.6	1.1747	0.0025
I	3.77	0.11	0.0341	1.1287	0.0016	0.7086	0.0025	238	104.4	0.7	1.1729	0.0021
J	4.18	0.10	0.0129	1.1289	0.0023	0.7728	0.0047	759	121.0	1.4	1.1814	0.0030
K	3.65	0.12	0.0222	1.1200	0.0021	0.7603	0.0021	380	119.5	0.7	1.1681	0.0028
L	4.77	0.11	0.0333	1.1276	0.0014	0.6705	0.0103	292	95.7	2.3	1.1672	0.0020
M	4.20	0.11	0.0223	1.1220	0.0016	0.6695	0.0024	383	96.3	0.6	1.1601	0.0020
N	4.01	0.11	0.0212	1.1361	0.0016	0.7662	0.0040	441	117.7	1.1	1.1899	0.0021
O	4.11	0.11	0.0216	1.1236	0.0020	0.7593	0.0029	438	118.4	0.9	1.1727	0.0027
P	3.28	0.11	0.0184	1.1336	0.0017	0.8737	0.0042	473	151.7	1.6	1.2052	0.0025
Q	4.17	0.11	0.0365	1.1656	0.0020	0.8208	0.0054	285	126.4	1.6	1.2366	0.0028
Terrace 2b												
LACMIP loc. 11752												
A	4.12	0.11	0.0301	1.1354	0.0022	0.7089	0.0027	295	103.4	0.7	1.1814	0.0028
B	4.55	0.11	0.0298	1.1429	0.0017	0.7440	0.0027	345	110.6	0.7	1.1953	0.0022
C	4.33	0.11	0.0364	1.1393	0.0017	0.7058	0.0023	255	102.0	0.6	1.1858	0.0022
D	4.13	0.11	0.0426	1.1505	0.0021	0.7322	0.0031	216	106.4	0.8	1.2033	0.0027
E	4.55	0.11	0.0477	1.1363	0.0021	0.7136	0.0043	207	104.3	1.1	1.1831	0.0027
G	4.21	0.11	0.0615	1.1419	0.0017	0.7184	0.0031	150	104.6	0.8	1.1906	0.0021
H	4.17	0.11	0.0440	1.1337	0.0017	0.7197	0.0048	207	106.2	1.2	1.1806	0.0023
I	3.95	0.11	0.0291	1.1347	0.0022	0.7099	0.0018	293	103.7	0.6	1.1806	0.0027
J	4.40	0.12	0.0308	1.1405	0.0029	0.7047	0.0035	305	101.5	0.9	1.1872	0.0036
K	4.65	0.11	0.0603	1.1342	0.0017	0.7490	0.0048	176	113.5	1.3	1.1850	0.0022
Terrace 2b												
LACMIP loc. 11749												
A	4.31	0.11	0.0297	1.1523	0.0019	0.8416	0.0034	371	135.6	1.1	1.2234	0.0025
B	4.42	0.11	0.0234	1.1416	0.0017	0.7965	0.0020	457	124.9	0.7	1.2016	0.0023
C	3.86	0.11	0.0585	1.1558	0.0025	0.8530	0.0037	171	138.2	1.3	1.2303	0.0033
D	4.11	0.12	0.0450	1.1790	0.0021	0.8985	0.0050	249	146.4	1.7	1.2707	0.0029
E	3.39	0.13	0.0841	1.1835	0.0020	0.8825	0.0028	108	140.1	1.0	1.2726	0.0027
F	3.61	0.11	0.0309	1.1675	0.0018	0.8432	0.0024	299	132.3	0.8	1.2434	0.0023
G	3.22	0.11	0.0362	1.1853	0.0018	0.8779	0.0026	237	138.2	0.9	1.2739	0.0024
H	3.70	0.12	0.0353	1.1471	0.0018	0.8343	0.0047	266	134.7	1.5	1.2153	0.0025
I-a	3.65	0.11	0.0287	1.1678	0.0021	0.8648	0.0024	334	138.8	0.9	1.2484	0.0028
I-b	3.81	0.11	0.0311	1.1786	0.0020	0.8882	0.0052	331	143.2	1.7	1.2676	0.0029
J	4.18	0.11	0.0555	1.1463	0.0018	0.8070	0.0033	185	126.8	1.0	1.2094	0.0024
K	3.48	0.11	0.0359	1.1647	0.0033	0.9037	0.0050	266	152.5	2.0	1.2534	0.0045
Terrace 2a												
SNI-GPS-302												
1	3.10	0.11	0.114	1.1114	0.0026	0.7905	0.0036	66	131.3	1.3	1.1614	0.0035
2	3.67	0.10	0.025	1.1257	0.0020	0.7494	0.0030	337	116.1	0.9	1.1746	0.0027
3	3.55	0.11	0.067	1.1376	0.0023	0.7622	0.0041	123	117.1	1.2	1.1916	0.0030
4	3.88	0.12	0.028	1.1050	0.0026	0.7365	0.0027	310	116.9	0.9	1.1462	0.0033

Table 1 (*continued*)

Marine terrace, LACMIP loc., and samples	U (ppm)	Error %	Th (ppm)	$^{234}U/^{238}U$ AR	+/−	$^{230}Th/^{238}U$ AR	+/−	$^{230}Th/^{232}Th$ AR	$^{230}Th/^{238}U$ age (ka)	+/−	$^{234}U/^{238}U$ initial AR	+/−
5	3.73	0.11	0.026	1.1131	0.0020	0.7906	0.0027	343	130.9	1.0	1.1638	0.0027
6	3.92	0.11	0.099	1.1258	0.0023	0.8776	0.0027	106	157.1	1.3	1.1962	0.0032
7	3.05	0.11	0.025	1.1484	0.0025	0.9192	0.0066	346	165.3	2.8	1.2368	0.0039
8	4.29	0.11	0.027	1.1122	0.0016	0.7611	0.0029	370	122.3	0.9	1.1585	0.0021

of *B. elegans* also have $^{234}U/^{238}U$ activity ratios that fall into this range (Muhs et al., 2002b). San Nicolas Island corals we analyzed from terraces 1, 2b and 2a have, with a couple exceptions from terrace 2a, calculated initial $^{234}U/^{238}U$ values that are higher than modern seawater values, ranging from 1.16 to 1.27 (Table 1). These results are similar to those for both solitary and colonial corals from many other localities (Stein et al., 1991, 1993; Gallup et al., 1994; Stirling et al., 1995, 1998; Edwards et al., 1997; Muhs et al., 2002a, 2002b, 2011; Cutler et al., 2003). Thus, almost all of our samples show an open-system history with respect to ^{230}Th and ^{234}U, with measured $^{234}U/^{238}U$ values that plot above a theoretical, closed-system isotopic evolution pathway on a $^{230}Th/^{238}U$ vs. $^{234}U/^{238}U$ diagram (Fig. 7).

Considerable effort has been made to understand the process that brings about this open-system history and there have even been efforts to model the process and correct for it (Gallup et al., 1994; Thompson et al., 2003; Thompson and Goldstein, 2005). Since the study of Gallup et al. (1994), there has been a general inference that corals affected in this way are biased to older apparent ages. In agreement with Gallup et al. (1994), Thompson et al. (2003) and Thompson and Goldstein (2005), we consider that corals that plot above the closed-system evolution curves are biased to somewhat older ages. Following these same workers, however, as well as our own studies in Florida (Muhs et al., 2011) we point out that many corals with open-system history show broad linear trends that extrapolate to apparent closed-system ages. These extrapolations form the basis for a quantitative "correction" for open-system history outlined by Thompson et al. (2003) and Thompson and Goldstein (2005). Here, we do not apply such corrections, but point out simply that corals from terrace 1 trend toward an age of ~80 ka when extrapolated to the closed-system evolution curve and corals from terrace 2a trend toward an age of ~120 ka. Corals from terrace 2b, however, show a more complex array of isotopic values. Samples from this terrace show two broad linear arrays, one trending toward a closed-system age of ~120 ka and the other trending toward a closed-system age of ~100 ka. On western San Nicolas Island, at the Rock Crusher locality, Muhs et al. (2006) also report that some corals from both terrace 1 and terrace 2a show open-system histories, although a significant number of corals from this locality also show closed-system histories (Fig. 8). Considering all data, we conclude that corals from terrace 2a (34–38 m) date to the ~120 ka high sea stand (marine isotope stage, or MIS 5.5 of Martinson et al., 1987), corals from terrace 2b (28–33 m) are a mix of fossils from the ~120 ka and ~100 ka sea stands (MIS 5.5 and 5.3), and corals from terrace 1 (8–10 m) date to the ~80 ka sea stand (MIS 5.1).

3.3. Marine invertebrate paleontology and paleozoogeography

Marine invertebrate fossils, particularly mollusks, provide important information on marine paleotemperatures during interglacial sea stands (Arnold, 1903; Woodring et al., 1946; Valentine, 1961, 1966; Valentine and Meade, 1961; Kern, 1977; Kennedy et al., 1982; Muhs et al., 2002b). San Nicolas Island is ~150 km south of Point Conception, the boundary between the Californian and Oregonian marine invertebrate faunal provinces (Fig. 1). Although San Nicolas Island is south of this important zoogeographic boundary, it is situated far enough southwest of mainland California that it is bathed by the innermost part of the cold, southward-moving California Current and is west of the

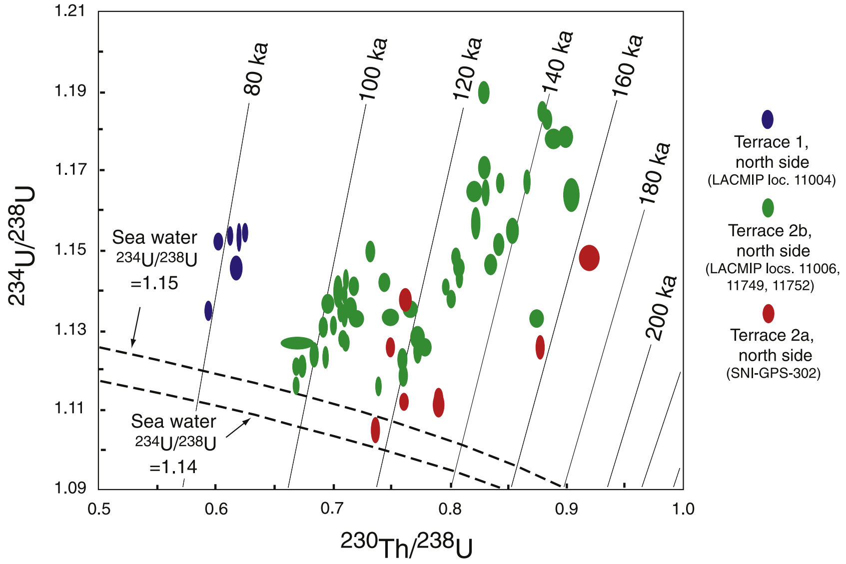


Fig. 7. Isotopic evolution curves (dashed lines) showing sympathetic variation in $^{230}Th/^{238}U$ and $^{234}U/^{238}U$ activity ratios over time in materials with no initial ^{230}Th and with two different initial $^{234}U/^{238}U$ activity ratios that define the bounds of modern seawater. Age in thousands of years (ka) is shown by isochrons (thin solid lines). Also shown are measured values of the solitary coral *Balanophyllia elegans* from the lowest three terraces on San Nicolas Island. Solid, colored ellipses define the measured values and 2-sigma uncertainties, as calculated using Isoplot/Ex software (Ludwig, 2001).

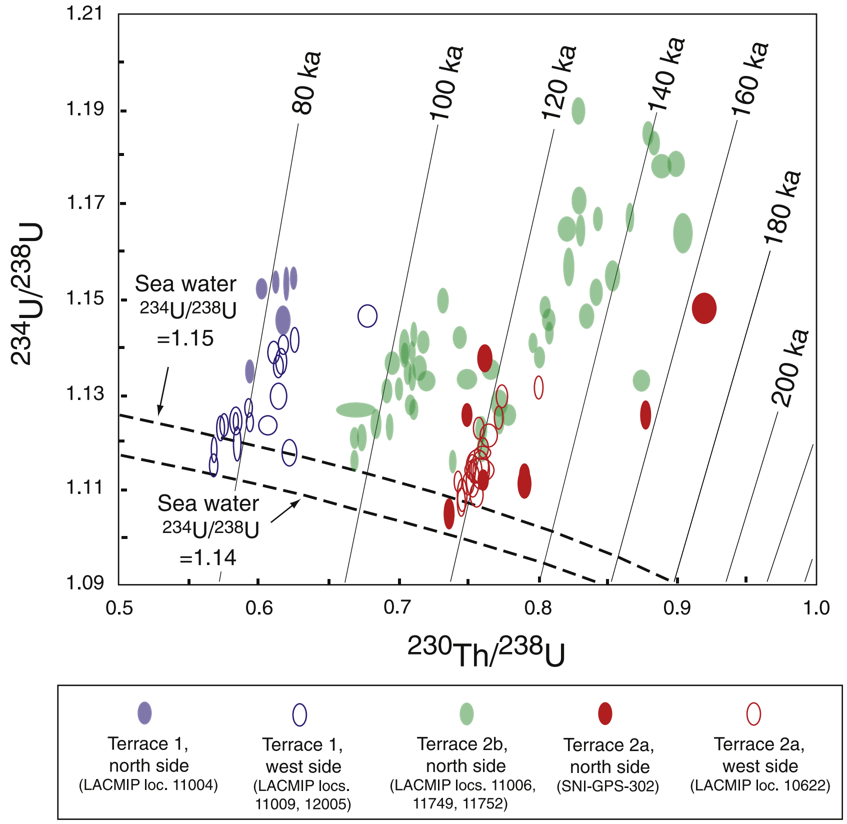


Fig. 8. Same as Fig. 7, except additional U-series data from terrace 2a and terrace 1, reported by Muhs et al. (2006) also shown, as open ellipses.

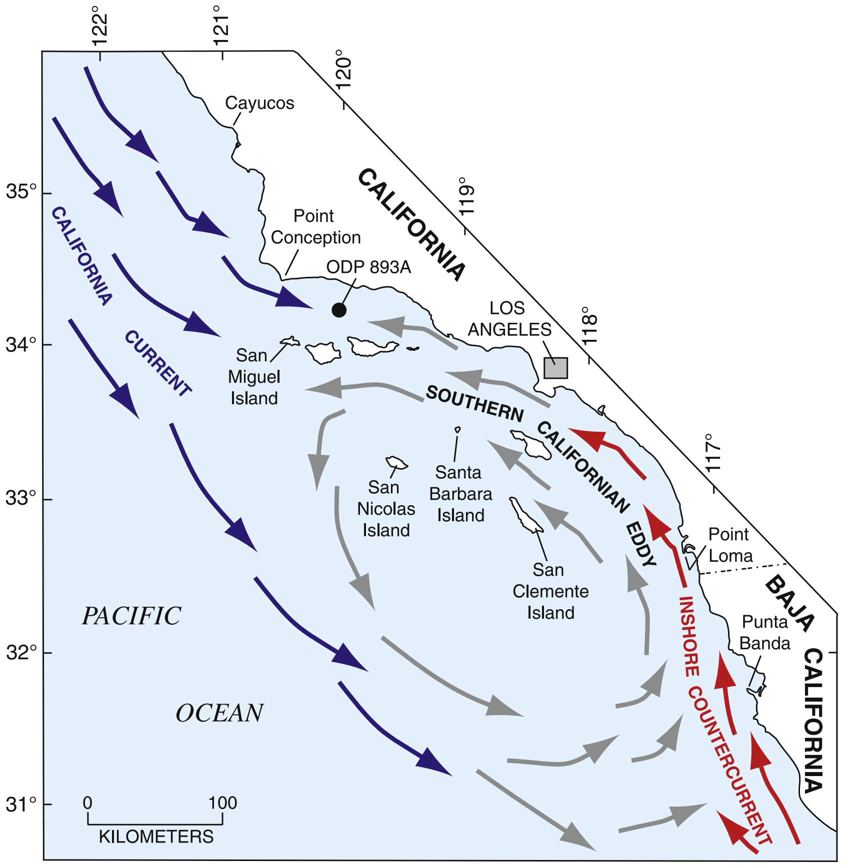


Fig. 9. Map of southern California showing ocean currents (modified from Hendy, 2010), location of San Nicolas Island, ODP hole 893A, and other localities referred to in the text.

warm, northward-flowing Inshore Current (Fig. 9). Marine invertebrates off San Nicolas Island and its northerly neighbor, San Miguel Island, have closer zoogeographic affinities with Cayucos, California (~120 km northwest of Point Conception; see Fig. 9) than they do with any of the other Channel Islands or mainland southern California to the south of Point Conception (Littler, 1980; Seapy and Littler, 1980, 1993; Eernisse et al., 2007). Thus, in our comparisons of San Nicolas Island fossils with modern range distributions, we consider as extralimital southern and northern species not only those taxa that occur (at present) south and north of San Nicolas Island, but also those that occur south and north of Point Conception (Fig. 1).

The complexity of paleozoogeographic interpretations on San Nicolas Island due to its geographic position near a major faunal boundary (Figs. 1 and 9) is illustrated by the mixes of southward-ranging and northward-ranging fossils found at single sites where ages are well constrained and there is little or no evidence for fossil mixing. On the west side of San Nicolas Island on terrace 2a (LACMIP loc. 10622; Fig. 2), U-series ages of corals show a narrow range, as discussed above, of ~116 ka to ~121 ka. Muhs et al. (2006) report a fauna from this locality that contains mostly taxa whose present ranges occur both well north and well south of San Nicolas Island (Table 2). Nevertheless, the fauna also contains three northward-ranging species (*Chlorostoma brunnea*, *Ocinebrina lurida*, and *Stylidium eschrichtii*), as well as one southward-ranging species (*Serpulorbis squamigerus*). Nearby, at Cormorant Rock (LACMIP loc. 12005; Fig. 2), corals on terrace 1 range from ~76 to ~87 ka, as discussed earlier. Muhs et al. (2006) emphasized the large number of extralimital northern or northward-ranging species from this locality (Table 2), although the deposit at LACMIP loc. 12005 also contains two southward-ranging species (*Astraea undosa* and *Bittium quadrifilatum*). Finally, even the Holocene record of marine invertebrate faunas shows complexity. Calibrated radiocarbon ages of midden deposits on San Nicolas Island indicate that although the oldest midden found on the island goes back to ~8500 yr BP, a third of the sites on the island date to the middle Holocene (6650–3350 yr BP) and two-thirds date to the late Holocene (<3350 yr BP) (Martz, 2005). Despite this narrow age range, all within the current interglacial, the archaeological molluscan record presented by Vedder and Norris (1963) shows that middens on San Nicolas Island contain three northward-ranging species (*Chlorostoma montereyi*, and *Cryptochiton stelleri*) and three southward-ranging species (*A. undosa*, *Norrisia norrisi*, and *Zonaria spadicea*).

Although it hosts one of the richest archives of Pleistocene marine invertebrates on the Pacific Coast of North America, there have only been a few studies of marine terrace fossils on San Nicolas Island. Vedder and Norris (1963) report faunas from most of the terraces on San Nicolas Island, and Russell (1991), Clark (1999) and Muhs et al. (2006) report faunas from terraces 1 and 2. Here, we report new faunal data from LACMIP localities 11004 and 11005 (terrace 1), 11006, 11752, SNI-134/135, and SNI-129 (terrace 2b), and SNI-302 (terrace 2a).

3.3.1. Fossils from the ~80 ka terrace 1 on San Nicolas Island

As discussed above, deposits of the ~80 ka terrace 1 on the west side of the island (LACMIP loc. 12005, at Cormorant Rock, Fig. 2; Table 2) host a large number of extralimital northern or northward-ranging species (Muhs et al., 2006). In contrast, on the northern side of the island, we find a more neutral assemblage (that is, without either northern or southern extralimital species) of taxa on the ~80 ka terrace. Fossils from LACMIP localities 11004 and 11005 contain a typical rocky-shore assemblage, including abundant bivalves such as *Mytilus californianus* and *Epilucina californica* and gastropods such as *Chlorostoma funebralis*, *Haliotis rufescens*, *Fissurella volcano*, *Acmaea mitra*, *Lottia gigantea* and other acmaeid limpets (Table 2). Most fossils from this locality are species whose range endpoints occur well to the north and south of San Nicolas Island today. Nevertheless, the assemblage includes two southward-ranging gastropods, *Tectura depicta* (=*Acmaea depicta* of Abbott (1974), *Notoacmea depicta* of McLean (1978) and "*Lottia depicta*" of McLean (2007)) and *Bittium quadrifilatum*. Both of these gastropods presently range from San Pedro, California to southern Baja California (McLean, 1978 and Natural History Museum of Los Angeles County [LACM] records), although McLean (2007) notes that the northern range of *T. depicta* has been extended to Monterey Bay during El Niño events. As discussed above, Muhs et al. (2006) also report *B. quadrifilatum*, as well as southward-ranging *A. undosa* from the Cormorant Rock locality on the ~80 ka terrace on the west end of San Nicolas Island (LACMIP loc. 12005). *Petricola* (*Petricolirus*) *californiensis* is a bivalve that also might be considered southward-ranging and is found in the assemblage at LACMIP loc. 11004. Although this species is reported as far north as Bolinas (37.9°N) and Pacific Grove, California (36.6°N), Coan et al. (2000) interpret these northern occurrences to be the result of settlement in exceptional warm years. Its main distribution is from Coal Oil Point, near Santa Barbara, California (34.4°N) to Bahía Magdalena, Baja California Sur (Coan et al., 2000).

In contrast to these southward-ranging species, however, Clark (1999) reports the occurrence of a chiton, *Tonicella lokii*, from LACMIP loc. 11004. *T. lokii* has a modern distribution from Humboldt County, California to San Miguel Island and is therefore an extralimital northern species (Fig. 10). In addition, at both LACMIP loc. 11005 and at a locality (N33.267754°; W119.499877°) to the west of loc. 11005, we found specimens of the gastropod *Harfordia harfordi*. This species has a modern distribution from Hope Island, British Columbia (Abbott, 1974) south only to Cormorant Cove, Mendocino County, California (Fig. 10), based on museum records (LACM 94-4.30). To our knowledge, this is one of the very few fossil occurrences of this extralimital northern species, and its presence on the ~80 ka terrace of San Nicolas Island indicates a southern range extension, relative to present, of ~700 km (Fig. 10). Overall, terrace 1 fossil localities of the north side of the island (LACMIP locs. 11004 and 11005) do not contain as many northern forms as this terrace hosts on the west side of the island (LACMIP loc. 12005), and indeed these localities include a few southward-ranging species. Nevertheless, the abundant northern forms from LACMIP loc. 12005, combined with the presence of extralimital northern *T. lokii* and *H. harfordi* from LACMIP locs. 11004 and 11005 indicate cooler than present waters around San Nicolas Island at ~80 ka.

3.3.2. Fossils from the ~100 ka/120 ka terrace 2b on San Nicolas Island

We report here faunas from four localities on terrace 2b, one (LACMIP loc. 11006) that is very close to locality SN-1 of Vedder and Norris (1963) and another (LACMIP loc. 11752) that is close to Russell's (1991) UCMP loc. 10461 (Fig. 2). In addition, we report faunas from two closely spaced localities on terrace 2b on the northeastern side of the island, SNI-134/135 and SNI-129. Vedder and Norris (1963) report more than twice the number of taxa at their locality SN-1 compared to what we found at LACMIP loc. 11006, indicating the two localities are not exactly the same or that human activities have removed much of what was exposed at the time Vedder and Norris (1963) conducted their studies. Nevertheless, the most abundant species we find at 11006 are also reported by Vedder and Norris (1963) and indicate a rocky intertidal environment at the time of deposition. Abundant species at LACMIP loc. 11006 and SN-1 include common rocky intertidal forms such as the gastropods *Chlorostoma funebralis*, *Haliotis rufescens*, *Fissurella volcano*, *Diodora aspera*, *Acmaea mitra*, *Lottia gigantea* and other

Table 2
Marine invertebrate faunas from fossil localities on San Nicolas Island, California.

Terrace	Terrace 1	Terrace 1	Terrace 1	Terrace 2b	Terrace 2b	Terrace 2b	Terrace 2b	Terrace 2a	Terrace 2a	Terrace 2a
LACMIP loc. #	11004	11005	12005	11006	11752	SNI-134/135	SNI-129	10622	SNI-205	SNI-302
MOLLUSCA										
Gastropoda										
Acanthinucella spirata (Blainville, 1832)						X	X	X		
Acmaea mitra Rathke, 1833	X	X	X	X	X			X	X	X
Acteocina inculta (Gould, 1855)				X						
Alia carinata (Hinds, 1844)		X	X		X	X	X			
Alia tuberosa (Carpenter, 1864)	X		X				X			
Alvania compacta (Carpenter, 1864)		X		X						
Alvania sp.		X		X						
Amphissa columbiana Dall, 1916			X							
Amphissa versicolor Dall, 1871	X				X			X	X	
Amphissa sp.		X			X		X			X
Amphithalamus inclusus Carpenter, 1864				X						
Amphithalamus tenuis Bartsch, 1911				X						
Antisabia panamensis (C.B. Adams, 1852) (formerly *Hipponix antiquatus*)	X	X	X	X	X			X	X	X
Astraea undosa (Wood, 1828)			X						X	X
Balcis thersites (Carpenter, 1864)			X							
Barleeia californica (Bartsch, 1920)				X						
Barleeia haliotiphilia (Carpenter, 1864)				X						
Barleeia sp.		X		X		X		X		
Bittium interfossa (Carpenter, 1864)				X						
Bittium quadrifilatum (Carpenter, 1864)	X	X	X							X
Bittium sp.		X		X	X	X		X		
Bulla gouldiana Pilsbry, 1893			X							
Caecum californicum Dall, 1885		X		X			X			
Caecum crebricinctum (Carpenter, 1864)	X			X						
Calicantharus fortis (Carpenter, 1864)					X				X	
Callianax baetica (Carpenter, 1864) (formerly *Olivella baetica*)		X			X					
Callianax biplicata (Sowerby, 1825) (formerly *Olivella biplicata*)	X	X		X	X	X	X	X	X	X
Calliostoma annulatum (Lightfoot, 1786)	X									
Calliostoma ligatum (Gould, 1849)			X	X						
Calliostoma sp.		X		X	X					
Cerithiopsis sp.						X		X		
Chlorostoma brunnea (Philippi, 1849) (formerly *Tegula brunnea*)			X					X		
Chlorostoma funebralis (A. Adams, 1855) (formerly *Tegula funebralis*)	X	X	X	X		X		X		
Chlorostoma gallina (Forbes, 1852) (formerly *Tegula gallina*)									X	
Chlorostoma montereyi (Kiener, 1850) (formerly *Tegula montereyi*)			X							
Chlorostoma sp.		X	X	X	X			X	X	X
Clathromangelia rhyssa (Dall, 1919)				X						
Clathurella sp.				X						
Conus californicus Reeve, 1844			X	X	X	X	X	X		
Crepidula aculeata (Gmelin, 1791)	X	X		X						
Crepidula naticarum Williams, 1905				X						
Crepidula onyx Sowerby, 1834	X									
Crepidula sp.		X		X	X		X		X	
Crepipatella lingulata (Gould, 1846)	X		X	X						
Crepipatella sp.					X					
Crossata californica (Hinds, 1843)							X			
Cymakra aspersa (Carpenter, 1864)						X				
Cysticus jewetti (Carpenter, 1857)	X									
Diodora arnoldi McLean, 1966	X									
Diodora aspersa (Rathke, 1833)			X	X	X			X		
Discurria insessa (Hinds, 1842)	X	X	X	X	X					X
Epitonium tinctum (Carpenter, 1864)			X	X						
Fissurella volcano (Reeve, 1849)	X	X	X	X	X			X	X	X
Fusinus luteopictus Dall, 1877			X							
Fusitriton oregonense (Redfield, 1846)			X							
Garnotia adunca (Sowerby, 1825)		X	X	X						
Glossaulax reclusiana (Deshayes, 1839)							X			
Granulina margaritula (Carpenter, 1857)	X			X	X	X				
Haliotis cracherodii Leach, 1814					X				X	X
Haliotis rufescens Swainson, 1822	X	X	X	X				X	X	
Haliotis sp.			X	X	X	X	X		X	X
Harfordia harfordi (Stearns, 1871)		X								
Harfordia sp.	X	X			X				X	X
Helminthoglypta sp.		X		X						X

Table 2 (*continued*)

Terrace	Terrace 1	Terrace 1	Terrace 1	Terrace 2b	Terrace 2b	Terrace 2b	Terrace 2b	Terrace 2a	Terrace 2a	Terrace 2a
LACMIP loc. #	11004	11005	12005	11006	11752	SNI-134/135	SNI-129	10622	SNI-205	SNI-302
Hima mendica (Gould, 1849) (formerly *Nassarius mendicus*)				X	X		X			
Hipponix tumens Carpenter, 1864	X	X	X	X	X			X	X	X
Hipponicid sp.					X					
Homalopoma luridum (Dall, 1885)	X		X	X				X		X
Homalopoma sp.		X		X				X		
Lacuna sp.				X		X	X	X		
Lirobittium attenuatum (Carpenter, 1864)						X				
Lirobuccinum dirum (Reeve, 1846)			X							
Littorina keenae Rosewater, 1978	X		X	X				X		
Littorina scutulata Gould, 1849				X				X		
Littorina sp.		X		X		X		X		X
Lottia digitalis (Rathke, 1833)			X							
Lottia gigantea Sowerby, 1834	X									
Lottia pelta (Rathke, 1833)	X									
Lottia scabra (Gould, 1846)	X	X	X	X	X	X		X	X	X
Lottia sp.		X	X	X	X		X	X	X	X
Merelina sp.		X								
Metaxia convexa (Carpenter, 1857)			X							
Mitra idae Melvill, 1893			X	X	X		X	X		
Mitromorpha carpenteri Glibert, 1954			X							
Nassarius perpinguis (Hinds, 1844)					X					
Norrisia norrisi (Sowerby, 1838)									X	X
Nucella emarginata (Deshayes, 1839)					X					
Ocinebrina circumtexta (Stearns, 1871)			X					X		
Ocinebrina foveolata (Hinds, 1844)			X							
Ocinebrina lurida (Middendorff, 1848)			X		X			X		
Ocinebrina sp.		X		X	X	X		X		X
Odostomia turricula Dall and Bartsch, 1903				X						
Odostomia (Evalea) sp.	X							X		
Opalia montereyensis (Dall, 1907)				X						
Opalia sp.			X							
Petaloconchus montereyensis Dall, 1919		X		X	X			X	X	X
Pseudomelatoma penicillata (Carpenter, 1864)			X							
Pseudomelatoma sp.	X	X		X	X		X			
Pusula californiana (Gray, 1827)							X			
Seila montereyensis Bartsch, 1907			X				X	X		
Serpulorbis squamigerus (Carpenter, 1857)					X		X	X	X	X
Siphonaria brannani Stearns, 1873		X	X							
Stylidium eschrichtii (Middendorff, 1849)			X					X		
Tectura depicta (Hinds, 1842)	X			X						
Tenaturris sp.			X							
Tricolia pulloides (Carpenter, 1865)				X						
Tricolia rubrilineata (Strong, 1928)				X						
Trimusculus reticulatus Sowerby, 1835		X			X		X	X		
Triphora pedroana (Bartsch, 1907)	X		X	X				X		
Trochidae indet.				X						
Turbonilla sp.	X			X						
Turritella cooperi Carpenter, 1864					X					
Vitrinella oldroydi Bartsch, 1907				X						
Vitrinella sp.			X							
Williamia peltoides (Carpenter, 1864)	X									
Zonaria spadicea (Swainson, 1823)										X
Bivalvia										
Bernardina bakeri Dall, 1910				X						
Chama arcana Bernard, 1976									X	
Chlamys hastata (Sowerby, 1842)				X						
Chlamys sp.					X					
Crassadoma gigantea (Gray, 1825)					X	X	X			
Cumingia californica Conrad, 1837	X	X		X	X	X		X	X	X
Epilucina californica (Conrad, 1837)	X	X	X	X	X		X	X	X	X
Gari californica (Conrad, 1849)						X	X			
Glans carpenteri (Lamy, 1922)	X	X	X	X	X			X		X
Glycymeris sp.					X					
Indet. bivalves	X								X	
Irusella lamellifera (Conrad, 1837)					X			X		
Kellia suborbicularis (Montagu, 1803)								X		
Leucoma staminea (Conrad, 1837) (formerly *Protothaca staminea*)	X		X		X	X				
Lucinid sp.					X					
Macoma nasuta (Conrad, 1837)			X							
Mactrotoma californica (Conrad, 1837)						X	X			
Modiolus sp.					X					

(*continued on next page*)

Table 2 (*continued*)

Terrace	Terrace 1	Terrace 1	Terrace 1	Terrace 2b	Terrace 2b	Terrace 2b	Terrace 2b	Terrace 2a	Terrace 2a	Terrace 2a
LACMIP loc. #	11004	11005	12005	11006	11752	SNI-134/135	SNI-129	10622	SNI-205	SNI-302
Musculus sp.								X		
Mytilus californianus Conrad, 1837	X		X		X	X	X	X		
Mytilus sp.			X							
Nutricola tantilla (Gould, 1853)				X		X	X			
Nutricola sp.		X		X						
Parapholas californica (Conrad, 1837)					X					
Parvilucina sp.		X								
Penitella penita (Conrad, 1837)						X				
Penitella turnerae Evans and Fischer, 1966			X							
Penitella sp.						X	X		X	X
Petricola californiensis Pilsbry and Lowe, 1932	X					X				
Petricola sp.					X					
Pectinid sp.					X					
Pododesmus macroschisma (Deshayes, 1839)							X			
Saxidomus gigantea Conrad, 1837						X	X			
Septifer bifurcatus (Conrad, 1837)	X								X	X
Trachycardium quadragenarium (Conrad, 1837)						X	X			
Tresus nuttalli (Conrad, 1837)						X				
Polyplacophora										
Cryptochiton stelleri (Middendorff, 1847)			X		X					
Tonicella sp.								X		
Mixed chiton plates	X	X		X	X			X	X	X
Scaphopoda										
Dentalium sp.				X	X					
CNIDARIA										
Balanophyllia elegans Verrill, 1864	X		X	X	X			X		X
ARTHROPODA										
Barnacle fragments	X		X	X	X				X	X
Crab claws	X	X		X				X	X	X
Ostracods				X						
Pagurus sp.				X						
ECHINODERMATA										
Dendraster excentricus (Eschscholtz, 1831)						X	X			
Strongylocentrotus sp.	X		X		X					
Echinoid spines and/or plates		X		X	X	X	X	X		X
BRYOZOA										
Bryozoan fragments	X	X		X	X		X			
ANNELLIDA										
Serpula sp.						X	X			
Worm tubes		X		X				X		
RHODOPHYTA										
Calcareous algae								X	X	

acmaeid limpets and the bivalves *Cumingia californica*, *Glans carpentari*, *Mytilus californianus* and *Epilucina californica*. In addition, sea urchin plates and spines (*Strongylocentrotus* [?] sp. or spp.) are also abundant, consistent with a rocky intertidal paleoenvironment. LACMIP loc. 11752 is situated on a more protected part of the island, where there are currently small bays with sandy beaches (Fig. 2). The fauna at LACMIP loc. 11752 (Table 2) is very similar to that reported by Russell (1991) for his nearby locality UCMP 10461. In his detailed analysis of taxa from UCMP loc. 10461, Russell (1991) reports that slightly more than 60% of the species represent a sandy-bottom environment and slightly less than 40% represent a rocky substrate, indicating a somewhat more protected paleoenvironment in contrast to LACMIP loc. 11006, but similar to what is found offshore today. A protected, bay type of environment is clearly indicated by invertebrates found at SNI-134/135 and SNI-129. Among these are the bivalves *Mactrotoma californica*, *Saxidomus gigantea*, *Nutricola tantilla*, *Trachycardium quadragenarium* and *Tresus nutalli*, and the sand dollar *Dendraster excentricus*.

As originally pointed out by Vedder and Norris (1963), fossils on terrace 2 of San Nicolas Island contain a number of southern species. Since the time that Vedder and Norris (1963) studied the fossils from this terrace, however, there have been a number of changes in molluscan taxonomy and more detailed information about the present marine invertebrate zoogeography of the Pacific Coast has emerged. Thus, we reassessed the fossil lists given by Vedder and Norris (1963) and Russell (1991), in addition to the new faunas reported here (Table 2). We emphasize that we have not examined personally the collections made by Vedder and Norris (1963) and Russell (1991), but make our interpretations directly from their fossil lists, updating only the taxonomy as it is now recognized and modern zoogeography as it is now known.

Based on all collections, we find there are 5 extralimital southern species of mollusks on terrace 2 (2b) on San Nicolas Island, including 4 gastropods and 1 bivalve. Extralimital southern gastropods include *Crepidula* cf. *C. excavata* (Golfo de California, Baja California and south to Panama (Keen, 1971), possibly as far north as the Palos Verdes Hills [CAS collections]); *Trachypolia lugubris* (reported as *Morula* cf. *M. lugubris* by Vedder and Norris (1963)), found only from San Diego to Panama (Keen, 1971; Abbott, 1974); and *Petaloconchus complicatus*, found as far north as Isla Socorro, Islas Revillagigedo, Mexico (18.75°–18.85°N; Quiñones and Michel-Morfín, 2006), on the mainland Mexican coast at least as far north as Playa Troncones, Guerrero, Mexico (17.78°N; Flores-Rodríguez et al., 2007) and south to Isla de Coco, Costa Rica and the Islas Galápagos, Ecuador (Keen, 1971). *P. complicatus* has also been reported from marine terrace deposits in

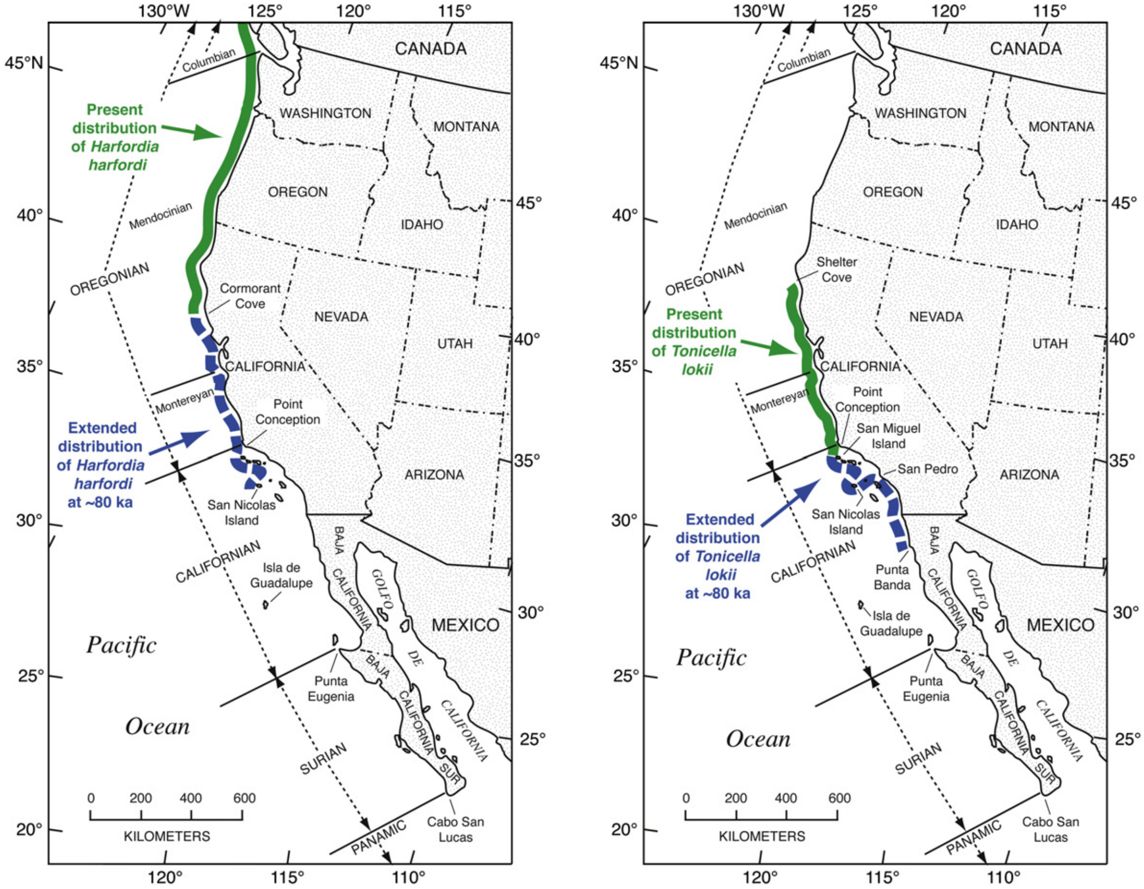
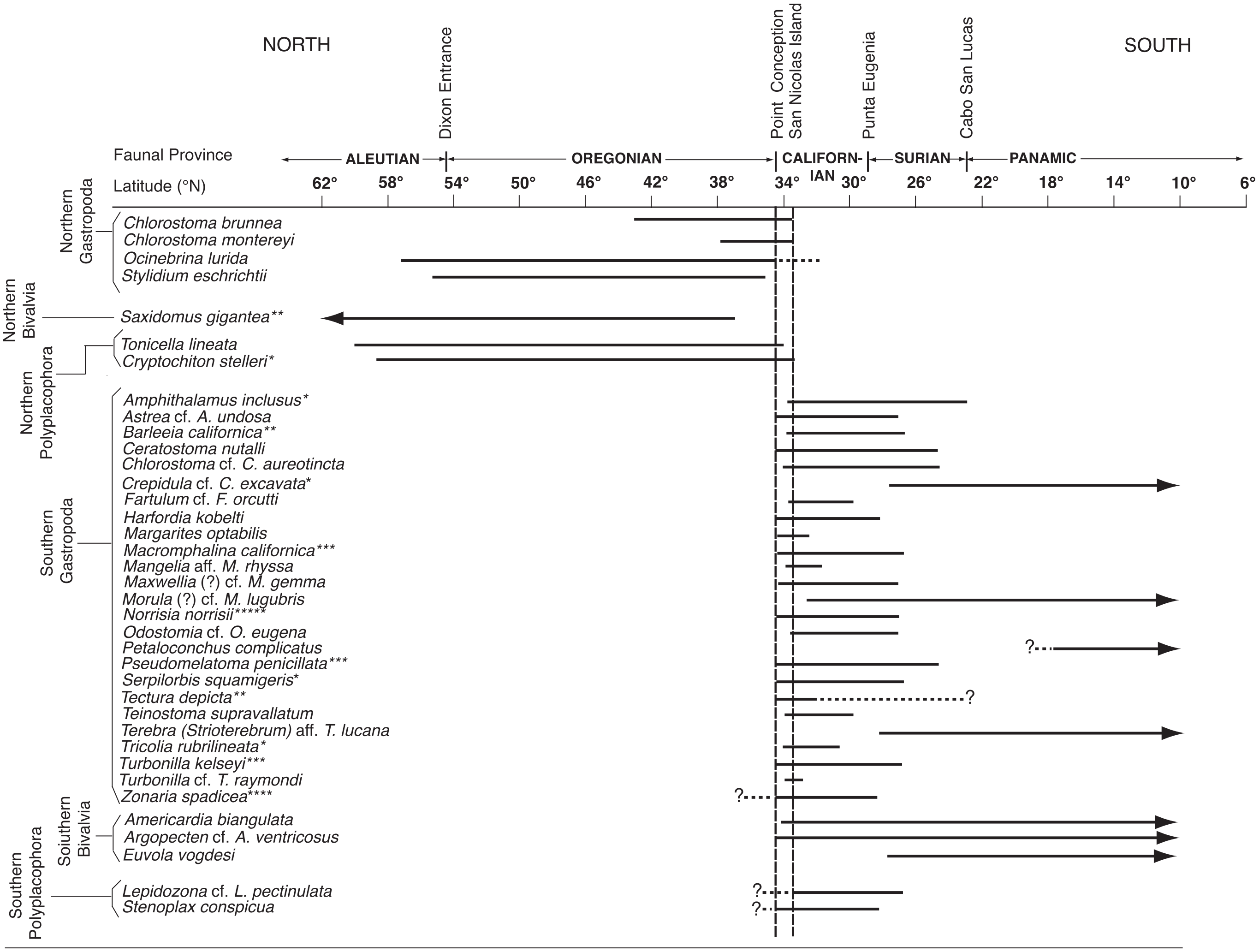


Fig. 10. Map of a portion of the Pacific Coast of North America, showing location of San Nicolas Island, marine invertebrate faunal zones (Valentine, 1966) and modern (green) and extended, ~80 ka (blue) distributions of *Harfordia harfordi* (this study) and *Tonicella lokii* (Clark, 1999), both extralimital northern species found in deposits of terrace 1 on San Nicolas Island. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

San Pedro (Valentine, 1962) and on Santa Barbara Island (Lipps et al., 1968) that amino acid data indicate are of Last Interglacial age (Muhs et al., 1992, 2010). The extralimital southern bivalve is *Euvola vogdesi* (reported as *Pecten vogdesi* by Vedder and Norris (1963)), found only from Baja California Sur (27.8°N) south to Panama (Coan et al., 2000).

As pointed out earlier, the modern marine invertebrate faunas of both San Nicolas Island and San Miguel Island have closer affinities to central California faunas (i.e., those north of Point Conception) than to southern California faunas (Seapy and Littler, 1980, 1993; Eernisse et al., 2007). Thus, in addition to strictly extralimital southern species, there are a number of species whose northern range endpoints are near Los Angeles, which currently has warmer waters than San Nicolas Island. These essentially extralimital southern species include: *Fartulum* cf. *F. orcutti* (Palos Verdes Hills to Isla San Geronimo, Baja California (McLean, 1978)); *Odostomia* cf. *O. eugena* (Redondo Beach, California to Punta San Hipolito, Baja California (Abbott, 1974)); *Teinostoma supravallatum* (Los Angeles to Isla San Geronimo, Baja California (McLean, 1978)); *Tricolia rubrilineata* (Los Angeles to Isla San Martin, Baja California (McLean, 1978)); *Turbonilla* cf. *T. raymondi* (Redondo Beach to San Diego, California (Abbott, 1974)) and a chiton, *Lepidozona californiensis* (reported as *Ischnochiton* (*Lepidozona*) cf. *I. californiensis* by Vedder and Norris (1963)) found only from Los Angeles County to Punta Abreojos, Baja California (Haderlie and Abbott, 1980). Finally, there are a large number of southward-ranging species whose modern northern range endpoints occur at San Nicolas Island, the Santa Barbara area, or Point Conception (Fig. 11).

Despite the abundance of extralimital southern or southward-ranging species of mollusks on terrace 2b on San Nicolas Island, there are a number of northern species as well (Fig. 11). We found previously unreported occurrences of the extralimital northern bivalve *Saxidomus gigantea* on terrace 2b at SNI-134/135 and SNI-129. At present, *S. gigantea* lives from Alaska only as far south as the Monterey-Pacific Grove area of central California (Coan et al., 2000). Museum records of *Stylidium eschrichtii* indicate a distribution from Ketchikan, Alaska [LACM 165048] to San Luis Obispo County, California [LACM 165052], making this a marginally extralimital northern species. *Ocinebrina lurida* has an extreme range from Sitka, Alaska to Punta Santo Tomas, Baja California, but McLean (1978) points out that it is chiefly a northern species, and is only occasionally found in southern California. *Lottia instabilis* is reported to occur as far south as San Diego (Abbott, 1974), but museum records indicate a range from southeastern Alaska [LACM 162214] only to Mendocino County, northern California [LACM 162219]. Two northward-ranging gastropods (*Chlorostoma brunnea* and *C. montereyi*) are present at other localities on terrace 2b; these species are only rarely found south of Point Conception. There are also two northern chitons found on terrace 2b on San Nicolas Island. One of these is *Tonicella lineata*, a northern extralimital species that is found from the Aleutian Islands of Alaska to only as far south as San Miguel Island (Haderlie and Abbott, 1980), although two lots (21 specimens) from San Pedro, Los Angeles County are in a museum collection (LACM 72–91.8 and 166102). In addition, a northward-ranging chiton, *Cryptochiton stelleri*, is reported by both Vedder and Norris (1963) and herein (Table 2). *C.*



Identified by Vedder and Norris (1963) only, except as follows: *identified by Vedder and Norris (1963) and this study; **identified in this study only; ***identified by Russell (1991) only; ****identified by Vedder and Norris (1963) and Russell (1991); *****identified in all three studies

Fig. 11. Graph showing the modern distribution, by latitude, of extralimital northern and southern and northward and southward-ranging taxa found on terrace 2b on San Nicolas Island. Data from Vedder and Norris (1963), Russell (1991) and this study. Geographic distributions taken from Abbott (1974), Abbott and Haderlie (1980), McLean (1978, 2007), Coan et al. (2000), Keen (1971), Clark (1999) and records from the Natural History Museum of Los Angeles County (LACM).

stelleri presently ranges from the Aleutian Islands to San Nicolas Island, but is rare south of Monterey Bay (Haderlie and Abbott, 1980). There are three lots (19 inarticulated plates) from San Nicolas Island in modern collections of the Natural History Museum of Los Angeles County (LACM 19509, 166238 and 177795). Nevertheless, as with *Chlorostoma brunnea* and *C. montereyi* discussed above, Kanter (1980), Russell (1991), and Seapy and Littler (1993) did not report *Cryptochiton stelleri* in modern surveys of intertidal invertebrates on San Nicolas Island and Eernisse et al. (2007) report that it is only rarely found as far south as the Channel Islands.

3.3.3. *Fossils from the ~120 ka terrace 2a*

Deposits of the small fragment of terrace 2a at SNI-302 and nearby at SNI-205 have a fauna that indicates a rocky intertidal environment, similar to most other localities on San Nicolas Island. No extralimital northern or northward-ranging species were found at these localities. However, we report here five southward-ranging species, all gastropods (Table 2). Both *Astraea undosa* and *Norrisia norrisi* presently live no farther north than Point Conception, but have ranges extending well into northern Baja California. *Bittium quadrifilatum* presently lives from San Pedro, California to southern Baja California (McLean, 1978; and LACM records). *Chlorostoma gallina* and *Serpilorbis squamigeris*, in its form as large, twisted masses, range no farther north than Point Conception (McLean, 1978). Collectively, the assemblage indicates water temperatures as warm or warmer than present at ~120 ka. An unexpected find from these localities is the presence of *Calicantharis fortis*, a gastropod that is extinct. This species was not thought to range into the late Pleistocene, so its presence in a ~120 ka marine deposit is the youngest occurrence of this fossil, to our knowledge. However, we cannot discount the possibility that this specimen was reworked from a higher, mid-Pleistocene terrace (e.g., Fig. 3(a)).

4. Discussion

4.1. *Timing of sea stands during the Last Interglacial complex*

It is difficult to estimate precise timing of sea stands on San Nicolas Island, given the open-system behavior (with respect to U-series isotopes) of many of the corals we studied. Open-system behavior of nuclides in the uranium-series is unfortunately more common than not in both solitary and colonial corals (Stein et al., 1991, 1993; Gallup et al., 1994; Edwards et al., 1997; Muhs et al., 2002a, 2002b; Thompson et al., 2003; Thompson and Goldstein, 2005). Nevertheless, we have sufficient data to ascertain how the low-elevation terraces on San Nicolas Island compare to global sea-level changes, recorded both in the deep-sea oxygen isotope record and the emergent coral reef record of tropical islands.

Despite many corals with open-system history, a number of our samples from terrace 2a on the west side of San Nicolas Island (LACMIP loc. 10622, reported by Muhs et al. (2006), but also shown in Fig. 8) as well as two corals from the north side (SNI-302; Table 1) show evidence of closed-system isotopic evolution, with an age range of ∼122 ka to ∼116 ka (Fig. 8). Thus, we correlate terrace 2a with the peak of the Last Interglacial period, marine isotope stage (MIS) 5.5, using the nomenclature of Martinson et al. (1987). Furthermore, other corals from terrace 2a, although showing evidence of open-system behavior, display a linear trend toward an age of ∼120 ka.

There has long been a debate as to whether the Last Interglacial period of MIS 5.5 consisted of a single sea stand or multiple sea stands. Geomorphic and stratigraphic evidence indicate there are two distinct coral reefs that date to the Last Interglacial period on New Guinea (Bloom et al., 1974; Chappell, 1974). Although early studies had minimal dating of the two reefs, later U-series analyses by TIMS show that both terraces likely date to the Last Interglacial period (Stein et al., 1993). Nevertheless, the age difference between the two terraces remains uncertain. More recently, two (Thompson and Goldstein, 2005) or even three (Schellmann and Radtke, 2004) high sea stands during MIS 5.5 have been reported for reef terraces on Barbados. Blanchon et al. (2009) also proposed a two-step sequence of sea-level high stands during the Last Interglacial period from the tectonically stable Yucatan Peninsula of Mexico. The statistical analysis of Kopp et al. (2009), based on a global compilation of sea level data from the Last Interglacial period, also provides some evidence for two sea level high stands during MIS 5.5, one peaking at ∼124 ka and the other at ∼118 ka. The fragmentary record left by terrace 2a does not allow us to test these hypothesized suborbital sea level fluctuations, but the range of closed-system ages (or nearly closed-system ages) from terrace 2a overlaps those of Last Interglacial reefs of both New Guinea and Barbados, as well as the global compilation of Kopp et al. (2009).

Terrace 2b, which occupies the main part of the “2nd terrace” complex mapped on the island (Figs. 2–5), has no corals that show closed-system histories, but the array of data points shows evidence of two ages of corals (Fig. 7). Slightly more than half the samples analyzed from this terrace trend toward a closed-system age of ∼120 ka (MIS 5.5), whereas slightly less than half the samples trend toward a closed-system age of ∼95–100 ka (MIS 5.3), indicating a mixed population. Based on the U-series ages of corals at different localities, the mixing process on San Nicolas Island was spatially complex. A locality just south of Coast Guard Beach (LACMIP loc. 11749; Figs. 2 and 4) contains corals that all trend toward an age of ∼120 ka, whereas a locality near Daytona Beach (LACMIP loc. 11752) contains only corals that trend toward an age of ∼100 ka. There is no geomorphic evidence that these two localities occur on different platforms, however. At NAVFAC Canyon, two localities (LACMIP loc. 11006 and a locality ∼50 m south of it) contain corals that fall into both ∼120 ka and ∼100 ka age groups. Our interpretation of these data is that terrace 2b formed during the ∼100 ka sea stand, represented in the oxygen isotope record as MIS 5.3. Because terrace 2b consists of a single platform (Fig. 5), corals on the terrace that trend toward a closed-system age of ∼120 ka were likely reworked from a once-broader terrace 2a. The broad, shore-normal extent of terrace 2b, in contrast to the narrow seaward extent of terrace 2a, likely resulted from initial formation of a broad terrace during MIS 5.5 at ∼120 ka, followed by little or no uplift, and then reoccupation and renewed platform cutting of all but the innermost part of the ∼120 ka terrace during the ∼100 ka sea stand. Platform reoccupation and renewed cutting at ∼100 ka would have trimmed the ∼120 ka platform landward by undercutting the sea cliff, leaving the small remnants present today as terrace 2a.

Elsewhere on the California coast, Muhs et al. (2002b) report similar bimodal age distributions for low marine terraces, long thought to be of a single, Last Interglacial age of ∼120 ka, at Cayucos and Point Loma (Fig. 9). Earlier studies, by Ku and Kern (1974) for Point Loma and Stein et al. (1991) for Cayucos, also report mixtures of ∼100 ka and ∼120 ka corals. Muhs et al. (2002b) hypothesized that the biomodal age distribution on the Cayucos and Nestor terraces could be explained by cliff retreat and platform reoccupation of the ∼120 ka marine terrace by the ∼100 ka sea stand, as discussed earlier. Unlike San Nicolas Island, however, both Point Loma and Cayucos do not have fragments of an older, ∼120 ka terrace at slightly higher elevations. This indicates complete removal of the ∼120 ka terrace during the ∼100 ka high sea stand at Cayucos and Point Loma. The terraces at Cayucos and Point Loma have lower shoreline angle elevations than terrace 2a or 2b on San Nicolas Island, indicating a lower rate of uplift. We suspect, therefore, that in those localities where the uplift rate is sufficiently high, such as San Nicolas Island, terraces for both the ∼100 ka and ∼120 ka sea stands are preserved, but in areas of low uplift rate such as Cayucos and Point Loma, only one terrace is preserved.

As with the peak of the Last Interglacial period during MIS 5.5 at around 120 ka, geomorphic and geochronologic data have been offered from Barbados as evidence for multiple sea stands during MIS 5.3 at around 100 ka (Potter et al., 2004; Schellmann and Radtke, 2004; Schellmann et al., 2004; Thompson and Goldstein, 2005). Because the elevation and uplift rate of the ∼100 ka terrace on San Nicolas Island are very similar to those of the ∼100 ka terrace on Barbados, one might expect similar evidence of multiple sea stands during MIS 5.3. There is, however, no evidence of more than one sea stand during MIS 5.3 on San Nicolas Island. We suspect the records on the two islands are different because of the fact that on Barbados, uplifted terraces are constructional, “keep-up” coral reefs, dominated by the rapidly growing, framebuilder coral, *Acropora palmata*. In such settings, rapidly growing corals can keep pace with a rising sea level and the terrace-forming process is constructional, not erosional. In contrast, marine terraces on San Nicolas Island are erosional landforms and evidence of a previous sea stand may be erased during a high stand that follows closely in time.

In our new analyses from terrace 1 on the north side of the island (LACMIP loc. 11004), all corals show evidence of open-system behavior, but trend toward an age of ∼80 ka, similar to corals from LACMIP locs. 11009 and 12005. Thus, consistent with Muhs et al. (2006), we correlate terrace 1 with MIS 5.1. As with the ∼120 ka and ∼100 ka sea stands, studies from Barbados (Potter et al., 2004; Schellmann and Radtke, 2004; Schellmann et al., 2004; Thompson and Goldstein, 2005) offer evidence that there may have been two separate sea stands during MIS 5.1. On Barbados, corals from reefs on either side of South Point, at the southernmost tip of the island, have distinct age clusters of ∼87 ka to ∼81 ka (on a higher reef) and ∼79 ka to ∼74 ka (on a lower reef). We have no geomorphic evidence for two sea stands during MIS 5.1 on San Nicolas Island. Indeed, corals from a *single* locality on terrace 1 (LACMIP loc. 12005) have closed-system ages (∼87 ka to ∼76 ka; see Fig. 8) that span most of the range of the two MIS 5.1 terraces on southern Barbados. As noted above, the difference in records between Barbados and San Nicolas Island may be a function of the different terrace-forming processes. Rapidly responding, constructional, keep-up reefs (Barbados) may record more details of sea level fluctuations within a given high sea stand than erosional terraces (San Nicolas Island).

4.2. Estimates of paleo-sea level during the Last Interglacial complex

It is possible to estimate past sea levels from marine terraces if an uplift rate can be calculated. Classic studies from Barbados and New Guinea (Broecker et al., 1968; Veeh and Chappell, 1970; Bloom et al., 1974; Chappell, 1974) have addressed this problem by calculating an uplift rate from the ~120 ka terrace using its age and an assumption of a paleo-sea level of +6 m at the time of reef formation. The paleo-sea level of +6 m used in these early studies is based on a rough average of ~120 ka reefs on tectonically stable islands (Veeh, 1966). Assuming a constant late Quaternary uplift rate, the ages and elevations of the ~100 ka and ~80 ka terraces can then be used to back-calculate paleo-sea levels at the times of their formation. Results from this approach have been an integral part of the support for the Milankovitch orbital forcing theory of climate change for the Quaternary (Broecker et al., 1968; Mesolella et al., 1969; Veeh and Chappell, 1970). For Barbados and New Guinea, paleo-sea level estimates for the ~100 ka and ~80 ka sea stands are well below present, both in the original studies cited above and refined studies with new elevation data and more precise dating (Chappell and Shackleton, 1986; Bard et al., 1990; Cutler et al., 2003; Potter et al., 2004; Schellmann and Radtke, 2004; Schellmann et al., 2004; Thompson and Goldstein, 2005). On Barbados, paleo-sea levels of about −20 m are estimated for both the ~100 and ~80 ka sea stands by Bard et al. (1990). Later work on southern Barbados by Potter et al. (2004) indicates paleo-sea levels of −14 for the ~100 ka sea stand, −19 m for the 87–81 ka sea stand, and −18 m for the ~79–74 ka sea stand. On New Guinea, Chappell and Shackleton (1986) estimate paleo-sea levels of −19 m at both ~100 ka and ~80 ka. Studies from other uplifting islands in the Caribbean, such as Haiti (Dodge et al., 1983), and in the Pacific, such as Atauro and Timor, Indonesia (Chappell and Veeh, 1978) are in broad agreement with the results from Barbados and New Guinea, though there are small differences in detail.

Sea level studies from tectonically stable islands and continental coastlines, particularly along the western Atlantic margin, show divergent estimates of paleo-sea levels at ~100 ka and ~80 ka compared to estimates from Barbados and New Guinea. There are few data from this region for paleo-sea level estimates for the ~100 ka (MIS 5.3) sea stand, but corals a few meters above sea level on Bermuda have been dated (by alpha spectrometry) to ~94–108 ka (Harmon et al., 1978, 1983) and at ~103–105 ka from the Bahamas (Neumann and Moore, 1975). For MIS 5.1, growth-position *Acropora palmata* dated to ~85 ka is found at −15 m off the Florida Keys (Toscano and Lundberg, 1999), in broad agreement with the Barbados and New Guinea records. On the other hand, abundant corals in a marine deposit ~1.5 m above sea level on tectonically stable Bermuda have ages from ~78 ka to ~84 ka (Muhs et al., 2002a). Finally, corals dating from ~73 ka to ~86 ka are found in marine deposits ~3–7.5 m above sea level on the Atlantic Coastal Plain, from Virginia to Georgia (Wehmiller et al., 2004).

We estimate relative paleo-sea levels for San Nicolas Island using the ages and elevations of terrace 2a (~120 ka), terrace 2b (~100 ka) and terrace 1 (~80 ka) presented herein. To calculate an uplift rate, we use the elevation of ~120 ka terrace 2a and an assumed paleo-sea level at ~120 ka. The closest tectonically stable locality to San Nicolas Island of which we are aware that hosts a dated marine deposit is Isla Guadalupe, Baja California, Mexico (Fig. 1). Isla Guadalupe is distant from any plate boundary, has no active faults nearby, has no active volcanoes on or near it, is bounded on its eastern side by a seafloor with undisturbed marine sediment, and has no history of recent earthquakes (Gonzalez-Garcia et al., 2003). Marine deposits on Isla Guadalupe have been dated to ~120 ka (Muhs et al., 2002b). These deposits have elevations ranging from near sea level to as high as ~6 m above sea level (Lindberg et al., 1980). A paleo-sea level of +6 m at ~120 ka is in good agreement with estimates from other tectonically stable coastlines and islands (see review in Muhs et al., 2011). Using this paleo-sea level and the shoreline angle elevations of the ~120 ka terrace given in Fig. 5, we calculate uplift rates of 0.267 m/ka (Dudleya-NAVFAC Canyon transect), 0.258 m/ka (Coast Guard Beach-Sandspit transect), and 0.254 m/ka (“L” Canyon transect). Using these uplift rates and the shoreline angle elevation data for the ~100 ka terrace, we estimate paleo-sea level to be about +6.8 m (Dudley-NAVFAC), +2.0 (Coast Guard Beach-Sandspit), or +6.0 m (“L” Canyon). For the ~80 ka terrace, we estimate paleo-sea levels of −11 m (Dudleya-NAVFAC), −12 m (Coast Guard Beach-Sandspit), and −12 m (“L” Canyon). Our paleo-sea level estimates of +2 to +6 m for the ~100 ka sea stand and −11 to −12 m for the ~80 ka sea stand are significantly higher than estimates from Barbados and New Guinea, particularly for the ~100 ka sea stand (Fig. 12). Although our estimates for the ~80 ka sea stand are similar to the record from the Florida Keys, they are substantially lower than those for the U.S. Atlantic Coastal Plain and Bermuda (Fig. 12).

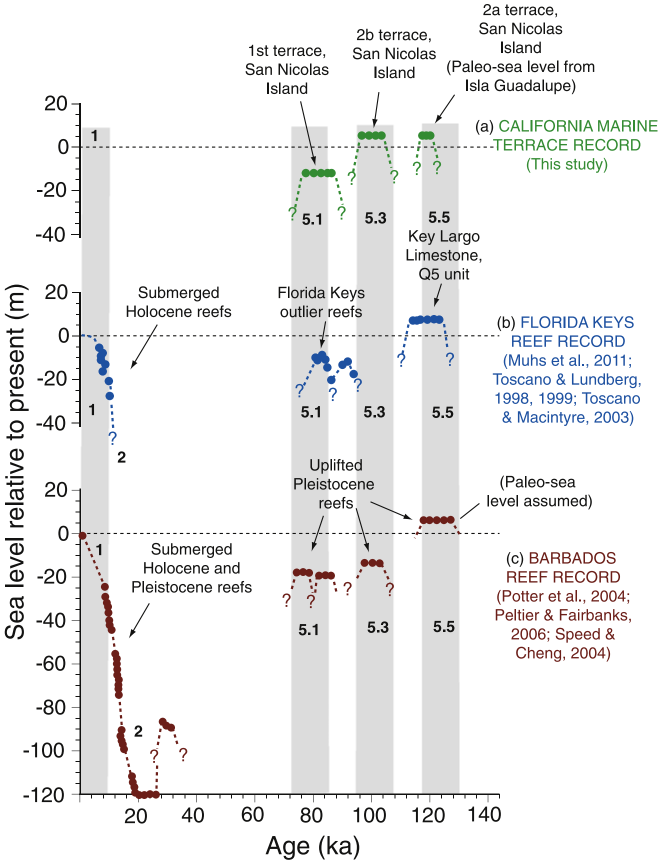


Fig. 12. Sea level records of the Last Interglacial–glacial cycle from three locations: San Nicolas Island, Florida Keys and Barbados. San Nicolas Island data from this study; Isla Guadalupe data from Lindberg et al. (1980) and Muhs et al. (2002b); Florida Keys data from Toscano and Lundberg (1998, 1999), Toscano and Macintyre (2003) and Muhs et al. (2011); Barbados data from Potter et al. (2004), Speed and Cheng (2004), and Peltier and Fairbanks (2006). Shaded areas with bold numbers represent relatively warm periods of the oxygen isotope record, as given in Martinson et al. (1987).

4.3. *Glacial isostatic adjustment (GIA) modeling*

Following the Potter and Lambeck (2003) analysis of high sea stands at ~80 ka in the western North Atlantic, we hypothesize that geographic differences in the peak high sea stands at both ~100 ka and ~80 ka are due, in large part, to the signal from glacial isostatic adjustment (GIA). To test this hypothesis, we have performed a numerical simulation of global-scale, GIA-induced sea-level changes over the past 250 kyr. The calculations are based on a gravitationally self-consistent sea-level theory that accounts for the gravitational, deformational and rotational effects of ice-age loading and the time-dependent geometry of oceans associated with both the migration of shorelines and changes in the extent of grounded, marine-based ice (Mitrovica and Milne, 2003; Kendall et al., 2005; Mitrovica et al., 2005). The sea-level simulation requires two main inputs, the space-time history of ice cover and a model for the depth profile of mantle viscosity. We discuss each of these inputs, in turn, after a brief review of the physics of post-glacial sea-level change.

During a glacial cycle and subsequent interglacial, GIA-induced effects on sea level lead to departures from eustasy that have a complex geometry and time history (Nakada and Lambeck, 1989; Mitrovica and Peltier, 1991; Milne and Mitrovica, 2008). The GIA signal includes changes in the direct gravitational attraction of the time-varying ice-plus-ocean load and perturbations in both crustal and sea-surface heights in response to load-induced deformation. Sea-level change during deglaciation and interglacial phases provides a useful illustration of the latter. Ice unloading initiates post-glacial rebound of the crust (and a sea-level fall) in glaciated regions, and subsidence of the crust (and sea-level rise) in the so-called peripheral bulges that encircle the areas of ancient ice cover. These two regions comprise what is informally termed the “near-field”. Outside these regions, in the “far-field”, the physics of sea-level change is more subtle. As an example, meltwater loading of the oceans causes the crust to tilt near coastlines, downward over the ocean and upward over land, contributing a sea-level rise and fall, respectively, in a process known as continental levering (Nakada and Lambeck, 1989). Furthermore, in ocean basins well away from shorelines, the migration of water into accommodation space formed by both the subsidence of peripheral bulge and zones of offshore levering leads to a large scale fall in sea level that is termed ocean syphoning (Mitrovica and Peltier, 1991; Mitrovica and Milne, 2002). The contribution of each of the above processes reverses during the glaciation phase and these geographically variable contributions act in tandem with globally averaged (eustatic) sea-level change to produce local (i.e., site-specific) sea-level histories.

Our initial numerical simulations were performed using the so-called ICE-5G history of global ice cover during the last glacial cycle (Peltier, 2004). This ice history is coupled to a radial profile of mantle viscosity known as VM2 (Peltier, 2004), which is characterized by a moderate, factor of ~4–5 increase in viscosity from the upper mantle (~5×10^{20} Pa s) to the lower mantle (~5×10^{21} Pa s), where the boundary between the two is taken to be 670 km depth. The calculation based on ICE-5G/VM2 retrodicted high stands at ~100 ka and ~80 ka at San Nicolas Island that were approximately 40 m below present sea level, and therefore inconsistent with our observations. In an effort to improve the fit between the numerical predictions and observations, we revised the ICE-5G ice history in two ways. First, the ICE-5G history over the interval 110 ka to 75 ka has a far more muted (~10–15 m) variability in ice volume than the variability (~30–40 m) inferred from oxygen isotope variations (e.g., Waelbroeck et al., 2002; see the inset to Fig. 6 of Peltier and Fairbanks, 2006). Accordingly, over this time interval, we scaled the ICE-5G ice increments to more closely match the latter. Second, we included a penultimate glacial cycle identical to the last cycle and ending at ~128 ka.

The predicted relative sea level history at San Nicolas Island over the last glacial cycle based on this modified ice history and the VM2 viscosity model is shown in Fig. 13A as a dashed red line (for the purpose of comparison, the black line on the same figure is the eustatic sea-level change associated with the adopted ice history). This calculation retrodicts high sea stands at 100 ka and 80 ka that are 15 m and 20 m below present-day sea level, respectively; these values remain well below the observed elevation of these high stands discussed above (Fig. 12).

To further refine our predictions of GIA-induced sea-level change, we turned to a consideration of different Earth models. Independent inferences of mantle viscosity based either on a suite of ice-age observations or a combination of these observations with data sets associated with mantle convection (e.g., Nakada and Lambeck, 1989; Mitrovica, 1996; Lambeck et al., 1998; Mitrovica and Forte, 2004) have converged to estimates with a mean upper mantle viscosity of ~2–5 × 10^{20} Pa s and mean lower mantle viscosity in the range 5–10 × 10^{21} Pa s. Accordingly, we performed a series of sea level simulations that adopted the two-cycle ice history described above, an upper mantle viscosity of 5×10^{20} Pa s, and a constant lower mantle viscosity that was progressively increased from 5 to 10 × 10^{21} Pa s. These models all provided improved fits to the San Nicolas Island observations – as an example, the relative sea-level history at this site predicted with a lower mantle viscosity of 8×10^{21} Pa s (henceforth, viscosity model LM) is shown in Fig. 13A (solid red line). In accord with the observations discussed above, this model yields high stands above

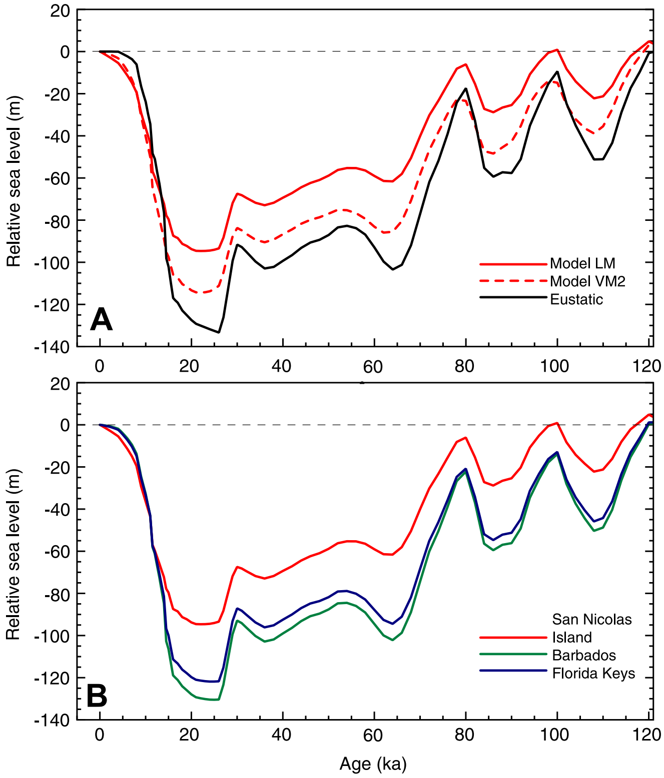


Fig. 13. Numerical predictions of relative sea-level change over the Last Interglacial–glacial cycle based on the ice history described in the text. (A) Predictions at San Nicolas Island based on the radial viscosity profiles (dashed red line) VM2 or (solid red line) LM. The black line is the eustatic sea-level curve for the adopted ice history. (B) Predictions at (red line) San Nicolas Island, (blue line) Florida Keys and (green line) Barbados.

sea level during the Last Interglacial and at 100 ka, and ∼10 m below sea level at 80 ka (Fig. 12).

In Fig. 13B we replot the model LM prediction at San Nicolas Island and include additional predictions for the Florida Keys (blue line) and Barbados (green line). The results for the latter two sites are also in excellent agreement with observational constraints. Specifically, relative sea level at the Florida Keys site is above present at the Last Interglacial and significantly below present at 80 ka (Fig. 12). Moreover, the predicted sea levels at both 100 ka and 80 ka on Barbados are approximately the same and close to 20 m below present sea level, consistent with field studies at this and other far-field sites cited in the Introduction (e.g., Potter et al., 2004; Schellmann et al., 2004; Thompson and Goldstein, 2005).

The predicted sea-level history for the Florida Keys and, in particular Barbados, more closely follow the eustatic curve associated with the model ice history than the prediction for San Nicolas Island. Thus, San Nicolas Island, which is ∼1500 km and ∼1800 km from the closest margins of the Cordilleran and Laurentide ice sheets during the last glacial period, is nevertheless subject to a significant GIA-induced sea-level perturbation. The details of the prediction will, of course, depend on assumptions related to the ice history and Earth model and our particular choices for these inputs may not be unique. However, the important conclusion is that the discrepancy between the observed elevation of high sea stands at this site, relative to the others, which is approximately +15 to +20 m at both 80 ka and 100 ka, and which leads to a high stand above present sea level at 100 ka, is a result of the imprint of glacial isostatic adjustment.

4.4. *Implications for tectonic geomorphology*

Marine terraces have long been attractive to geomorphologists seeking evidence of Quaternary tectonic activity, particularly uplift. In addition to recording uplift, emergent marine terraces also can provide information on local or regional structures. Because marine terraces begin as essentially horizontal surfaces in a shore-parallel sense, evidence of folding, faulting or differential uplift can be documented by careful measurement of terrace elevations combined with accurate dating. In the absence of materials suitable for dating, geomorphologists have devised methods for graphical correlation of suites of marine terraces with a “global” sea level curve. Virtually all of these schemes assume that the detailed paleo-sea level record of the Huon Peninsula of New Guinea (Chappell and Shackleton, 1986) is a faithful representation of global, eustatic sea level change. Indeed, Lajoie (1986) stated that dating of a marine terrace suite was reduced simply to correlating the undated landforms with the appropriate peaks on the New Guinea sea level curve. Assuming the New Guinea sea level curve is a global eustatic record and that uplift rates have been constant in many parts of the world during the Quaternary, Bull (1985) proposed that dating of an entire suite of otherwise undated marine terraces could be accomplished solely by graphical means. In this method, the investigator assigns a given terrace an age and paleo-sea level corresponding to a possible correlative terrace on New Guinea. The resultant uplift rate, along with the New Guinea sea level curve, is used to plot inferred amounts of uplift for each other terrace. The process is repeated for different assumed ages of the original terrace chosen and different uplift rates. The plot that yields the best linear array of points on an inferred uplift vs. age plot is interpreted to be the correct correlation and uplift rate. In this method, once the “correct” uplift rate is identified, all terraces in the suite are dated simultaneously. The technique and variations of it have been applied to undated or partially dated terrace sequences in New Zealand (Bull and Cooper, 1986), northern California (Merritts and Bull, 1989), central California (Hanson et al., 1994), southern California (Trecker et al., 1998), Mexico (Mayer and Vincent, 1999) and Italy (Calanchi et al., 2002). Many of these localities are in mid-latitude regions of the Northern Hemisphere where GIA effects can and should be expected. Recognition that there is no “global” eustatic sea level curve, due to GIA processes, means that use of the New Guinea “global” sea level curve will likely yield spurious correlations that may not be apparent to the unwary researcher. In principle, the approach could work for those far-field regions that can be assumed to have had a similar relative sea level history as New Guinea. Nevertheless, it is likely that virtually all mid-latitude and high-latitude regions in the Northern Hemisphere have had relative sea level histories that differ from those on New Guinea due to GIA processes from the Laurentide, Cordilleran and Fennoscandian ice sheets.

4.5. *Implications for paleozoogeography*

Our results have important implications for inferences about marine paleotemperatures based on the terrace faunas of the Pacific Coast. We observe that terrace 1 on San Nicolas Island has only corals dating to the ∼80 ka sea stand. Within the suite of exotic taxa on this terrace, most are northern extralimital and northward-ranging mollusks, similar to other ∼80 ka localities on the Pacific Coast (Kennedy et al., 1982; Muhs et al., 2002b, 2006), indicating cooler than modern waters. In contrast, terrace 2a (SNI-302 and 205) has no extralimital northern or northward-ranging species but has five southward-ranging species, indicating waters as warm or warmer than present. Terrace 2b on San Nicolas Island has corals dating to both the ∼100 ka and ∼120 ka sea stands, and hosts a mixture of extralimital northern or northward-ranging taxa and extralimital southern or southward-ranging taxa. As discussed above, we hypothesize that the southern species represent warmer conditions during the ∼120 ka sea stand (MIS 5.5) and the northern species represent cooler conditions during the ∼100 ka sea stand (MIS 5.3). It is difficult, however, to assess from marine terrace faunal data whether conditions on the Pacific Coast were cooler than present during MIS 5.3 at ∼100 ka, because terraces dating solely to this period are rare. Kennedy et al. (1992) report the occurrence of three terraces west of Santa Barbara that correlate to MIS 5.5, 5.3, and 5.1 on the basis of amino acid geochronology and minimum-limiting U-series ages on marine mammal bones. If their chronology is correct, then the faunal assemblages indicate cooler than present marine paleotemperatures during MIS 5.1 and 5.3, and warmer than present marine paleotemperatures during MIS 5.5, consistent with our interpretation. Nevertheless, lack of precise age control in the Kennedy et al. (1992) study makes this a less than-optimal test of our hypothesis. Unfortunately, we know of no other localities on the Pacific Coast where there is adequate dating of a marine terrace to ∼100 ka (MIS 5.3) along with a detailed molluscan fauna.

An alternative method of testing our paleotemperature reconstructions is to compare the marine terrace molluscan faunas with other marine fossil data. Planktonic foraminiferal assemblages provide an analogous proxy for marine paleotemperatures to terrace mollusks. Globally, planktonic foraminifera assemblages can be identified by distinct biogeographic zones (Bé, 1977). On the Pacific Coast, modern biogeographic zones of planktonic foraminifera are, from north to south, subarctic (Seward Peninsula of Alaska to central/southern British Columbia), transitional (central/southern British Columbia to southern Baja California), subtropical (a limited zone off southern Baja California, but also including a much larger area farther offshore), and tropical (southern Baja California to southern Peru). The southern California coast is dominated at present by the transitional assemblage, despite its mid-latitude location, because of the influence of the cool, southward-flowing California Current and upwelling of cold water offshore (Kennett and Venz, 1995). The most complete planktonic foramineral record of paleoclimate off southern California is that from ODP Site 893A (Fig. 9) in the Santa Barbara Basin (Kennett and Venz, 1995; Hendy, 2010). A 196-m-long core from this basin has a sediment record of the past ∼160 ka, extending well into MIS 6. Planktonic foraminifera from this core show that conditions as warm or warmer than present can be identified by the abundance of dextral-coiled *Neogloboquadrina pachyderma* (now referred to as *Neogloboquadrina incompta*; see Hendy, 2010) one of the dominant species today in Santa Barbara Basin. This species prefers water temperatures warmer than ∼10 °C (Kennett and Venz, 1995). In waters cooler than ∼10 °C, sinistral-coiled *N. pachyderma* increases in abundance, and is dominant in water temperatures cooler than ∼6 °C. In addition to *N. incompta*, there are four other warm-water species that are useful for paleoclimatic interpretations in the eastern Pacific Ocean, including *Globigerinoides ruber*, *Neogloboquadrina dutertrei*, *Globorotalia inflata*, and *Orbulina universa* (Kennett and Venz, 1995). Because they occur in much lower abundances than *N. incompta*, following Kennett and Venz (1995) and Hendy (2010), we have summed the individual percentages of *G. ruber*, *N. dutertrei*, *G. inflata*, and *O. universa* to attain an aggregate warm-water species abundance measure (in addition to percentages of *N. incompta*). Although the core from site 893A has been sampled and analyzed at a very high resolution by Hendy (2010), her record covers the period from ∼10 to ∼60 ka. Hence, here we use the lower-resolution, but longer record reported by Kennett and Venz (1995).

The Santa Barbara Basin record shows that MIS 1 and 5.5 are by far the warmest two periods of the past ∼160 ka (Fig. 14). Abundances of *N. incompta* reach maximum values during MIS 5.5 and the early Holocene (MIS 1). There are smaller peaks of this species occurring during MIS 3 and one unexplained peak during MIS 2. Nevertheless, MIS 6, 4 and most of MIS 2, all glacial periods, generally show low abundances of *N. incompta*. In addition, MIS 5.3 and 5.1 also show very low abundances of *N. incompta*, even lower than during MIS 3, considered to be an interstadial period. The other warm-water forms (*G. ruber*, *N. dutertrei*, *G. inflata*, and *O. universa*) show abundances that are consistent with *N. incompta*, with high values in MIS 5.5 and 1 and somewhat lower values in MIS 3. There is one peak within MIS 6 and another within MIS 2 that are unexplained, but otherwise MIS 6, 4, and 2 generally show low abundances of these warm-water taxa. Consistent with *N. incompta*, the other warm-water forms also show very low abundances during MIS 5.3 and 5.1. Overall, the planktonic foraminiferal record indicates conditions as warm or warmer than present in some parts of the Holocene (early MIS 1) and the peak of the Last Interglacial period (MIS 5.5). However, the record for MIS 5.3 and 5.1 indicates water temperatures off Santa Barbara much cooler than present.

In coastal California with its Mediterranean climate, vegetation on land is strongly influenced by ocean temperatures. Thus, records

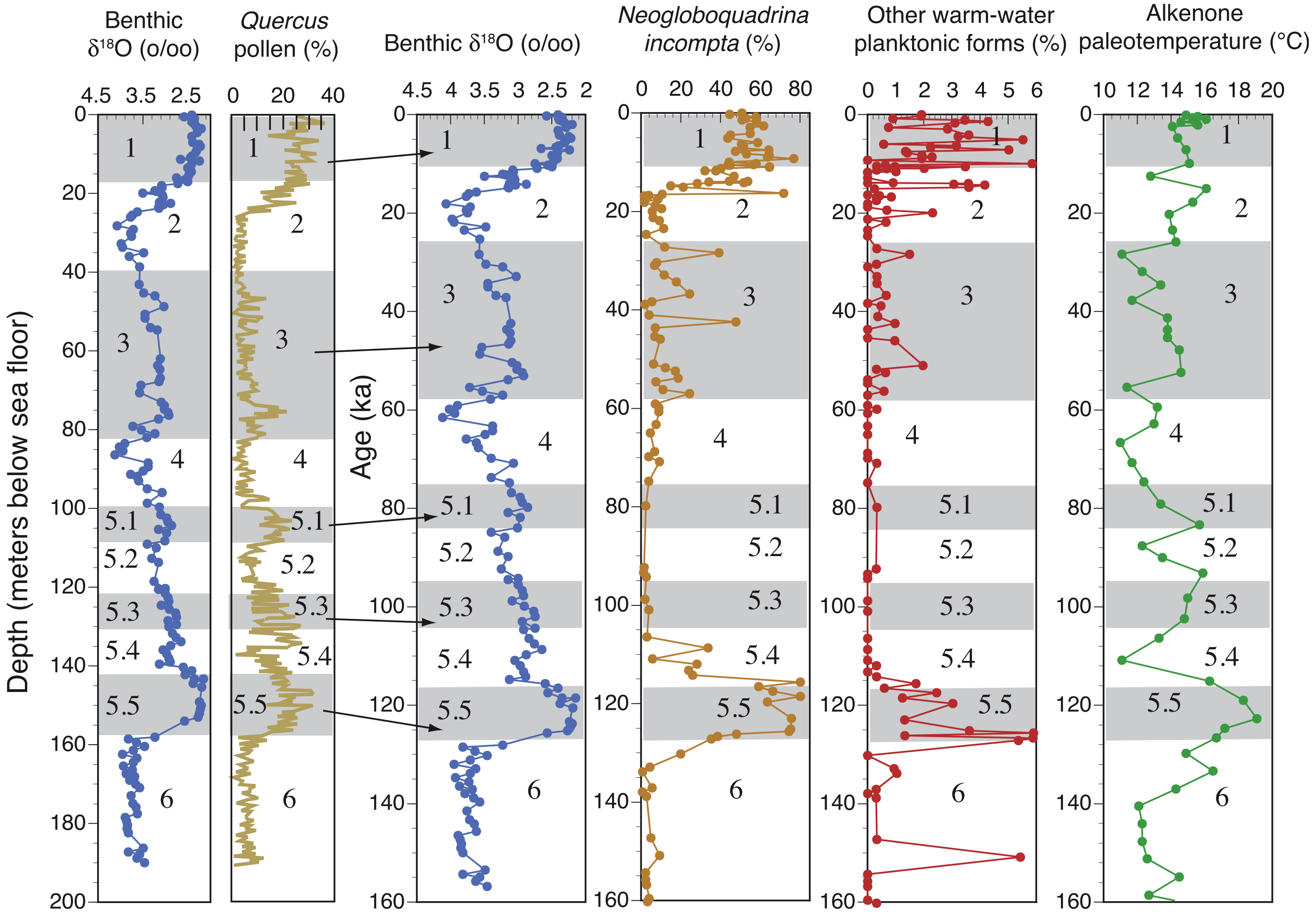


Fig. 14. Paleoclimate records from Santa Barbara Basin, from ODP hole 893A. Data from Heusser (1995, 2000) for pollen; Kennett (1995) and Kennett and Venz (1995) for chronology and all foraminifera data; and Herbert et al. (1995, 2001) for alkenones.

of past vegetation on land reflect, to a great degree, past climates that were influenced by paleotemperatures of the ocean. A good example of this is the modern oak-grass woodland (with trees dominated by *Quercus agrifolia* and *Q. dumosa*) of coastal southern and central California. This biome is limited to low elevations on the coast with moderate temperatures year-round. It is not present at high elevations in coastal mountains and is absent from the interior deserts, as well as from cooler coastal regions of northern California and warmer regions of coastal Baja California (Thompson et al., 1999; Heusser, 2000). At higher elevations in the coastal mountains of southern California, where temperatures are lower and precipitation is higher, coniferous vegetation becomes more important than oak and grass. Thus, the pollen record in ODP Hole 893A in the Santa Barbara Basin (Heusser, 1995, 2000) is highly complementary to the planktonic foraminiferal record for paleotemperatures. Furthermore, because the pollen record integrates grains from a broad area draining to Santa Barbara Basin, it can be viewed as a regional paleoclimatic record. The pollen record of oak (*Quercus* spp.) in 893A mirrors that of the warm-water species in the planktonic foraminiferal record (Fig. 14). MIS 5.5 and MIS 1 show the highest values of *Quercus* pollen and MIS 6, 4 and 2 show the lowest values. In contrast, glacial periods MIS 6, 4 and 2 have much higher abundances of *Pinus* pollen. Intermediate values of oak pollen are apparent in MIS 5.3, 5.1, and 3. Heusser (2000) interprets the record of *Quercus* pollen in Santa Barbara Basin to be primarily a paleotemperature indicator. Her data indicate, therefore, that MIS 5.3 and 5.1 were cooler than both MIS 5.5 and the Holocene.

The alkenone paleotemperature record from Santa Barbara Basin (Herbert et al., 1995, 2001) is not entirely consistent with the planktonic foraminiferal and pollen records (Fig. 14). In this record, MIS 5.5 is again the warmest period of the past ~160 ka, and MIS 6 and 4 are relatively cold, but unlike the planktonic foraminiferal record, MIS 5.3 and 5.1 appear as warm periods. In addition, however, the alkenone record shows a warm peak during MIS 2, and MIS 2 itself is not particularly cool compared to other periods of the past ~160 ka. Hendy (2010) also noted the disagreement between planktonic foraminiferal records and alkenone records of the past 60 ka in cores off southern California. She indicates that part of the apparent discrepancy in the two records may be a function of differences in the seasonal responses of the two records.

Considering the planktonic foraminiferal and pollen records that are consistent with each other as paleotemperature indicators, relatively warm-water conditions are implied for MIS 5.5 and 1, both interglacial periods, and much cooler waters during MIS 6, 4, and 2, all glacial periods. MIS 5.3 and 5.1 appear as relatively cool periods as well, certainly cooler than both MIS 5.5 and 1. Following Kennett and Venz (1995), we interpret cooler than modern waters along the southern California coast to be the result of a strengthening of the cold, southward-moving California Current (Fig. 9). In contrast, warmer than modern waters likely result from a weaker California Current, with perhaps a strengthening of the warm, northward-moving Inshore Current.

If our interpretations of the planktonic foraminiferal and pollen records are correct, then cooler than present waters off southern California should be seen in marine terrace faunas during both MIS 5.3 and 5.1 and warmer than present waters should be seen in marine terrace faunas that date to MIS 5.5. Viewed in this context, the mixture of southern and northern mollusks on terrace 2b on San Nicolas Island is consistent with the mixture of ~120 and ~100 ka corals. Furthermore, a similar mixing of terrace faunas should be expected in those areas where the uplift rate is low enough that the ~120 ka terrace was not raised tectonically to a sufficiently high elevation to escape the ~100 ka sea stand. In addition to Cayucos and Point Loma, discussed earlier, other localities in California and Baja California have evidence of possible mixing of ~120 ka and ~100 ka faunas. In the Newport Bay area, Grant et al. (1999) report a U-series age of ~120 ka on a single coral from a 32–35-m-high terrace. Examination of the fossil mollusk record of this terrace, reported by Kanakoff and Emerson (1959), using updated zoogeographic information, shows that there are abundant extralimital southern species (perhaps as many as 16 extralimital bivalve species alone). Nevertheless, there are also a number of extralimital northern species as well, including at least three bivalves (*Macoma inquinata*, *Patinopecten caurinus*, and *Modiolus modiolus*) whose modern southern range endpoints are well to the north of Newport Bay. Other localities on the Pacific Coast where mixtures of northern and southern species occur in low-elevation terraces thought to be of Last Interglacial age include San Luis Obispo County (Kennedy, 2000) and Santa Barbara Island, California (Lipps et al., 1968), as well as Camalú (Valentine, 1980), San Quintin (Valentine and Meade, 1961), and Bahía Tortugas, Baja California (Emerson et al., 1981), over a north-south coastal distance of more than ~1000 km. The mixture of northern and southern species is not limited to terraces from the Last Interglacial complex, either. Vedder and Norris (1963) report mixtures of northern and southern forms in deposits from the 5th, 8th, and 10th terraces on San Nicolas Island. Thus, in areas of modest uplift rate, reoccupation of terraces by younger sea stands may have taken place during at least four interglacial complexes of the Quaternary. We conclude, therefore, that reconstruction of marine paleotemperatures and correlation of marine terraces using faunal data must take into account the possibility that an individual terrace deposit may represent more than one sea stand and that paleotemperatures differed during sea stands.

5. Conclusions

(1) Of the 14 marine terraces mapped by Vedder and Norris (1963) on San Nicolas Island, one of the best expressed geomorphically is terrace 2. Detailed study of this terrace reveals it is composed of two marine platforms, a broad (200–400 m), well-preserved surface (terrace 2b) on the seaward side with shoreline angle elevations of 28–33 m, and isolated fragments of a narrow (5–10 m), higher terrace (terrace 2a) on the landward side, with shoreline angle elevations of 36–38 m. Terrace 1 is the lowest terrace of all and is cut into terrace 2b, with shoreline angle elevations of 8–13 m.

(2) Uranium-series dating shows that many corals have experienced open-system conditions with respect to U and its long-lived daughter products. Nevertheless, consideration of open-system models that have been developed, along with those corals that show closed-system behavior, indicate that three ages of corals are present: ~120 ka on terrace 2a, ~120 and ~100 ka on terrace 2b, and ~80 ka on terrace 1. These ages correspond to MIS 5.5, 5.3, and 5.1 of the Last Interglacial complex, respectively. We consider that corals on terrace 2b that date to ~120 ka were reworked from a formerly broader terrace 2a during the ~100 ka sea stand.

(3) Recent studies on the island of Barbados indicate that two or three terraces may have formed during suborbital-scale fluctuations of sea level, during MIS 5.5, 5.3, and 5.1. On San Nicolas Island, there is no geomorphic evidence for more than one marine terrace during each of these sea stands. Nevertheless, the apparent difference in sea level records from the two islands may be explained by the fact that on Barbados, terraces are constructional landforms composed of the rapidly growing colonial coral *Acropora palmata*. These terraces form as "keep-up" reefs during each rise in sea level and thus minor

fluctuations in sea level may be recorded rapidly. In contrast, marine terraces on San Nicolas Island are erosional landforms and evidence of a previous high stand may be removed during a subsequent sea stand if there was little time in between.

(4) Fossil molluscan assemblages on San Nicolas Island show distinct differences on the three Last Interglacial terraces, with mostly neutral or southward-ranging species on isolated fragments of terrace 2a, extralimital southern and extralimital northern species on terrace 2b, and extralimital northern species on terrace 1. If, like the corals, many of the mollusks on terrace 2b were reworked from a formerly more extensive terrace 2a, then the extralimital southern species (warmer than present waters) are interpreted to be from the ~120 ka sea stand and the extralimital northern species (cooler than present waters) are interpreted to be from the ~100 ka sea stand. Terrace 1 contains abundant extralimital northern species, indicating cooler than present waters at ~80 ka. These paleoclimatic interpretations are consistent with the planktonic foraminiferal and pollen records from nearby Santa Barbara Basin. Higher, older terraces on San Nicolas Island also contain mixtures of extralimital southern and northern species, indicating that fossil mixing probably has occurred during other interglacial periods of the Quaternary.

(5) With terrace 2a representing the peak of the Last Interglacial period at ~120 ka, and assuming that sea level was ~6 m higher than present at that time, we calculate late Quaternary uplift rates of ~0.25–0.27 m/ka. These uplift rates, along with shoreline angle elevations and ages of terrace 2b (~100 ka) and terrace 1 (~80 ka), yield relative (local) paleo-sea level elevations of +2 to +6 m for the ~100 ka sea stand and −11 to −12 m for the ~80 ka sea stand. A higher than present sea stand at ~100 ka explains how the terrace cut during the ~120 ka high stand was eroded landward and many of its fossils reworked onto a younger terrace.

(6) Our paleo-sea level estimates for the ~100 ka and ~80 ka sea stands on San Nicolas Island are higher, however, than those estimated for the ~100 ka and ~80 ka sea stands on New Guinea, Barbados and (at 80 ka) for the Florida Keys. We have demonstrated that these differences, and the absolute elevations of the sea stands, are a consequence of the departure from eustasy of the geographically variable signal from glacial isostatic adjustment. Indeed, our modeling suggests that the elevations serve as a useful constraint on ice volume fluctuations during this interval and on the radial profile of viscosity within the Earth's mantle.

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References

Abbott, D.F., Haderlie, E.C., 1980. Prosobranchia: marine snails. In: Morris, R.H., Abbott, D.P., Haderlie, E.C. (Eds.), Intertidal Invertebrates of California. Stanford University Press, Stanford, pp. 230–307.

Abbott, R.T., 1974. American Seashells: the Marine Mollusca of the Atlantic and Pacific Coasts of North America, second ed. Van Nostrand Reinhold Company, New York, 633 pp.

Alexander, C.S., 1953. The Marine and Stream Terraces of the Capitola-Watsonville Area. University of California Publications in Geography, vol. 10. 1–44 pp.

Arnold, R., 1903. The paleontology and stratigraphy of the marine Pliocene and Pleistocene of San Pedro, California: Memoirs of the California Academy of Sciences, vol. 3, 420 pp.

Bard, E., Hamelin, B., Fairbanks, R.G., 1990. U-Th ages obtained by mass spectrometry in corals from Barbados: sea level during the past 130,000 years. Nature 346, 456–458.

Bé, A.W.H., 1977. An ecological, zoogeographic and taxonomic review of recent planktonic foraminifera. In: Ramsay, A.T.S. (Ed.), Oceanic Micropalaeontology. Academic Press, London, pp. 1–100.

Blanchon, P., Eisenhauer, A., Fietzke, J., Liebetrau, V., 2009. Rapid sea-level rise and reef back-stepping at the close of the last interglacial highstand. Nature 458, 881–885.

Bloom, A.L., Broecker, W.S., Chappell, J.M.A., Matthews, R.K., Mesolella, K.J., 1974. Quaternary sea level fluctuations on a tectonic coast: new ^{230}Th/^{234}U dates from the Huon Peninsula, New Guinea. Quaternary Research 4, 185–205.

Bock, Y., Bear, J., Fang, P., Dean, J., Leigh, R., 1997. Scripps Orbit and Permanent Array center (SOPAC) and Southern Californian Permanent Geodetic Array (PGGA). In: The Global Positioning System for Geosciences. National Academy Press, Washington, D.C., pp. 55–61.

Broecker, W.S., Thurber, D.L., Goddard, J., Ku, T.-L., Matthews, R.K., Mesolella, K.J., 1968. Milankovitch hypothesis supported by precise dating of coral reefs and deep-sea sediments. Science 159, 297–300.

Bull, W.B., 1985. Correlation of flights of global marine terraces. In: Morisawa, M., Hack, J.T. (Eds.), Tectonic Geomorphology. Allen & Unwin, Boston, pp. 129–152.

Bull, W.B., Cooper, A.F., 1986. Uplifted marine terraces along the Alpine fault, New Zealand. Science 234, 1225–1228.

Calanchi, N., Lucchi, F., Pirazzoli, P.A., Romagnoli, C., Tranne, C.A., Radtke, U., Reyss, J.L., Rossi, P.L., 2002. Late Quaternary relative sea-level changes and vertical movements at Lipari (Aeolian Islands). Journal of Quaternary Science 17, 459–467.

Chappell, J., 1974. Geology of coral terraces, Huon Peninsula, New Guinea: a study of Quaternary tectonic movements and sea-level changes. Geological Society of America Bulletin 85, 553–570.

Chappell, J., Shackleton, N.J., 1986. Oxygen isotopes and sea level. Nature 324, 137–140.

Chappell, J., Veeh, H.H., 1978. Late Quaternary tectonic movements and sea-level changes at Timor and Atauro Island. Geological Society of America Bulletin 89, 356–368.

Chen, J.H., Edwards, R.L., Wasserburg, G.J., 1986. ^{238}U, ^{234}U, and ^{232}Th in seawater. Earth and Planetary Science Letters 80, 241–251.

Cheng, H., Edwards, R.L., Hoff, J., Gallup, C.D., Richards, D.A., Asmerom, Y., 2000. The half-lives of uranium-234 and thorium-230. Chemical Geology 169, 17–33.

Clark, R.N., 1999. The *Tonicella lineata* (Wood, 1815) species complex (Polyplacophora: Tonicellidae), with descriptions of two new species. American Malacological Bulletin 15, 33–46.

Coan, E.V., Scott, P.V., Bernard, F.R., 2000. Bivalve Seashells of Western North America: Marine Bivalve Mollusks from Arctic Alaska to Baja California. Santa Barbara Museum of Natural History Monographs, Issue 2. Santa Barbara, 764 pp.

Cutler, K.B., Edwards, R.L., Taylor, F.W., Cheng, H., Adkins, A., Gallup, C.D., Cutler, P.M., Burr, G.S., Bloom, A.L., 2003. Rapid sea-level fall and deep-ocean temperature change since the last interglacial period. Earth and Planetary Science Letters 206, 253–271.

Dodge, R.E., Fairbanks, R.G., Benninger, L.K., Maurrasse, F., 1983. Pleistocene sea levels from raised coral reefs of Haiti. Science 219, 1423–1425.

Edwards, R.L., Cheng, H., Murrell, M.T., Goldstein, S.J., 1997. Protactinium-231 dating of carbonates by thermal ionization mass spectrometry: implications for Quaternary climate change. Science 276, 782–786.

Eernisse, D.J., Clark, R.N., Draeger, A., 2007. Polyplacophora. In: Carlton, J.T. (Ed.), The Light and Smith Manual: Intertidal Invertebrates from Central California to Oregon, fourth ed. University of California Press, pp. 701–713.

Emerson, W.K., 1956. Upwelling and associated marine life along Pacific Baja California, Mexico. Journal of Paleontology 30, 393–397.

Emerson, W.K., Kennedy, G.L., Wehmiller, J.F., Keenan, E., 1981. Age relations and zoogeographic implications of late Pleistocene marine invertebrate faunas from Turtle Bay, Baja California Sur, Mexico. The Nautilus 95, 105–116.

Flores-Rodríguez, P., Flores-Garza, R., García-Ibáñez, S., Valdés-González, A., 2007. Variación en la diversidad malacológica del mesolitoral rocoso en Playa Troncones, La Unión, Guerrero, México. Revista Mexicana de Biodiversidad 78, 33S–40S.

Gallup, C.D., Edwards, R.L., Johnson, R.G., 1994. The timing of high sea levels over the past 200,000 years. Science 263, 796–800.

Gerrodette, T., 1979. Equatorial submergence in a solitary coral, *Balanophyllia elegans*, and the critical life stage excluding the species from shallow water in the south. Marine Ecology-Progress Series 1, 227–235.

Gonzalez-Garcia, J.J., Prawirodirdjo, L., Bock, Y., Agnew, D., 2003. Guadalupe Island, Mexico as a new constraint for Pacific plate motion. Geophysical Research Letters 30 (16), 1872. doi:10.1029/2003GL017732.

Grant, L.B., Mueller, K.J., Gath, E.M., Cheng, H., Edwards, R.L., Munro, R., Kennedy, G.L., 1999. Late Quaternary uplift and earthquake potential of the San Joaquin Hills, southern Los Angeles Basin, California. Geology 27, 1031–1034.

Haderlie, E.C., Abbott, D.P., 1980. Polyplacophora: the chitons. In: Morris, R.H., Abbott, D.P., Haderlie, E.C. (Eds.), Intertidal Invertebrates of California. Stanford University Press, Stanford, pp. 412–494.

Hanson, K.L., Wesling, J.R., Lettis, W.R., Kelson, K.I., Mezger, L., 1994. Correlation and ages of Quaternary marine terraces, south-central coastal California. In: Alterman, I.B., McMullen, R.B., Cluff, L.S., Slemmons, D.B. (Eds.), Seismotectonics of the Central California Coast Ranges. Geological Society of America Special Paper, vol. 292, pp. 45–71.

Harmon, R.S., Schwarcz, H.P., Ford, D.C., 1978. Late Pleistocene sea level history of Bermuda. Quaternary Research 9, 205–218.

Harmon, R.S., Mitterer, R.M., Kriausakul, N., Land, L.S., Schwarcz, H.P., Garrett, P., Larson, G.J., Vacher, H.L., Rowe, M., 1983. U-series and amino-acid racemization geochronology of Bermuda: implications for eustatic sea-level fluctuation over the past 250,000 years. Palaeogeography, Palaeoclimatology, Palaeoecology 44, 41–70.

Hendy, I.L., 2010. The paleoclimatic response of the southern Californian margin to the rapid climate change of the last 60 ka: a regional overview. Quaternary International 215, 62–73.

Herbert, T.D., Yasuda, M., Burnett, C., 1995. Glacial-interglacial sea-surface temperature record inferred from alkenone unsaturation indicies, site 893, Santa Barbara Basin. In: Kennett, J.P., Baldauf, J.G., Lyles, M. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results, vol. 146 (Part 2), pp. 257–264.

Herbert, T.D., Schuffert, J.D., Andreasen, D., Heusser, L., Lyle, M., Mix, A., Ravelo, A.C., Stott, L.D., Herguera, J.C., 2001. Collapse of the California Current during glacial maxima linked to climate change on land. Science 293, 71–76.

Heusser, L.E., 1995. Pollen stratigraphy and paleoecologic interpretation of the 160-k.y. record from Santa Barbara Basin, Hole 893A. In: Kennett, J.P., Baldauf, J.G., Lyle, M. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results, vol. 146 (pt. 2), pp. 265–279.

Heusser, L.E., 2000. Rapid oscillations in western North America vegetation and climate during oxygen isotope stage 5 inferred from pollen data from Santa Barbara Basin (Hole 893A). Palaeogeography, Palaeoclimatology, Palaeoecology 161, 407–421.

Kanakoff, G.P., Emerson, W.K., 1959. Late Pleistocene Invertebrates of the Newport Bay Area, California. Los Angeles County Museum Contributions in Science, no. 31. 47 pp.

Kanter, R.G., 1980. Biogeographic patterns in mussel community distribution from the Southern California Bight. In: Power, D.M. (Ed.), The California Islands: Proceedings of a Multidisciplinary Symposium. Santa Barbara Museum of Natural History, Santa Barbara, pp. 341–355.

Keen, A.M., 1971. Sea Shells of Tropical West America-Marine Mollusks from Baja California to Peru, second ed. Stanford University Press, Stanford, California, 1064 pp.

Kendall, R.A., Mitrovica, J.X., Milne, G.A., 2005. On post-glacial sea level - II. Numerical formulation and comparative results on spherically symmetric models. Geophysical Journal International 161, 679–706.

Kennedy, G.L., 2000. Zoogeographic correlation of marine invertebrate faunas. In: Noller, J.S., Sowers, J.M., Lettis, W.R. (Eds.). Quaternary Geochronology: American Geophysical Union Reference Shelf, vol. 4, pp. 413–424.

Kennedy, G.L., Lajoie, K.R., Wehmiller, J.F., 1982. Aminostratigraphy and faunal correlations of late Quaternary marine terraces, Pacific Coast, USA. Nature 299, 545–547.

Kennedy, G.L., Wehmiller, J.F., Rockwell, T.K., 1992. Paleoecology and paleozoogeography of late Pleistocene marine-terrace faunas of southwestern Santa Barbara County, California. In: Fletcher III, C.H., Wehmiller, J.F. (Eds.), Quaternary Coasts of the United States: Marine and Lacustrine Systems. SEPM (Society for Sedimentary Geology) Special Publication, no. 48, pp. 343–361.

Kennett, J.P., 1995. Latest Quaternary benthic oxygen and carbon isotope stratigraphy: hole 893A, Santa Barbara Basin, California. In: Kennett, J.P., Baldauf, J.G., Lyles, M. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results, vol. 146 (Part 2), pp. 3–18.

Kennett, J.P., Venz, K., 1995. Late Quaternary climatically related planktonic foraminiferal assemblage changes: hole 893A, Santa Barbara Basin, California. In: Kennett, J.P., Baldauf, J.G., Lyles, M. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results, vol. 146 (Part 2), pp. 281–293.

Kern, J.P., 1971. Paleoenvironmental analysis of a late Pleistocene estuary in southern California. Journal of Paleontology 45, 810–823.

Kern, J.P., 1977. Origin and history of upper Pleistocene marine terraces, San Diego, California. Geological Society of America Bulletin 88, 1553–1566.

Kopp, R.E., Simons, F.J., Mitrovica, J.X., Maloof, A.C., Oppenheimer, M., 2009. Probabilistic assessment of sea level during the last interglacial stage. Nature 462, 863–868.

Ku, T.-L., Kern, J.P., 1974. Uranium-series age of the upper Pleistocene Nestor terrace, San Diego, California. Geological Society of America Bulletin 85, 1713–1716.

Lajoie, K.R., 1986. Coastal tectonics. In: Wallace, R. (Ed.), Active Tectonics. National Academy Press, Washington, pp. 95–124.

Lajoie, K.R., Ponti, D.J., Powell II, C.L., Mathieson, S.A., Sarna-Wojcicki, A.M., 1991. Emergent marine strandlines and associated sediments, coastal California; A record of Quaternary sea-level fluctuations, vertical tectonic movements, climatic changes, and coastal processes. In: Morrison, R.B. (Ed.), Quaternary Nonglacial Geology; Conterminous U.S. The Geology of North America, vol. K-2. Geological Society of America, Boulder, Colorado, pp. 190–203.

Lambeck, K., Nakada, M., 1992. Constraints on the age and duration of the last interglacial period and on sea-level variations. Nature 357, 125–128.

Lambeck, K., Smither, C., Johnston, P., 1998. Sea-level change, glacial rebound and mantle viscosity for northern Europe. Geophysical Journal International 134, 102–144.

Lindberg, D.R., Roth, B., Kellogg, M.G., Hubbs, C.L., 1980. Invertebrate megafossils of Pleistocene (Sangamon interglacial) age from Isla de Guadalupe, Baja California, Mexico. In: Power, D.M. (Ed.), The California Islands: Proceedings of a Multidisciplinary Symposium. Santa Barbara Museum of Natural History, Santa Barbara, pp. 41–62.

Lipps, J.E., Valentine, J.W., Mitchell, E., 1968. Pleistocene paleoecology and biostratigraphy, Santa Barbara Island, California. Journal of Paleontology 42, 291–307.

Littler, M.M., 1980. Overview of the rocky intertidal systems of southern California. In: Power, D.M. (Ed.), The California Islands: Proceedings of a Multidisciplinary Symposium. Santa Barbara Museum of Natural History, Santa Barbara, pp. 265–306.

Ludwig, K.R., 2001. Users Manual for Isoplot/Ex, Rev. 2.49. Berkeley Geochronology Center, Berkeley, California, Special Publication No. 1a, 55 pp.

Ludwig, K.R., Simmons, K.R., Szabo, B.J., Winograd, I.J., Landwehr, J.M., Riggs, A.C., Hoffman, R.J., 1992. Mass-spectrometric ^{230}Th-^{234}U-^{238}U dating of the Devils Hole calcite vein. Science 258, 284–287.

Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, J., Moore Jr., T.C., Shackleton, N.J., 1987. Age dating and the orbital theory of the ice ages: development of a high-resolution 0 to 300,000-year chronostratigraphy. Quaternary Research 27, 1–29.

Martz, P.C., 2005. Prehistoric settlement and subsistence on San Nicolas Island. In: Garcelon, D.K., Schwemm, C.A. (Eds.), Proceedings of the Sixth California Islands Symposium, Ventura, California, December 1–3, 2003. Arcata, California: Institute for Wildlife Studies and National Park Service, pp. 65–82.

Matthews, R.K., 1973. Relative elevation of late Pleistocene high sea level stands: Barbados uplift rates and their implications. Quaternary Research 3, 147–153.

Mayer, L., Vincent, K.R., 1999. Active tectonics of the Loreto area, Baja California Sur, Mexico. Geomorphology 27, 243–255.

McLean, J.H., 1978. Marine Shells of Southern California. Natural History Museum of Los Angeles County Science Series, no. 24 (revised), 104 pp.

McLean, J.H., 2007. Gastropoda. In: Carlton, J.T. (Ed.), The Light and Smith Manual: Intertidal Invertebrates from Central California to Oregon, fourth ed. University of California Press, pp. 713–753.

Merritts, D., Bull, W.B., 1989. Interpreting Quaternary uplift rates at the Mendocino triple junction, northern California, from uplifted marine terraces. Geology 17, 1020–1024.

Mesolella, K.J., Matthews, R.K., Broecker, W.S., Thurber, D.L., 1969. The astronomical theory of climatic change: Barbados data. Journal of Geology 77, 250–274.

Milne, G.A., Mitrovica, J.X., 2008. Searching for eustasy in deglacial sea-level histories. Quaternary Science Reviews 27, 2292–2302.

Mitrovica, J.X., 1996. Haskell [1935] revisited. Journal of Geophysical Research 101, 555–569.

Mitrovica, J.X., Forte, A.M., 2004. A new inference of mantle viscosity based upon joint inversion of convection and glacial isostatic adjustment data. Earth and Planetary Science Letters 225, 177–189.

Mitrovica, J.X., Milne, G.A., 2002. On the origin of late Holocene sea-level highstands within equatorial ocean basins. Quaternary Science Reviews 21, 2179–2190.

Mitrovica, J.X., Milne, G.A., 2003. On post-glacial sea level: I. General theory. Geophysical Journal International 154, 253–267.

Mitrovica, J.X., Peltier, W.R., 1991. On postglacial geoid subsidence over the equatorial oceans. Journal of Geophysical Research 96, 20053–20071.

Mitrovica, J.X., Wahr, J., Matsuyama, I., Paulson, A., 2005. The rotational stability of an ice age Earth. Geophysical Journal International 161, 491–506.

Muhs, D.R., 1985. Amino acid age estimates of marine terraces and sea levels, San Nicolas Island, California. Geology 13, 58–61.

Muhs, D.R., Rosholt, J.N., Bush, C.A., 1989. The uranium-trend dating method: principles and application to southern California marine terrace deposits. Quaternary International 1, 19–34.

Muhs, D.R., Kennedy, G.L., Rockwell, T.K., 1994. Uranium-series ages of marine terrace corals from the Pacific coast of North America and implications for last-interglacial sea level history. Quaternary Research 42, 72–87.

Muhs, D.R., Miller, G.H., Whelan, J.F., Kennedy, G.L., 1992. Aminostratigraphy and oxygen isotope stratigraphy of marine-terrace deposits, Palos Verdes Hills and San Pedro areas, Los Angeles County, California. In: Fletcher III, C.H., Wehmiller, J.F. (Eds.), Quaternary Coasts of the United States: Marine and Lacustrine Systems. SEPM (Society for Sedimentary Geology) Special Publication, no. 48, pp. 363–376.

Muhs, D.R., Simmons, K.R., Steinke, B., 2002a. Timing and warmth of the last interglacial period: new U-series evidence from Hawaii and Bermuda and a new fossil compilation for North America. Quaternary Science Reviews 21, 1355–1383.

Muhs, D.R., Simmons, K.R., Kennedy, G.L., Rockwell, T.K., 2002b. The last interglacial period on the Pacific Coast of North America: timing and paleoclimate. Geological Society of America Bulletin 114, 569–592.

Muhs, D.R., Wehmiller, J.F., Simmons, K.R., York, L.L., 2004. Quaternary sea level history of the United States. In: Gillespie, A.R., Porter, S.C., Atwater, B.F. (Eds.), The Quaternary Period in the United States. Elsevier, Amsterdam, pp. 147–183.

Muhs, D.R., Simmons, K.R., Kennedy, G.L., Ludwig, K.R., Groves, L.T., 2006. A cool eastern Pacific Ocean at the close of the last interglacial complex. Quaternary Science Reviews 25, 235–262.

Muhs, D.R., Skipp, G., Schumann, R.R., Johnson, D.L., McGeehin, J.P., Beann, J., Freeman, J., Pearce, T.A., Rowland, Z.M., 2009. The origin and paleoclimatic significance of carbonate sand dunes deposited on the California Channel Islands during the last glacial period. In: Damiani, C.C., Garcelon, D.K. (Eds.), Proceedings of the 7th California Islands Symposium. Arcata, California: Institute for Wildlife Studies, pp. 3–14.

Muhs, D.R., Simmons, K.R., Schumann, R.R., Groves, L.T., DeVogel, S., Patterson, D., Richards, D.V., 2010. Last interglacial sea-level history on Santa Barbara and Anacapa Islands, Channel Islands National Park, California. Geological Society of America Abstracts with Programs 42 (5), 563.

Muhs, D.R., Simmons, K.R., Schumann, R.R., Halley, R.B., 2011. Sea-level history of the past two interglacial periods: new evidence from U-series dating of reef corals from south Florida. Quaternary Science Reviews 30, 570–590.

Murray-Wallace, C.V., 2002. Pleistocene coastal stratigraphy, sea-level highstands and neotectonism of the southern Australian passive continental margin – a review. Journal of Quaternary Science 17, 469–489.

Murray-Wallace, C.V., Belperio, A.P., 1991. The last interglacial shoreline in Australia – a review. Quaternary Science Reviews 10, 441–461.

Nakada, M., Lambeck, K., 1989. Late Pleistocene and Holocene sea-level change in the Australian region and mantle rheology. Geophysical Journal International 96, 497–517.

Neumann, A.C., Moore, W.S., 1975. Sea level events and Pleistocene coral ages in the northern Bahamas. Quaternary Research 5, 215–224.

O'Clair, R.M., O'Clair, C.E., 1998. Southeast Alaska's Rocky Shores: Animals. Plant Press, Auke Bay, Alaska, 561 pp.

Omura, A., 1983. Uranium-series ages of some solitary corals from the Riukiu Limestone on the Kikai-Mima, Ryukyu Islands. Transactions and Proceedings of the Palaeontological Society of Japan 130, 117–122.

Ota, Y., Omura, A., 1992. Contrasting styles and rates of tectonic uplift of coral reef terraces in the Ryukyu and Daito Islands, southwestern Japan. Quaternary International 15/16, 17–29.

Peltier, W.R., 2004. Global glacial isostasy and the surface of the ice age Earth: the ICE-5G(VM2) model and GRACE. Annual Review of Earth and Planetary Sciences 32, 111–149.

Peltier, W.R., Fairbanks, R.G., 2006. Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record. Quaternary Science Reviews 25, 3322–3337.

Potter, E.-K., Lambeck, K., 2003. Reconciliation of sea-level observations in the western North Atlantic during the last glacial cycle. Earth and Planetary Science Letters 217, 171–181.

Potter, E.-K., Esat, T.M., Schellmann, G., Radtke, U., Lambeck, K., McCulloch, M.T., 2004. Suborbital-period sea-level oscillations during marine isotope substages 5a and 5c. Earth and Planetary Science Letters 225, 191–204.

Quiñones, O.E.H., Michel-Morfín, J.E., 2006. Population structure and accompanying biota of the snail *Turbo* (*Callopoma*) *funiculosus* (Gastropoda: Turbinidae), on Socorro Island, Revillagigedo Archipelago, Mexico. Revista de Biología Tropical 54, 1079–1084.

Radtke, U., Grün, R., Omura, A., Mangini, A., 1996. The Quaternary coral reef tracts of Hateruma, Ryukyu Islands, Japan. Quaternary International 31, 61–70.

Russell, M.P., 1991. Modern death assemblages and Pleistocene fossil assemblages in open coast high energy environments, San Nicolas Island, California. Palaios 6, 179–191.

Schellmann, G., Radtke, U., 2004. A revised morpho- and chronostratigraphy of the Late and Middle Pleistocene coral reef terraces on southern Barbados (West Indies). Earth-Science Reviews 64, 157–187.

Schellmann, G., Radtke, U., Potter, E.-K., Esat, T.M., McCulloch, M.T., 2004. Comparison of ESR and TIMS U/Th dating of marine isotope stage (MIS) 5e, 5c, and 5a coral from Barbados – implications for palaeo sea-level changes in the Caribbean. Quaternary International 120, 41–50.

Seapy, R.R., Littler, M.M., 1980. Biogeography of rocky intertidal macroinvertebrates of the Southern California Islands. In: Power, D.M. (Ed.), The California Islands: Proceedings of a Multidisciplinary Symposium. Santa Barbara Museum of Natural History, Santa Barbara, pp. 307–323.

Seapy, R.R., Littler, M.M., 1993. Rocky intertidal macroinvertebrates of the Southern California Bight: an overview and checklist. In: Hochberg, F.G. (Ed.), Third California Islands Symposium: Recent Advances in Research on the California Islands. Santa Barbara Museum of Natural History, Santa Barbara, pp. 293–322.

Speed, R.C., Cheng, H., 2004. Evolution of marine terraces and sea level in the last interglacial, Cave Hill, Barbados. Geological Society of America Bulletin 116, 219–232.

Stein, M., Wasserburg, G.J., Lajoie, K.R., Chen, J.H., 1991. U-series ages of solitary corals from the California coast by mass spectrometry. Geochimica et Cosmochimica Acta 55, 3709–3722.

Stein, M., Wasserburg, G.J., Aharon, P., Chen, J.H., Zhu, Z.R., Bloom, A., Chappell, J., 1993. TIMS U-series dating and stable isotopes of the last interglacial event in Papua New Guinea. Geochimica et Cosmochimica Acta 57, 2541–2554.

Stirling, C.H., Esat, T.M., McCulloch, M.T., Lambeck, K., 1995. High-precision U-series dating of corals from Western Australia and implications for the timing and duration of the last interglacial. Earth and Planetary Science Letters 135, 115–130.

Stirling, C.H., Esat, T.M., Lambeck, K., McCulloch, M.T., 1998. Timing and duration of the last interglacial; evidence for a restricted interval of widespread coral reef growth. Earth and Planetary Science Letters 160, 745–762.

Strange, W., Weston, N., 1997. National Geodetic Survey Continuously Operating Reference System (CORS). In: The Global Positioning System for Geosciences. National Academy Press, Washington, D.C., pp. 103–109.

Tamisiea, M.E., Mitrovica, J.X., 2011. The moving boundaries of sea level change: understanding the origins of geographic variability. Oceanography 24, 24–39.

Thompson, R.S., Anderson, K.H., Bartlein, P.J., 1999. Atlas of Relations Between Climatic Parameters and Distributions of Important Trees and Shrubs in North America—Hardwoods. U.S. Geological Survey Professional Paper 1650-B, 423 pp.

Thompson, W.G., Goldstein, S.L., 2005. Open-system coral ages reveal persistent suborbital sea-level cycles. Science 308, 401–404.

Thompson, W.G., Spiegelman, M.W., Goldstein, S.L., Speed, R.C., 2003. An open-system model for U-series age determinations of fossil corals. Earth and Planetary Science Letters 210, 365–381.

Toscano, M.A., Lundberg, J., 1998. Early Holocene sea-level record from submerged fossil reefs on the southeast Florida margin. Geology 26, 255–258.

Toscano, M.A., Lundberg, J., 1999. Submerged late Pleistocene reefs on the tectonically-stable S.E. Florida margin: high-precision geochronology, stratigraphy, resolution of substage 5a sea-level elevation, and orbital forcing. Quaternary Science Reviews 18, 753–767.

Toscano, M.A., Macintyre, I.G., 2003. Corrected western Atlantic sea-level curve for the last 11,000 years based on calibrated ^{14}C dates from *Acropora palmata* framework and intertidal mangrove peat. Coral Reefs 22, 257–270.

Trecker, M.A., Gurrola, L.D., Keller, E.A., 1998. Oxygen-isotope correlation of marine terraces and uplift of the Mesa Hills, Santa Barbara, California, USA. In: Stewart, I.S., Vita-Finzi, C. (Eds.), Coastal Tectonics. Geological Society of London Special Publications 146, London, pp. 57–69.

Valentine, J.W., 1955. Upwelling and thermally anomalous Pacific Coast Pleistocene molluscan faunas. American Journal of Science 253, 452–474.

Valentine, J.W., 1958. Late Pleistocene megafauna of Cayucos, California and its zoogeographic significance. Journal of Paleontology 32, 687–696.

Valentine, J.W., 1961. Paleoecologic Molluscan Geography of the Californian Pleistocene. University of California Publications in Geological Sciences 34, 309–442 pp.

Valentine, J.W., 1962. Pleistocene molluscan notes. 4. Older terrace faunas from Palos Verdes Hills, California. Journal of Geology 70, 92–101.

Valentine, J.W., 1966. Numerical analysis of marine molluscan ranges on the extratropical northeastern Pacific shelf. Limnology and Oceanography 11, 198–211.

Valentine, J.W., 1980. Camalú: a Pleistocene terrace fauna from Baja California. Journal of Paleontology 54, 1310–1318.

Valentine, J.W., Meade, R.F., 1961. Californian Pleistocene Paleotemperatures. University of California Publications in Geological Sciences 40, 1–45 pp.

Valentine, J.W., Veeh, H.H., 1969. Radiometric ages of Pleistocene terraces from San Nicolas Island, California. Geological Society of America Bulletin 80, 1415–1418.

Vedder, J.G., Norris, R.M., 1963. Geology of San Nicolas Island California. U.S. Geological Survey Professional Paper 369, 1–65 pp.

Veeh, H.H., 1966. ^{230}Th/^{238}U and ^{234}U/^{238}U ages of Pleistocene high sea-level stand. Journal of Geophysical Research 71, 3379–3386.

Veeh, H.H., Chappell, J., 1970. Astronomical theory of climatic change: support from New Guinea. Science 167, 862–865.

Waelbroeck, C., Labeyrie, L., Michel, E., Duplessy, J.-C., McManus, J., Lambeck, K., Balbon, E., Labracherie, M., 2002. Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records. Quaternary Science Reviews 21, 295–305.

Wehmiller, J.F., Lajoie, K.R., Kvenvolden, K.A., Peterson, E., Belknap, D.F., Kennedy, G.L., Addicott, W.O., Vedder, J.G., Wright, R.W., 1977. Correlation and Chronology of Pacific Coast Marine Terrace Deposits of Continental United States by Fossil Amino Acid Stereochemistry – Technique Evaluation, Relative Ages, Kinetic Model Ages, and Geologic Implications. U.S. Geological Survey Open-File Report 77–680, 196 pp.

Wehmiller, J.F., Simmons, K.R., Cheng, H., Edwards, R.L., Martin-McNaughton, J., York, L.L., Krantz, D.E., Shen, C.-C., 2004. Uranium-series coral ages from the U.S Atlantic Coastal Plain—the "80 ka problem" revisited. Quaternary International 120, 3–14.

Woodring, W.P., 1935. Fossils from the marine Pleistocene terraces of the San Pedro Hills, California. American Journal of Science 29, 292–305.

Woodring, W.P., 1957. Marine Pleistocene of California. In: Ladd, H.S. (Ed.). Treatise on Marine Ecology and Paleoecology, Geological Society of America Memoir, vol. 67, pp. 589–597.

Woodring, W.P., Bramlette, M.N., Kew, W.S.W., 1946. Geology and Paleontology of Palos Verdes Hills, California. U.S. Geological Survey Professional Paper 207, 145 pp.

Zinsmeister, W.J., 1974. A new interpretation of thermally anomalous molluscan assemblages of the California Pleistocene. Journal of Paleontology 48, 84–94.