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Coastal tectonics on the eastern margin of the Pacific Rim: late Quaternary sea-level history and uplift rates, Channel Islands National Park, California, USA



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ABSTRACT

The Pacific Rim is a region where tectonic processes play a significant role in coastal landscape evolution. Coastal California, on the eastern margin of the Pacific Rim, is very active tectonically and geomorphic expressions of this include uplifted marine terraces. There have been, however, conflicting estimates of the rate of late Quaternary uplift of marine terraces in coastal California, particularly for the northern Channel Islands. In the present study, the terraces on San Miguel Island and Santa Rosa Island were mapped and new age estimates were generated using uranium-series dating of fossil corals and amino acid geochronology of fossil mollusks. Results indicate that the 2nd terrace on both islands is ~120 ka and the 1st terrace on Santa Rosa Island is ~80 ka. These ages correspond to two global high-sea stands of the Last Interglacial complex, marine isotope stages (MIS) 5.5 and 5.1, respectively. The age estimates indicate that San Miguel Island and Santa Rosa Island have been tectonically uplifted at rates of 0.12–0.20 m/ka in the late Quaternary, similar to uplift rates inferred from previous studies on neighboring Santa Cruz Island. The newly estimated uplift rates for the northern Channel Islands are, however, an order of magnitude lower than a recent study that generated uplift rates from an offshore terrace dating to the Last Glacial period. The differences between the estimated uplift rates in the present study and the offshore study are explained by the magnitude of glacial isostatic adjustment (GIA) effects that were not known at the time of the earlier study. Set in the larger context of northeastern Pacific Rim tectonics, Channel Islands uplift rates are higher than those coastal localities on the margin of the East Pacific Rise spreading center, but slightly lower than those of most localities adjacent to the Cascadia subduction zone. The uplift rates reported here for the northern Channel Islands are similar to those reported for most other localities where strike-slip tectonics are dominant, but lower than localities where restraining bends (such as the Big Bend of the San Andreas Fault) result in crustal shortening.

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1. Introduction

The Pacific Rim is highly active tectonically, with its margins characterized by spreading centers, subduction zones, and transform faults. On the eastern margin of the Pacific Rim, the coast of western North America is situated at the boundary between the Pacific plate and the North American plate (Fig. 1). The nature of this plate boundary changes from south to north. In the Gulf of

California, the East Pacific Rise (spreading ridge) separates the two plates, whereas farther north in California, the San Andreas transform fault forms the boundary. Still farther north, from northern California to southwestern Canada, smaller subplates (Juan de Fuca and Gorda plates) are being subducted under the North American plate. Coastal geomorphic evolution in western North America is influenced strongly by tectonic processes, but the nature and rates of those processes differ along the coastline because of the changing nature of the plate boundary. Coastal uplift rates, a reflection of this tectonic activity, can be ascertained by the study of emergent marine terraces (Keller and Pinter, 2002; Murray-Wallace and Woodroffe, 2014).

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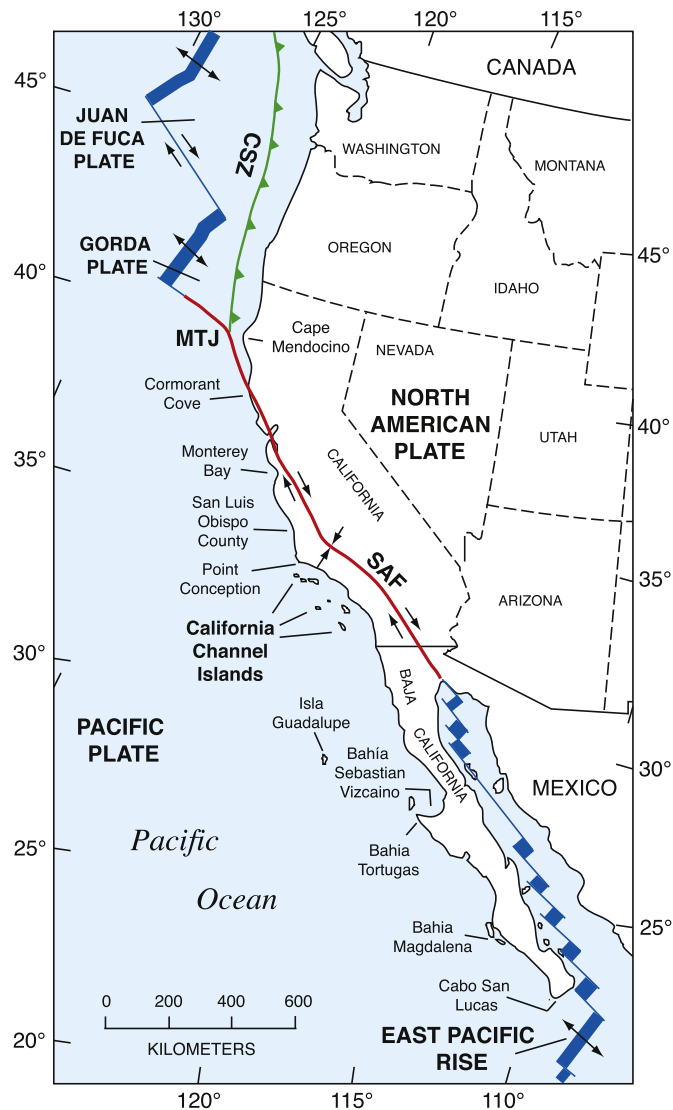


Fig. 1. Map showing the plate tectonic setting of western North America (simplified from Drummond (1981) and Simkin et al. (2006)), location of the California Channel Islands, and other localities referred to in the text. SAF, San Andreas Fault; MTJ, Mendocino Triple Junction; CSZ, Cascadia subduction zone.

Southern California is divided by the San Andreas Fault (Fig. 2). Much crustal deformation along the San Andreas and other faults in coastal California is horizontal, due to the dominance of a strike-slip movement. Thus, along much of the southern California mainland coast and the adjacent islands, late Quaternary uplift rates are expected to be modest. There are exceptions to this generalization, however. An area in southern California where dramatic upward movement has been documented in late Quaternary time is the western Transverse Ranges physiographic province, an east–west-trending series of fault-bounded mountain ranges and intervening valleys. Although right-lateral, strike-slip movement characterizes much of the San Andreas Fault zone, there is considerable crustal contraction and shortening adjacent to the “Big Bend” of this fault (Fig. 2). Thus, south of this major restraining bend, faults of the western Transverse Ranges strike east–west and fold axes also strike east–west. Along the coast between Goleta/Santa Barbara and Ventura, which is part of this major fault and fold belt, there are numerous geomorphic indicators of rapid crustal deformation, including uplifted, faulted, and folded marine terraces

(Wehmler et al., 1978, 1979; Lajoie et al., 1979; Wehmler, 1982; Sarna-Wojcicki et al., 1987; Trecker et al., 1998; Minor et al., 2009; Gurrola et al., 2014).

The northern Channel Islands (San Miguel, Santa Rosa, Santa Cruz, and Anacapa islands) are situated in Santa Barbara Channel, south of the Big Bend area of the San Andreas Fault zone and also south of the Santa Barbara–Ventura fault and fold belt region (Fig. 2). The crustal platform on which these islands are located has also been studied for estimating rates of tectonic uplift. Using estimated marine terrace ages from Santa Rosa Island, Sorlien (1994) suggested that the northern Channel Islands could have been uplifted at rates of 0.5–1.0 m/ka. Because these estimates were based on assumed ages of marine terraces, they were, however, presented as hypothetical. Pinter et al. (1998a, 1998b, 2003) studied marine terraces on the western portion of Santa Cruz Island. The lowest of three terraces mapped by these investigators dates to the ~120 ka high-sea stand of the Last Interglacial period, or marine isotope stage (MIS) 5.5 (nomenclature of Martinson et al. (1987)), based on U-series analyses of fossil corals. Elevation measurements indicate that the maximum uplift rate of Santa Cruz Island is ~0.1 m/ka, and the westernmost part of the island could have experienced little or no uplift since the Last Interglacial high-sea stand. In contrast, Chaytor et al. (2008) infer rapid uplift of a submerged marine terrace they mapped around the southern, submarine portion of the northern Channel Islands crustal block. Radiocarbon ages of fossil shells associated with the submerged terrace give a Last-Glacial-period age (~23–12 ka). Chaytor et al. (2008) used the terrace age, elevation (~95–120 m below present sea level), and the Last-Glacial-to-Holocene sea level curve of Lambeck et al. (2002) to generate an uplift rate. Because the Lambeck et al. (2002) curve indicates a Last Glacial maximum (LGM) paleo-sea level of ~140 m below present, Chaytor et al. (2008) calculated an uplift rate of ~1.5 m/ka for the past ~23 ka in the northern Channel Islands region. This uplift rate is more than an order of magnitude higher than the highest possible uplift rate derived from the data of Pinter et al. (1998a, 1998b, 2003) for nearby Santa Cruz Island.

The emergent marine terraces on the northern Channel Islands were studied in the present effort in order to evaluate the competing hypotheses of low (Pinter et al., 1998a, 1998b, 2003) versus moderate (Sorlien, 1994) versus high (Chaytor et al., 2008) uplift rates for the northern Channel Islands region. The highly divergent estimates of late Quaternary uplift rate for the northern Channel Islands crustal block have quite different implications for seismic hazard, assuming that high uplift rates imply a region with more frequent earthquakes. The present paper reports new mapping, elevation measurements, and ages of emergent marine terraces on the northern Channel Islands that allow new estimates of late Quaternary uplift rates. The resulting uplift rates for this part of California are also compared to those calculated from uplifted marine terrace data from other tectonic settings in the northeastern part of the Pacific Rim, on the west coast of North America.

2. Field and laboratory methods

2.1. Field and GPS methods

Marine terrace deposits and other surficial sediments were mapped on San Miguel Island and Santa Rosa Island, in part modified from mapping conducted by Weaver et al. (1969). Unlike Weaver et al. (1969), however, the present work distinguishes between low terraces (less than ~30 m elevation), hypothesized to be of probable late Quaternary age (based on elevation, stratigraphic position, and faunal assemblages) and high terraces (greater than ~30 m elevation), hypothesized to be of middle-to-early Quaternary

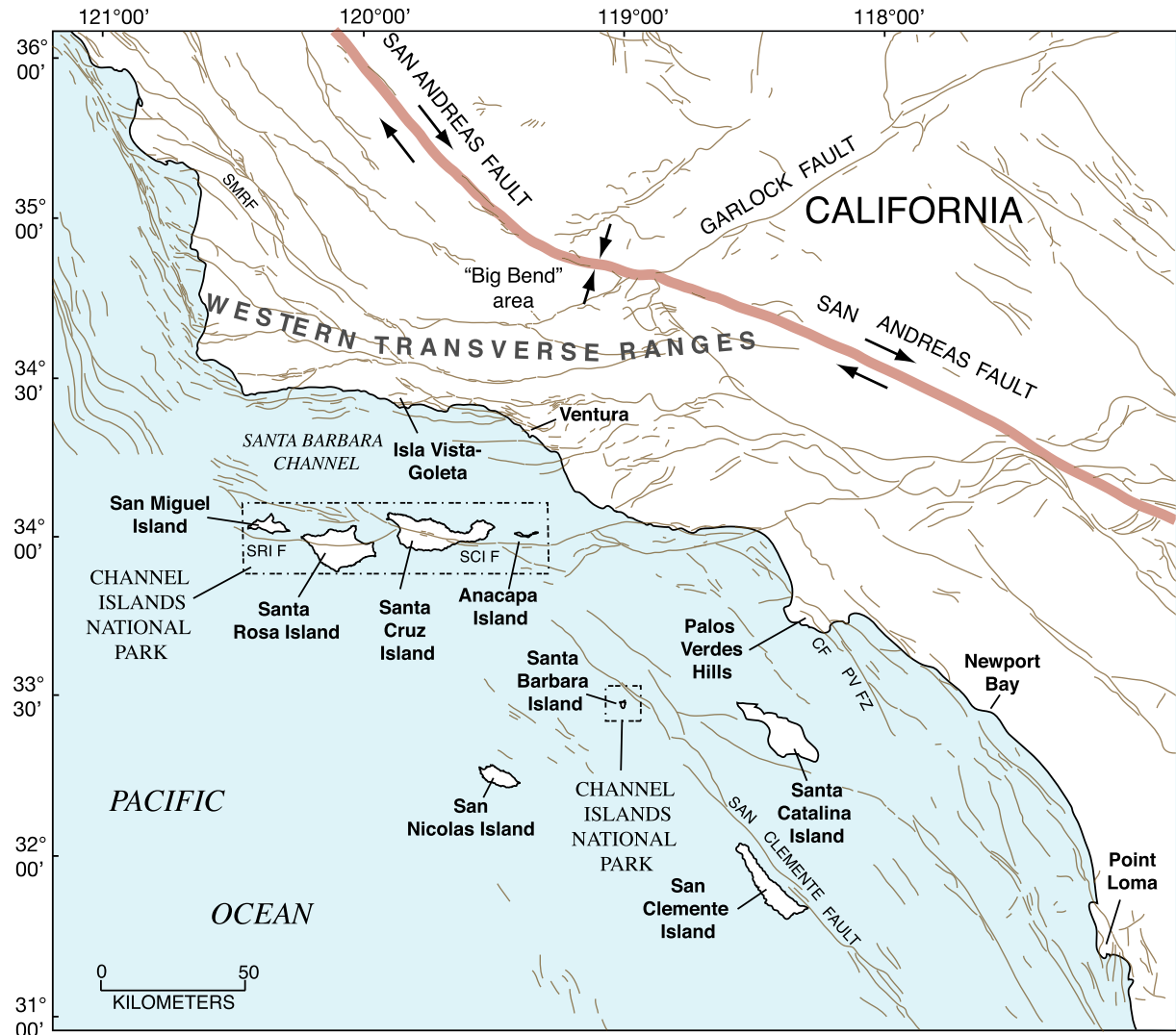


Fig. 2. Fault map of southern California (redrawn from Jennings (1994)) and localities referred to in text. Pairs of opposing arrows adjacent to the San Andreas Fault indicate sense of strike-slip movement (left and right pairs) and approximate direction of crustal contraction due to bend in fault (central pair), which is also referred to as the “Big Bend.” SRI F, Santa Rosa Island fault; SCI F, Santa Cruz Island fault; SMRF, Santa Maria River fault; CF, Cabrillo fault; PV FZ, Palos Verdes fault zone.

age. The middle-to-early Quaternary age of deposits of high-elevation terraces can be inferred by the presence of specimens of the extinct gastropod *Calicantharus fortis* (Carpenter, 1866). Low-elevation terraces are designated as map unit “Qes/Qty” or “Qac/Qty” for both San Miguel Island and Santa Rosa Island. The composite designation indicates that marine terrace deposits (Qty) are not exposed at the surface, but are covered by younger eolian sand (Qes) or alluvium and/or colluvium (Qac). The spatial extent of these units was determined by initial mapping on aerial photographs and topographic maps, refined by field examination of terrace geomorphology, exposures in sea cliffs, and outcrops in shore-normal-trending canyons.

No attempt was made to differentiate different ages of probable middle-to-early Quaternary marine terraces. These older marine terrace deposits (Qto) on both San Miguel Island and Santa Rosa Island are identified by the presence of wave-cut platforms covered by rounded, wave-worn gravel clasts, particularly those with evidence of boring by pholad bivalves, and/or deposits containing marine invertebrate fossils. On both islands, older marine deposits are also typically covered by younger eolian sand (Qes) or alluvium and/or colluvium (Qac). Thus, the older terraces are designated “Qes/Qto” or “Qac/Qto.” On Santa Rosa Island, possible marine

terraces, mapped as unit “Qtpo,” are old, high-elevation, low-relief surfaces with gentle seaward slopes, identifiable in the field and on aerial photographs and topographic maps, that lack definitive marine deposits (rounded, pholad-bored gravels and marine fossils). These surfaces, interpreted as uplifted but eroded terraces, have geomorphic evidence of a marine origin. They are backed on their landward margins by what appear to be paleo-sea cliffs and have planar surfaces that dip gently seaward, interpreted as wave-cut platforms. The platforms have elevations that are concordant with other, low-relief surfaces bounded by adjacent drainages.

Accurate and precise determination of the elevations of geomorphic features that mark past sea level is critical to the present work. On high-wave-energy coastlines such as California, the best paleo-sea level indicator is the shoreline angle, which is the junction of the wave-cut platform and the former sea cliff, found at the landward edge of the wave-cut platform. Where ancient shoreline angles are not exposed, which is often the case, their elevations can be estimated in a shore-normal profile by projecting lines defined by measurements of the elevations of the wave-cut platform landward and elevations of the paleo-sea cliff downward. Intersection of these two lines is a close approximation of a shoreline angle position. Exposures of the inner, landward parts of

what are considered to be late Quaternary marine terraces are numerous enough that 20 shore-normal elevation transects were examined on the two islands; more than half of these permit direct or very close estimates of shoreline angle elevations.

Elevations of all localities studied were determined using differential Global Positioning System (GPS) measurements. Latitude–longitude data and elevations were ascertained using a portable differential GPS instrument connected to a handheld computer. At each location, data were collected from at least four, and usually six to eight, satellites for at least 500 s 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. Comparison of GPS-derived elevations with benchmarks and taped elevations shows good agreement, within the limits of instrumental uncertainty.

2.2. Uranium-series methods of dating marine terrace corals

All corals, whether colonial or solitary, take up U in isotopic equilibrium with seawater, contain little or no Th, 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* Verrill, 1864 currently lives along the Pacific Coast of North America from southeastern Alaska to central Baja California, Mexico (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, 2002a, 2006).

Fossil corals collected from marine terrace deposits on San Miguel Island and Santa Rosa Island were cleaned mechanically, washed in distilled water, and X-rayed for aragonite purity. All samples are at least 95% aragonite and most are 97–100% aragonite. Analyses were made of individual corals of *B. elegans* and sample preparation follows methods outlined by Ludwig et al. (1992), summarized briefly here. Cleaned corals were dissolved in HNO_3 , spiked with ^{229}Th , ^{233}U , and ^{236}U (calibrated primarily with a secular equilibrium standard; see Ludwig et al. (1992)) 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 for ^{230}Th of 75,584 yr and a half-life for ^{234}U of 245,620 yr (Cheng et al., 2013). Also reported here are recalculated ages for corals from Santa Cruz Island, given previously in Pinter et al. (1998a) and corals from two localities in Baja California Sur, Mexico, given previously in Johnson et al. (2007). These corals were analyzed in laboratories of the U.S. Geological Survey, but at the time the Pinter et al. (1998a) and Johnson et al. (2007) studies were published, the new half-lives of Cheng et al. (2013) were not known. In addition, full isotopic data are provided for a marine terrace coral from Isla Vista (Goleta), California, also analyzed in laboratories of the U.S. Geological Survey; the coral age was recently reported by Gurrola et al. (2014).

2.3. Amino acid geochronology/aminostratigraphy of marine terrace mollusks

Amino acid dating of fossil mollusks from emergent marine deposits is an important geochronological tool that is highly

complementary to U-series dating of fossil corals. Wehmiller (1982, 1992, 2013a, 2013b), Wehmiller and Miller (2000) and Miller and Clarke (2007) review the method in detail. Amino acid racemization and epimerization in fossil mollusks have been used for more than three decades for marine terraces in California, beginning with the pioneering work of Wehmiller et al. (1977, 1978), Wehmiller and Belknap (1978), and Kennedy et al. (1982). For amino acid geochronology on the Channel Islands, the present study utilizes the common rocky intertidal gastropod *Chlorostoma* (formerly *Tegula* [McLean, 2007]), usually *Chlorostoma funebris* (A. Adams, 1855) and the intertidal bivalve *Epilucina californica* (Conrad, 1837). Previous studies have shown that *Chlorostoma* is a reliable genus for amino acid geochronology, with *Epilucina* perhaps somewhat less reliable (Wehmiller et al., 1977; Muhs, 1983, 1985; Muhs et al., 1992). Relative abundances (using peak heights on chromatograms) of D and L enantiomers of the amino acids valine and glutamic acid were measured in fossil specimens of these genera, using reverse-phase liquid chromatography (Kaufman and Manley, 1998). D/L values for valine and glutamic acid were measured using both peak areas and peak heights. Comparison of D/L values computed by both peak heights and peak areas shows no significant differences (Supplementary data Tables 1 and 2). Somewhat better run-to-run agreement was achieved with peak-height ratios, however, so these values were used in figures and interpretations.

Amino acid racemization is a temperature-dependent process, with racemization occurring at lower rates in cooler climates. In comparing amino acid ratios of fossil mollusks from the Channel Islands, D/L values were measured in newly collected fossil *Chlorostoma* and *Epilucina* specimens from other, dated marine terrace localities. These collections were made from localities along a roughly north-south temperature gradient from central California to northern Baja California (Fig. 3). The localities shown in Fig. 3 host deposits containing corals that have been dated independently by U-series methods to ~80 ka (MIS 5.1) and either ~120 ka (MIS 5.5) or a mix of ~100 ka (MIS 5.3) and ~120 ka (MIS 5.5) ages, based on studies by Muhs et al. (1994, 2002a, 2006, 2012) and the present work. Under favorable conditions, D/L values in shells from deposits of the same age form an isochron line or band with northward-decreasing values. Shells of younger deposits should yield a parallel or subparallel isochron band of D/L values below that defined by an older suite of shells. Thus, D/L values in shells of a deposit of unknown age can be plotted on these latitudinal arrays for purposes of correlation.

3. Results

3.1. Marine terraces on San Miguel Island

Quaternary deposits cover almost all of San Miguel Island and consist of marine terrace deposits, eolian sand, alluvium and colluvium. Only rarely, however, are marine terrace deposits the uppermost surficial deposit. Highly calcareous eolian sand of Pleistocene age covers large areas of western, central and eastern San Miguel Island and mantles many of the marine terrace deposits (Fig. 4a). In some places, this sand has been weakly cemented into eolianite. Radiocarbon ages and degree of soil development indicate that some eolian sand is greater than ~40 ka (radiocarbon years), whereas other deposits of eolian sand date between ~25 ka and ~10 ka (radiocarbon years), indicating deposition during the LGM (Johnson, 1977). Still other deposits of eolian sand date to Holocene or historic time and overlie Pleistocene sand. Much eolian sand became active after the introduction of livestock to the island in the 19th century; vegetation loss from grazing animals reactivated previously stabilized Pleistocene eolian sand (Johnson, 1980). In other places on San Miguel Island, particularly the

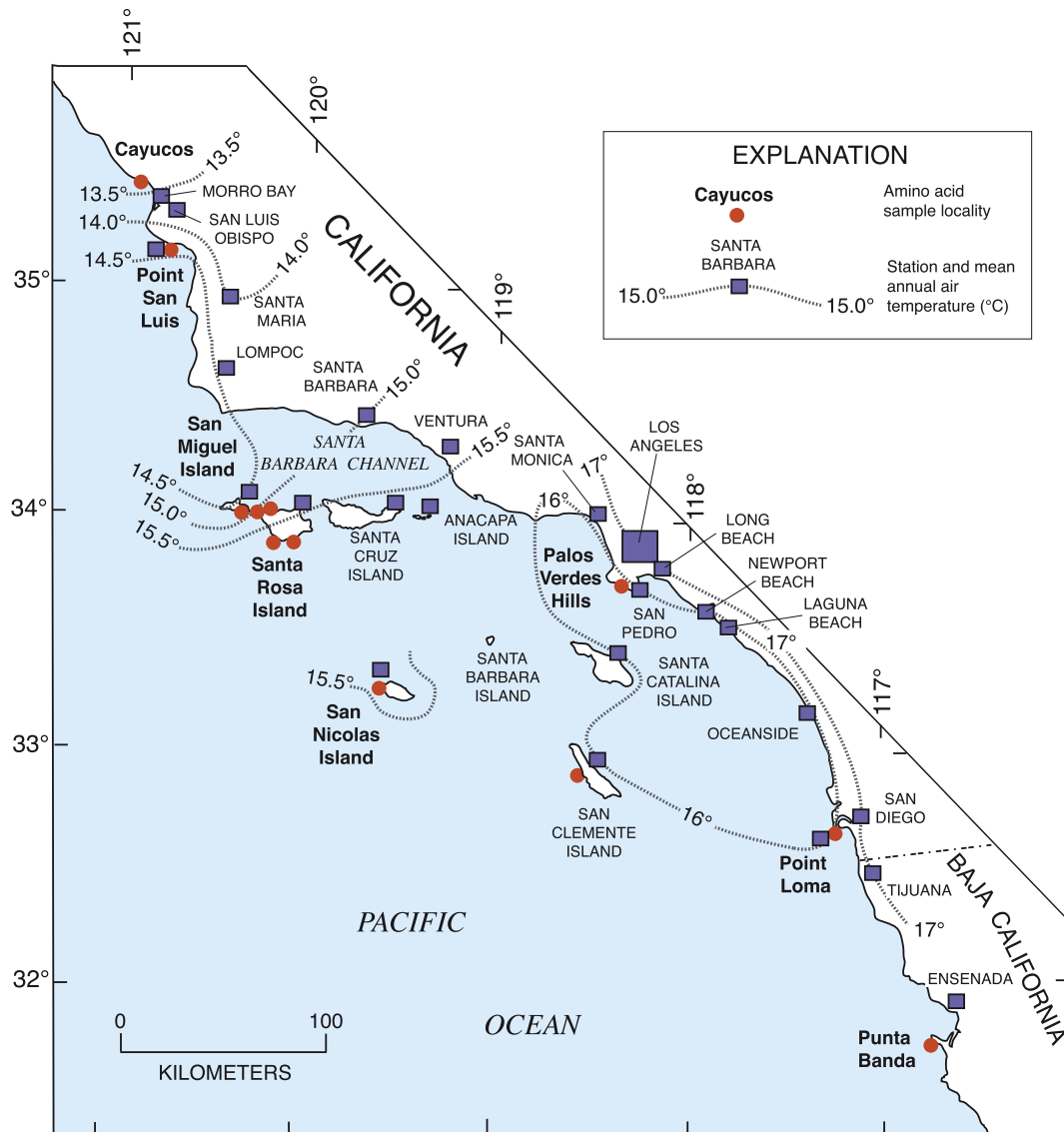


Fig. 3. Map showing the location of the California Channel Islands, marine terrace localities with amino acid data presented here (solid red dots), and isotherms of mean annual air temperature, using historic records from coastal weather stations (solid blue squares). Temperature data taken from National Weather Service, U.S. Navy, and U.S. National Park Service records with variable lengths, from archives of the Western Regional Climate Center (<http://www.wrcc.dri.edu>) and other sources. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

southern coast of the island, marine terrace deposits are masked by alluvium or colluvium on the surface (Fig. 4b), but are exposed on sea cliffs.

Marine terraces hypothesized to be of middle-to-early Quaternary age are found over much of San Miguel Island (Fig. 5), but a lack of exposures does not allow differentiation of individual terraces. Because of the blanket of eolian sand, these older marine terrace deposits crop out mainly on canyon walls and sea cliffs, although there are a few exposures on the surface where erosion has removed the overlying eolian cover. The highest possible marine deposits observed consist of a lag deposit of gravels on bedrock on the west and north sides of San Miguel Hill (Fig. 5). No fossils are present, but well-rounded pebbles, cobbles, and rare boulders are found around the circumference of the hill at an elevation of ~230–235 m. Because of the absence of fossils or pholad-bored gravels, it is not certain that these deposits truly represent ancient marine sediments, but their occurrence at concordant elevations around San Miguel Hill certainly permits such a possibility.

Below this, the highest definitive terraces observed are exposed on the southeast wall of a valley that drains to Cuyler Harbor (Fig. 5). Two wave-cut benches with fossiliferous marine deposits are present here, one at an elevation of ~110 m (SMI-1) and the other seaward (northeast) of the first, at an elevation of ~90–99 m (SMI-310). Deposits at SMI-1 contain *Callianax biplicata* (Sowerby, 1825), *E. californica*, *Fissurella volcano* Reeve, 1849, *Mytilus*, *Haliotis*, and *Serpulorbis*, among other taxa, indicating a rocky-shore, intertidal habitat. Several meters of eolianite cover the marine deposits at SMI-1, which probably accounts for the good preservation of these fossils. In the eastern part of the island, where the eolian cover is somewhat thinner than elsewhere, wave-cut platforms with overlying, fossiliferous (*C. biplicata*, *E. californica*, and *C. fortis*) marine deposits were observed at two locations (SMI-248 and SMI-308), both at elevations of ~70 m and presumably on the same terrace surface. Shoreline angles were not observed for this terrace, but it is inferred that these localities are close to the outer edge of a terrace that faced to the east. On the western flank of the island (to the

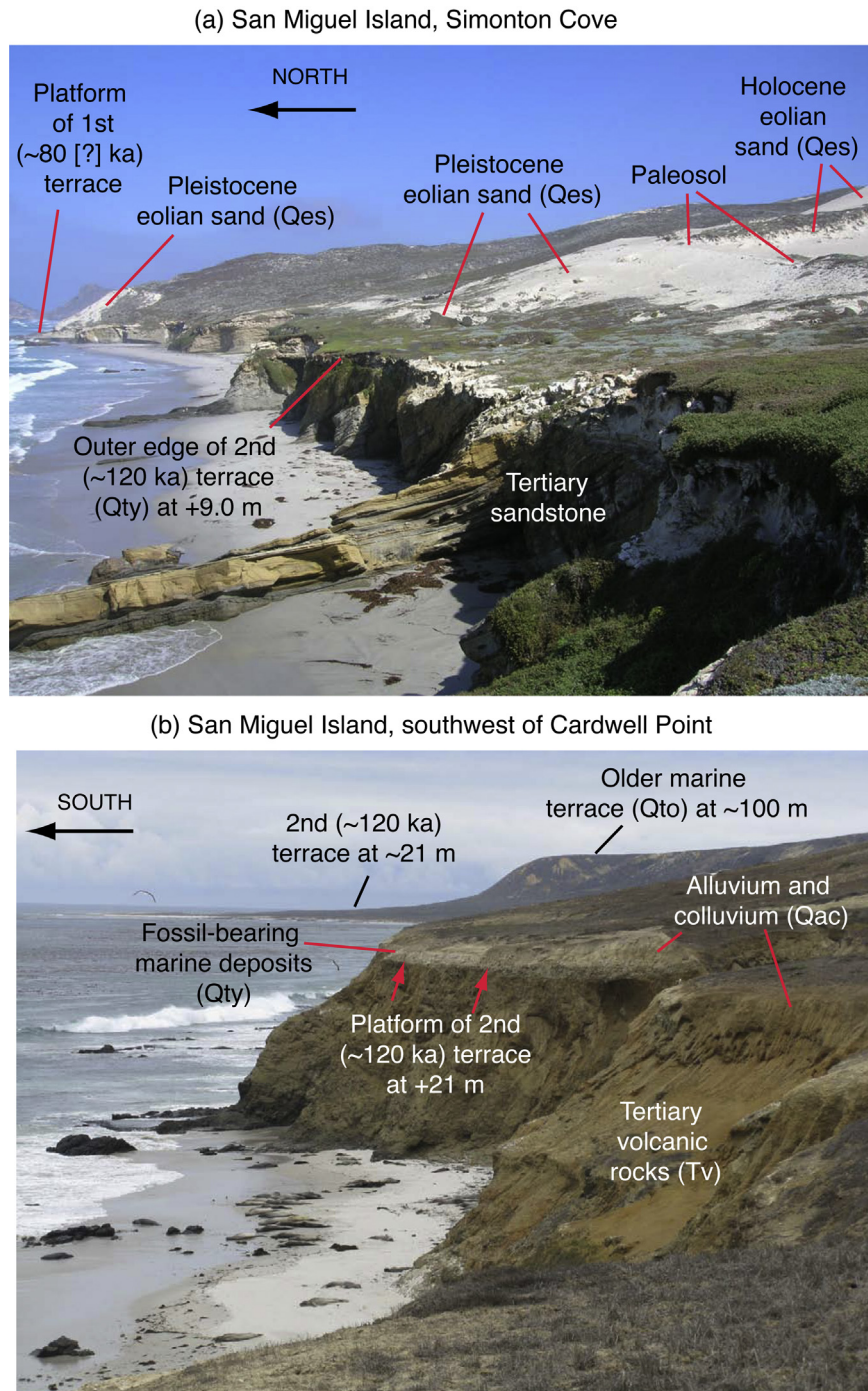


Fig. 4. View of marine terraces on (a) the northern coast of San Miguel Island, near Simonton Cove, showing outer edge of 2nd terrace and its deposits (Qty), with inner edge overlain by eolian sand (Qes) of both Pleistocene and Holocene age. Platform of 1st terrace is barely visible in upper left; and (b) southern coast of San Miguel Island, southwest of Cardwell Point, showing outer edge of 2nd terrace at locality SMI-236 (see Fig. 5 for location), terrace deposits (Qty), and overlying alluvium and colluvium (Qac). Older, higher (~100 m) terrace (Qto) is visible on skyline in background.

northwest of Tyler Bight; Fig. 5), where a small portion of the area has no overlying eolian deposits, observations were made of what is interpreted to be the outer portion of a wave-cut platform, overlain by fossiliferous (*C. biplicata*, *E. californica*, *C. fortis*, *Glycymeris*, and *Protothaca*, among others) marine sands and gravels at an elevation of ~84 m (SMI-242). About 1.1 km to the northwest of SMI-242, an outer terrace edge is exposed at SMI-322 (Fig. 5) at an elevation of ~69 m. Terrace sands here expose exceptionally well-preserved specimens of *C. fortis*, *Acanthinucella paucilirata*,

Chlorostoma spp., and numerous specimens of *Nutricola tantilla*, with many individual shells retaining color. Still farther west, above Point Bennett, a lower-elevation terrace is found in an area that is free of covering eolian sand. Here, a wave-cut platform is overlain by highly fossiliferous (*C. biplicata*, *E. californica*, *C. fortis*, *Chlorostoma*, *Cumingia*, *Conus*, *Glans*, and *Serpulorbis*) marine terrace deposits (SMI-311). The wave-cut bench at SMI-311 has an elevation of ~57 m at its outer, seaward edge and a shoreline angle elevation of ~62 m.

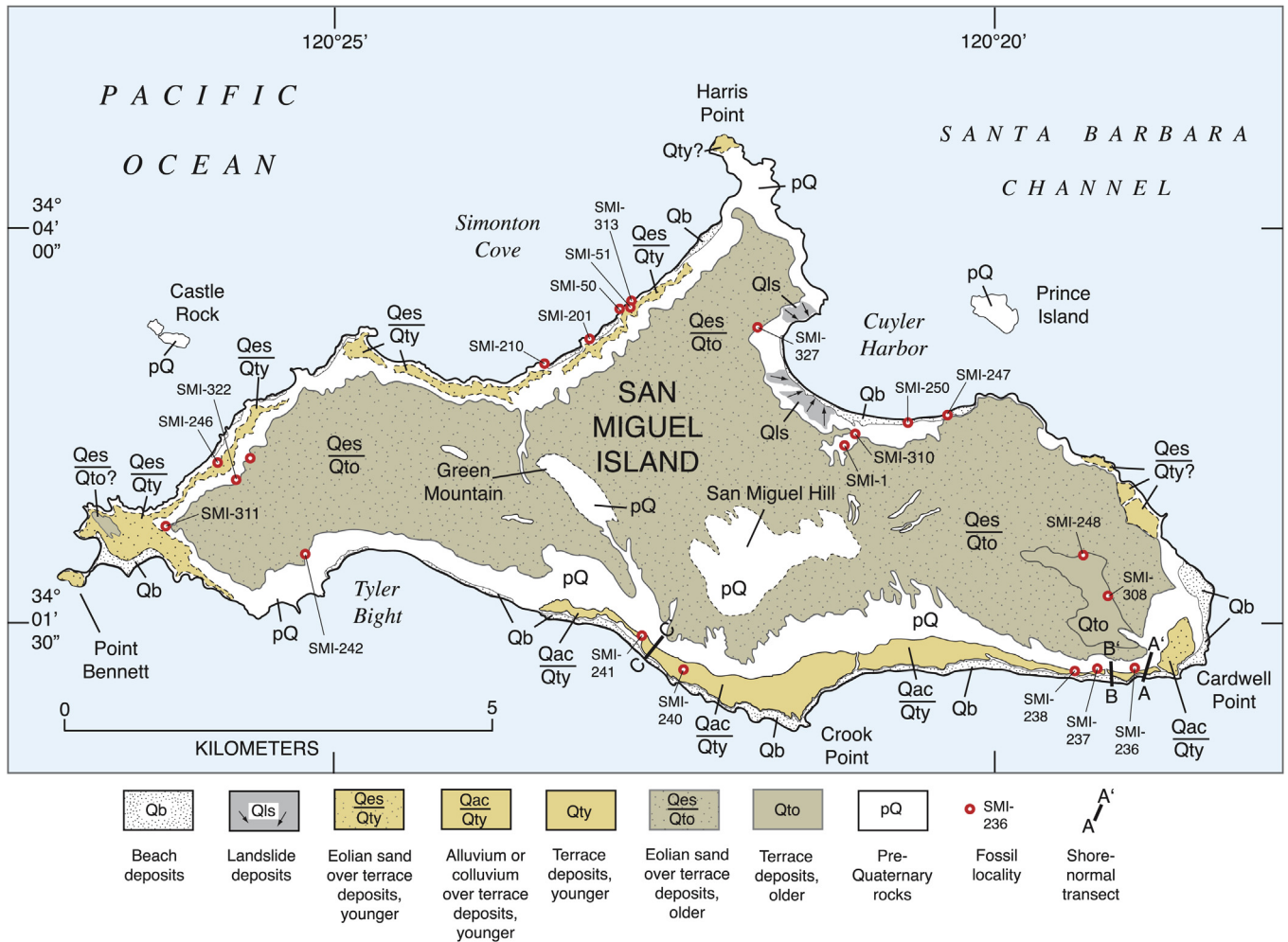


Fig. 5. Surficial geologic map of San Miguel Island, showing marine terrace deposits and other surficial deposits, fossil localities, and locations of shore-normal elevation transects or cliff sections. White areas are pre-Quaternary bedrock (pQ), in places overlain by alluvium or colluvium. All mapping done by the authors.

A pair of terraces interpreted to be of late Quaternary age can be found around much of the perimeter of San Miguel Island (Fig. 5). On the northern side of the island, low-elevation marine terrace deposits of two ages crop out in sea cliff exposures (Fig. 4a). The lower surface has a shoreline angle elevation of ~3.5 m and the upper one has an outer edge elevation of ~9–11 m, depending on location, but the shoreline angle is buried by eolianite. The lower terrace has a thin veneer of sparsely fossiliferous (*C. buplicata* and *F. volcano*) marine sand and gravel, cemented into beach rock (originally noted by Johnson (1969)). Marine deposits of the upper terrace are generally less than a meter thick and are also sparsely fossiliferous (*C. buplicata*, *E. californica*, and various limpets). Along the southern coast of the island, a low-elevation marine terrace is overlain by several meters of alluvium (Fig. 4b), but canyons cutting through the alluvium expose the marine terrace deposits (~1 m thick) and the wave-cut platform. From Cardwell Point to Crook Point and continuing west almost to Tyler Bight (localities SMI-236, 237, 238, 240, 241 on Fig. 5), all exposures of lower-elevation marine terrace deposits observed are richly fossiliferous and most contain corals. From ~1.8 km east of Crook Point (Fig. 5) to ~1.4 km west of it, intermittent observations were made of a possible younger, low terrace, similar to the one with a shoreline angle of ~3.5 m on the north side of the island. Exposures were too few, however, to determine whether this might be the same feature as the low terrace on the north side of San Miguel Island.

The richest, fossil-bearing, low-elevation marine terrace deposit observed is in southeastern San Miguel Island, at SMI-236 (Figs. 4b, 5 and 6). At this locality, at least 42 species of mollusks are present, along with fossil echinoderms and arthropods (Table 1). Also found were numerous specimens of the coral *B. elegans*, which were analyzed for U-series dating. As a whole, the fossil assemblage indicates a rocky-shore, intertidal habitat, very similar to the modern shore in this part of San Miguel Island. A number of species from this locality have paleozoogeographic significance, discussed later.

Because of the lack of exposed shoreline angles on the northern coast of San Miguel Island, detailed elevation measurements of marine terraces were concentrated along three transects (A–A', B–B', and C–C' on Fig. 5) on the southern coast of the island. Although shoreline angles are not exposed in any of the canyons surveyed, a sufficient number of paleo-sea cliff and wave-cut bench exposures were found so that it was possible to construct cross sections with extrapolated cliff and platform slopes. Intersections of these slopes (Fig. 6) give fairly close estimates of shoreline angle elevations of ~22 m (A–A'), ~24 m (B–B'), and ~21 m (C–C').

3.2. Marine terraces on Santa Rosa Island

Orr (1960, 1968) and Weaver et al. (1969) conducted the earliest mapping of marine terraces on Santa Rosa Island. Orr's mapping was limited to the northwestern part of the island, whereas Weaver

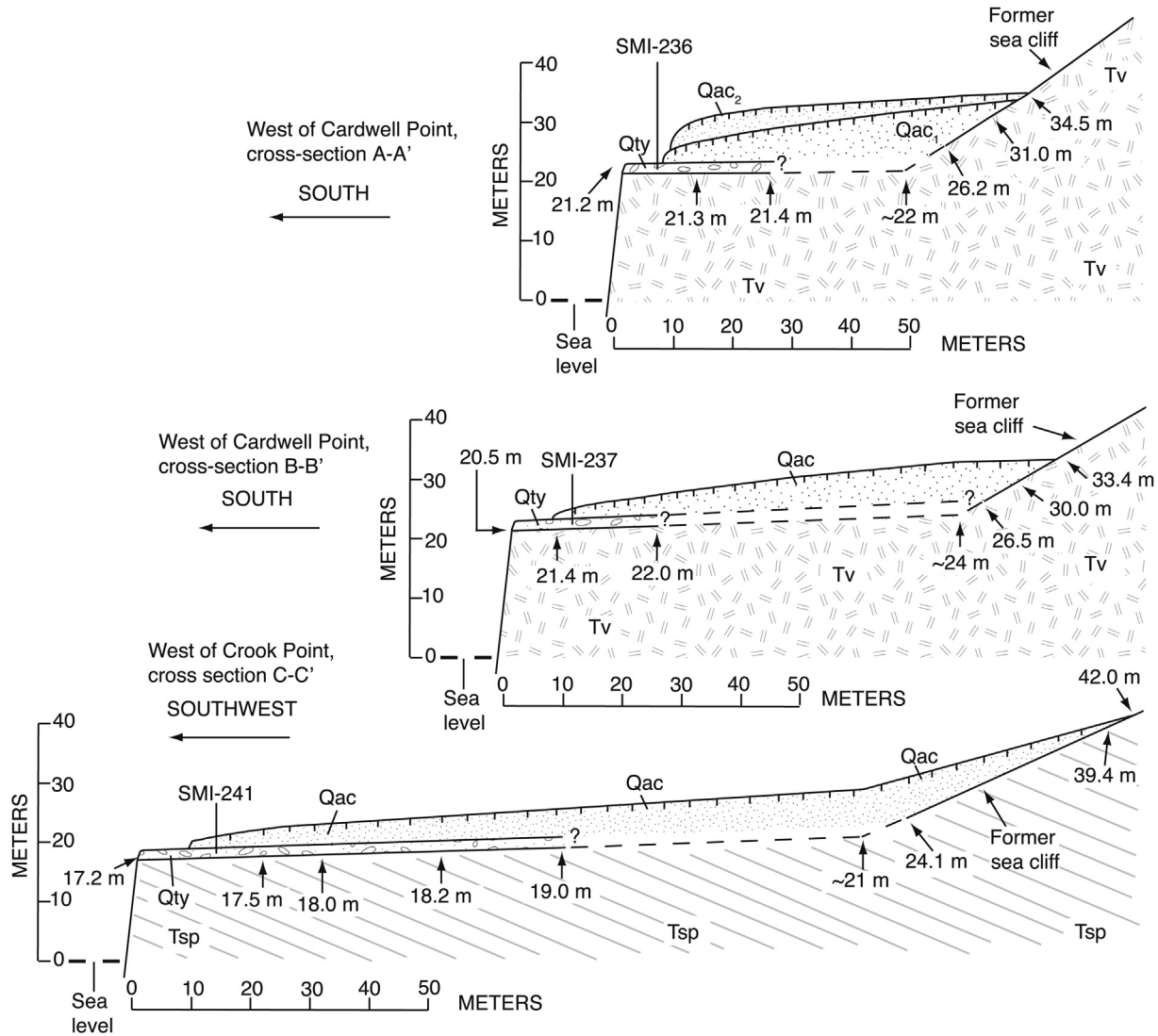


Fig. 6. Shore-normal transects A–A', B–B', and C–C' (Fig. 5) of southern San Miguel Island, showing marine terraces, elevations from GPS surveys, overlying deposits, and fossil localities. Qac, alluvium and/or colluvium; Qty, marine terrace deposits, younger; Tsp, South Point Formation; Tv, Tertiary volcanic rocks.

et al. (1969) mapped the entire island. Although conducted independently, the marine terrace mapping on Santa Rosa Island presented here is similar to Weaver et al. (1969), as well as later mapping by Dibblee and Ehrenspeck (1998), Dibblee et al. (1998) and Pinter et al. (2001). The geomorphology of marine terraces is well expressed on the island although, as with San Miguel Island, many terrace surfaces are covered with eolian sand, alluvium and/or colluvium (Fig. 7). For example, near the mouth of Arlington Canyon, situated between Brockway Point and Sandy Point (Fig. 8), late Quaternary terrace deposits (Qty) are covered by thick deposits of alluvium (Qac), even through the original terrace form is still well expressed at the surface (Fig. 7a). The same is true for the late Quaternary marine terrace in the Bechers Bay area (Fig. 8), where alluvial/colluvial deposits are several meters thick but the terrace geomorphology is still well expressed (Fig. 7b, c) and the former shoreline can be traced easily (Fig. 7c). At other localities around Bechers Bay, particularly just south of Carrington Point (Fig. 8), marine terrace deposits are mantled with thick accumulations of eolian sand (Fig. 7d).

Unambiguous evidence of marine terraces is found over much of Santa Rosa Island, with shoreline angles and well-rounded marine gravels overlying wave-cut benches up to at least ~272 m elevation,

in good agreement with Pinter et al. (2001). For example, near Black Mountain (Fig. 8), observations were made of at least two high-elevation marine terraces. One of these has a well-defined wave-cut bench with a shoreline angle elevation of 248 m; the other has a wave-cut bench with wave-worn gravels and a shoreline angle elevation of 272 m. In the western part of Santa Rosa Island, a terrace was found at ~122–127 m elevation (locality SRI-13 on Fig. 8), with a fossil assemblage consisting of *E. californica*, *Saxidomus*, *Mytilus*, *Conus*, *C. biplicata*, and *C. fortis*, among others. As on San Miguel Island, no attempt was made to differentiate individual terraces that are found above ~30 m elevation. Ongoing studies may reveal more details about high-elevation terraces on Santa Rosa Island (Bedford et al., 2013; Schmidt et al., 2013).

Much of Orr's (1960, 1968) marine terrace work on the north-western side of Santa Rosa Island was based on field studies conducted between Sandy Point and Brockway Point (Fig. 8), in Garañon Canyon and Arlington Canyon. Exposures that were examined along the outer part of Garañon Canyon (SRI-5D,E,G,H,J localities in Fig. 8) in the present study display two late Quaternary marine terraces that are believed to be the equivalent of Orr's (1960, 1968) ~7 m and ~23 m terraces and their associated sediments, what Orr (1960, 1968) called the Garañon Member and Fox

Table 1
Invertebrate fauna from fossil locality SMI-236, San Miguel Island, California.

MOLLUSCA
Bivalvia
<i>Chione</i> sp.
<i>Chlamys hastata</i> (Sowerby, 1842)
<i>Crassadoma gigantea</i> (Gray, 1825)
<i>Cumingia californica</i> Conrad, 1837
<i>Epilucina californica</i> (Conrad, 1837)
<i>Glans carpenteri</i> (Lamy, 1922)
<i>Irusella lamellifera</i> (Conrad, 1837)
<i>Mytilus californianus</i> Conrad, 1837
<i>Septifer bifurcatus</i> (Conrad, 1837)
Gastropoda
<i>Acmaea mitra</i> Rathke, 1833
<i>Alia carinata</i> (Hinds, 1844)
<i>Astyris tuberosa</i> (Carpenter, 1864)
<i>Amphissa versicolor</i> Dall, 1871
<i>Antisabia panamensis</i> (C.B. Adams, 1862)
<i>Barleeia haliotiphila</i> Carpenter, 1864
<i>Bittium</i> sp.
<i>Callianax biplicata</i> (Sowerby, 1825)
<i>Calliostoma ligatum</i> (Gould, 1849)
<i>Ceratostoma</i> cf. <i>C. nuttalli</i> (Conrad, 1837)
<i>Cerithiopsis</i> sp.
<i>Chlorostoma brunnea</i> (Philippi, 1849)
<i>Chlorostoma funebris</i> (A. Adams, 1855)
<i>Conus californicus</i> Reeve, 1844
<i>Crepidula</i> spp.
<i>Diodora aspera</i> (Rathke, 1833)
<i>Discurra insessa</i> (Hinds, 1842)
<i>Epitonium tinctum</i> (Carpenter, 1864)
<i>Fissurella volcano</i> Reeve, 1849
<i>Garnotia adunca</i> (Sowerby, 1825)
<i>Haliotis cracherodii</i> Leach, 1814
<i>Haliotis rufescens</i> (Swainson, 1822)
<i>Harfordia harfordi</i> (Stearns, 1871)
<i>Hipponix tumens</i> Carpenter, 1864
<i>Littorina scutulata</i> Gould, 1849
<i>Lottia</i> spp.
<i>Mitra idae</i> Melvill, 1893
<i>Ocenebrina</i> cf. <i>O. lurida</i> (Middendorff, 1848)
<i>Pomaulax gibberosa</i> (Dillwyn, 1817)
<i>Pusula californiana</i> (Gray, 1827)
<i>Serpulorbis squamigeris</i> (Carpenter, 1857)
<i>Zonaria spadicea</i> (Swainson, 1823)
Polyplacophora
<i>Cryptochiton stelleri</i> Middendorff, 1847
Chiton plates
ECHINODERMATA
Echinoidea
<i>Strongylocentrotus</i> sp. (tests and fragments)
<i>Eucidaris</i> sp. (spines)
ARTHROPODA
Cirripedia
<i>Balanus</i> sp.
Barnacle fragments
CNIDARIA
Scleractinia
<i>Balanophyllia elegans</i> Verrill, 1864

(intra) member of the Santa Rosa Island Formation, respectively. In Garañon Canyon, the shoreline angle elevation is 7.4 m for the lower terrace and ~24 m for the higher terrace (Fig. 9b). Hereafter, these are referred to as the “1st” (~7 m) and “2nd” (~24 m) terraces. Marine deposits on both terraces are ~0.5–1.0 m thick. About 4–6 m of alluvium and eolian sand overlie marine deposits of the 2nd terrace and 16–17 m of alluvium overlie marine deposits of the 1st terrace. In sea cliff exposures, the wave-cut bench of the 1st terrace can be traced almost continuously west to Sandy Point (Figs. 8 and 9).

Both the 1st and 2nd terraces on the northwest coast of Santa Rosa Island are richly fossiliferous. Deposits of the 2nd terrace, where they are exposed in Garañon Canyon (fossil localities SRI-5D,

5E, and 5J), and in canyons to the east of it (SRI-5F in Fig. 8) contain a typical rocky-shore assemblage, including *E. californica*, *Cumingia californica* Conrad, 1837, *Glans*, *C. biplicata*, *Conus californicus* Reeve, 1844, *F. volcano*, *Chlorostoma*, *Haliotis*, *Acmaea*, and other mollusks, as well as *B. elegans*. A specimen of *B. elegans* from SRI-5F on the 2nd terrace was analyzed for U-series dating, discussed below. The 1st terrace in the same area (SRI-5; Fig. 9c) has a somewhat less diverse rocky-shore assemblage, consisting of *E. californica*, *Glans carpenteri* Lamy, 1922, *F. volcano*, *Haliotis*, *Acmaea*, and rare *B. elegans*. Fossils in deposits of the 1st terrace a short distance northeast of Sandy Point (SRI-27 in Figs. 8 and 9a) are more abundant, containing the same taxa as at SRI-5, but also hosting *Mytilus californianus* Conrad, 1837, *Chlorostoma*, *Serpulorbis squamigeris* (Carpenter, 1857) and abundant *B. elegans*.

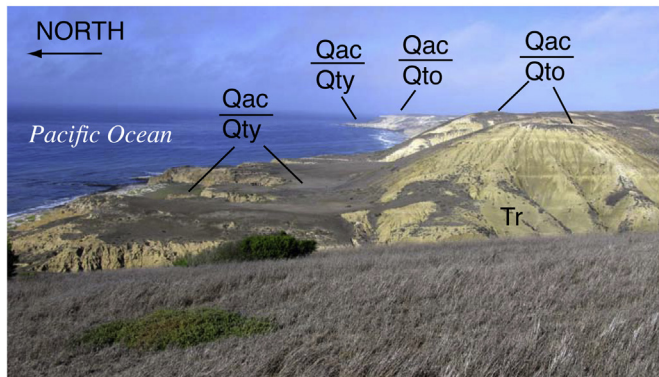
On the south side of Santa Rosa Island, at Johnsons Lee (Fig. 8), two low-elevation terraces are also present. Canyons cutting through this terrace complex expose a broad (~100–150 m in a shore-normal sense) wave-cut bench with an outer edge elevation of ~12–14 m. Although thick alluvium blankets the marine terrace deposits, it is possible to trace the wave-cut bench landward and observe shoreline angles (~20 m elevation) in three transects (Fig. 10b, c, d). Just southwest of transect #1, below the outer edge of the broad, ~20 m terrace, there is a lower terrace with a shoreline angle elevation of ~5.4 m (Fig. 10a). The wave-cut benches of both the ~5.4 m and ~20 m terraces at Johnsons Lee have minor fault displacements. The 1st (~5.4 m) and 2nd (~20 m) terraces at Johnsons Lee are likely the equivalents of the 1st and 2nd terraces on the northern coast of Santa Rosa Island, based on amino acid geochronology, discussed later.

As with the terrace deposits on the northern side of the island, the fossils on terraces at Johnsons Lee constitute a rocky-shore assemblage. The 2nd terrace, at locality SRI-4 (Figs. 8 and 10b), has deposits that contain *E. californica*, *G. carpenteri*, *Mytilus californicus*, *C. biplicata*, *Chlorostoma*, *C. californicus*, *Serpulorbis squamigeris*, *Haliotis*, *Acmaea*, and numerous specimens of *B. elegans*. Deposits of the 1st terrace at SRI-14 and SRI-15 (Figs. 8 and 10a) contain a less diverse, but similar rocky-shore assemblage, including *E. californica*, *C. biplicata* and limpets, with rare *B. elegans*.

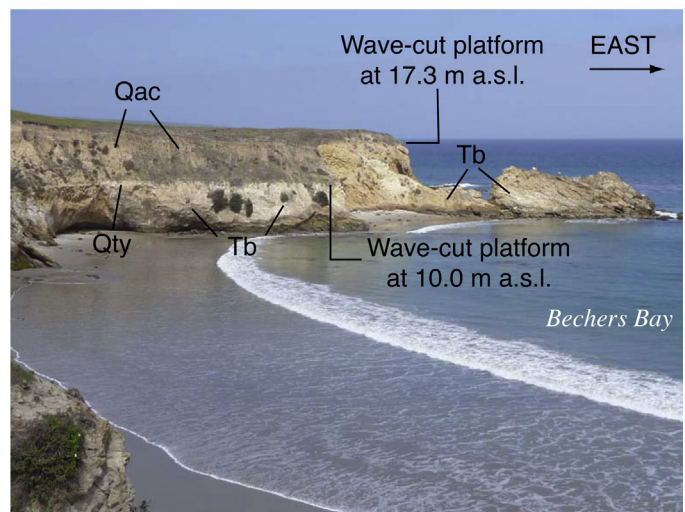
On the eastern side of Santa Rosa Island, around Bechers Bay (Fig. 8), only a single, low-elevation marine terrace was observed. Although thin marine sands and gravels are visible resting on a wave-cut bench in sea cliff exposures, eolian sand, alluvium, and colluvium blanket most of what is mapped as the late Quaternary marine terrace (Qty) in this area (Figs. 7b, c, d and 11). The terrace platform and deposits were examined in all shore-normal-trending canyons of the Bechers Bay area. Other than in the Southeast Anchorage area (Fig. 8), discussed below, shoreline angles were not observed. Thus, in most of the Bechers Bay area, the highest-elevation wave-cut platforms provide only minimum-limiting elevations and the lowest-elevation bedrock exposures on the paleo-sea cliff provide maximum-limiting elevations. By these criteria, north of the Santa Rosa Island fault, along transect #5 (Water Canyon), the shoreline angle must lie between ~19.4 m and ~25.0 m and on transect #6 (Torrey Pines trailhead), it must lie between ~14.6 m and ~28.4 m (Figs. 8 and 11a, b). It is estimated that the likely elevation of the shoreline angle is ~20–23 m above sea level in these two canyons. This estimate is similar to the elevations of 2nd terrace along the southern and northwestern sides of Santa Rosa Island (Figs. 9 and 10).

South of the Santa Rosa Island fault, a wave-cut platform and inferred shoreline angles are exposed inland of Southeast Anchorage (Fig. 8; transects #18, 19) over a shore-normal distance of ~150 m (Fig. 11c, d). This wave-cut platform has a lag gravel with very well-rounded pebble- and cobble-sized clasts, in turn overlain

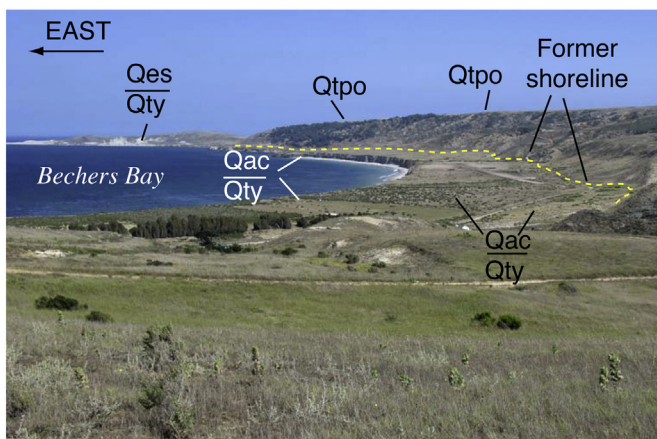
(a) Near Arlington Canyon



(b) Headlands near Santa Rosa Island fault



(c) Bechers Bay, looking south



(d) South of Carrington Point

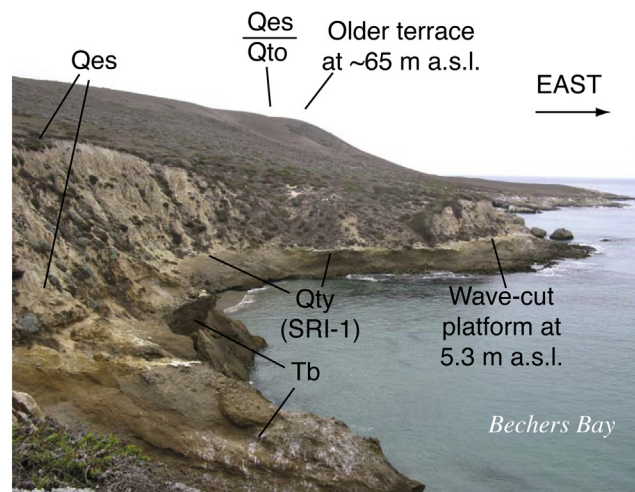


Fig. 7. Views of marine terrace mapping units shown in Fig. 8 on Santa Rosa Island, near (a) Arlington Canyon, (b) Bechers Bay, near the Santa Rosa Island fault, (c) Bechers Bay, looking south, and (d) northern Bechers Bay, south of Carrington Point, and SRI-1 fossil locality. Unit designations as in Figs. 4 and 5, except “Tr” is Rincon Formation and “Tb” is Bechers Bay (informal) formation (Weaver et al., 1969).

by remnants of eolian sand that have been carved into yardang-like landforms. The outer, seaward edge of this platform is as low as ~2.6 m and the shoreline angle is only ~13 m to ~15 m above sea level. The outer edge of this terrace can be traced continuously northward to Water Canyon and beyond. Although more study is needed, the lower elevation of the shoreline angle of the terrace at Southeast Anchorage, south of the Santa Rosa Island fault, compared to north of the fault (at Torrey Pines and Water Canyon) indicates that the southern portion of the late Quaternary terrace may have been displaced downward as much as ~5 m or more since terrace formation. Near the Santa Rosa Island fault itself, shoreline angles are not exposed, but the outer edge of the wave-cut platform is well exposed (Fig. 7b). Measurements of the outer platform elevations were made in a north-to-south, shore-parallel transect across the fault and indicate that it is likely that there has been vertical, post-terrace movement along the Santa Rosa Island fault in the late Quaternary (Figs. 7b and 12). On the north side of the fault, the outer edge of the platform has an elevation of 17.3 m, whereas on the south side of the fault, the outer edge of the platform has an elevation of 10.0 m.

Farther north in Bechers Bay, eolian sand covers much of the terrace complex from Carrington Point to a point ~2 km south of it

(Fig. 7d). The outer edge of the wave-cut platform in this eolian-sand-covered area appears to be laterally traceable with the wave-cut platform farther south, all the way to the Santa Rosa Island fault. However, elevations of the outer edge of the wave-cut platform just south of Carrington Point are significantly lower, ranging from ~4.5 to ~5.5 m. Unlike the rest of the Bechers Bay area, however, the terrace deposits exposed for ~2 km south of Carrington Point are fossiliferous (localities SRI-1, 1B, 1C on Fig. 8). At SRI-1, a typical rocky-shore assemblage was found including, among other taxa, *E. californica*, *G. carpenteri*, *M. californicus*, *C. biphlicata*, *Chlorostoma*, *C. californicus*, *S. squamageris*, *Haliotis rufescens*, *Lottia scabra* (Gould, 1846), *Hipponix tumens* Carpenter, 1864, as well as three specimens of *B. elegans*.

3.3. Uranium-series ages of marine terrace corals

On San Miguel Island, five corals from the 2nd terrace (loc. SMI-236 on Fig. 5) yielded ages ranging from 121.2 ± 0.5 ka to 113.8 ± 0.7 ka (Table 2). All five corals have U contents similar to living specimens of *B. elegans*, indicating no significant gain or loss of U. Concentrations of Th are low and $^{230}\text{Th}/^{232}\text{Th}$ activity values are high, both of which indicate little or no contribution of

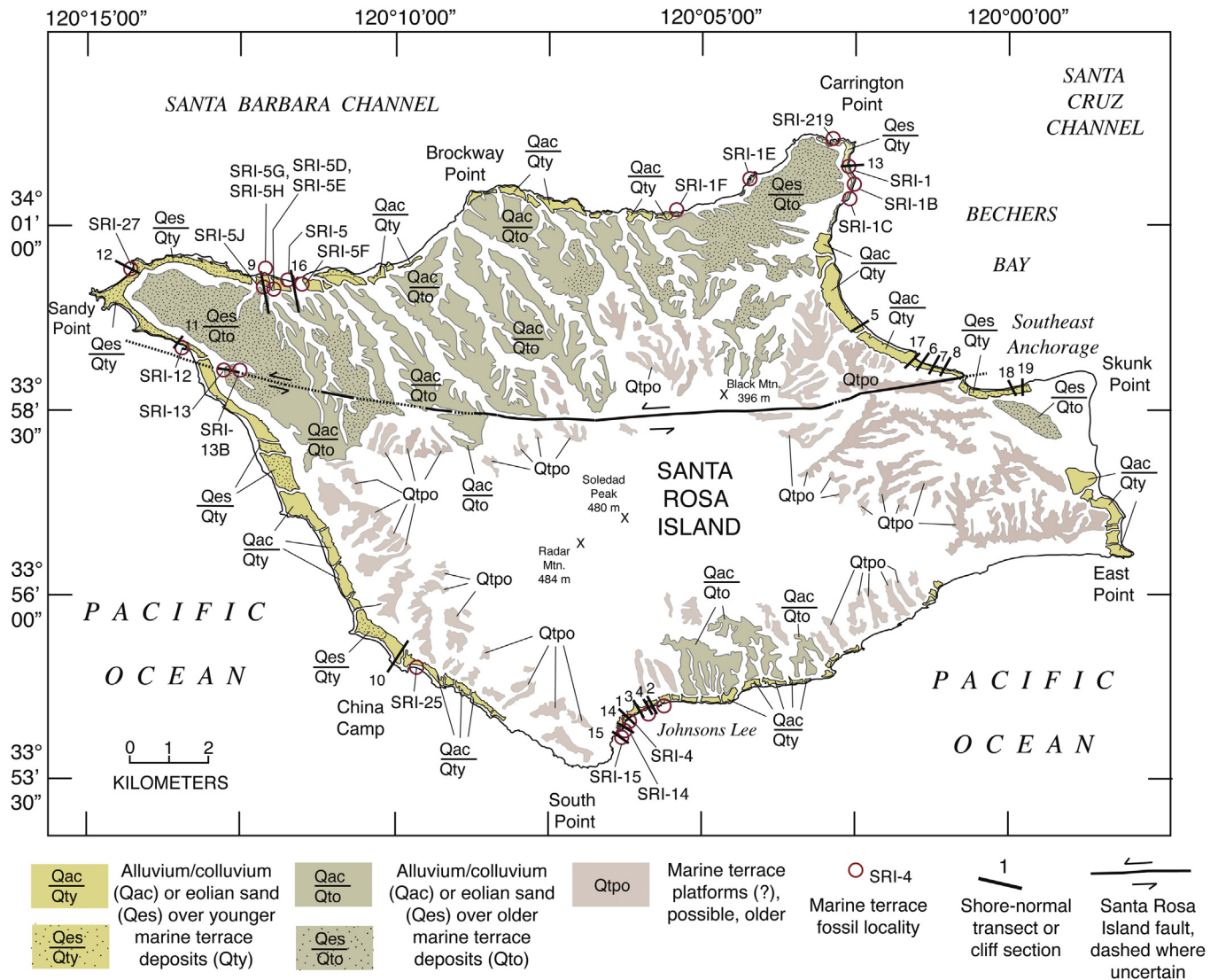


Fig. 8. Map of Santa Rosa Island, showing marine terrace deposits and other surficial deposits, fossil localities, and locations of shore-normal elevation transects or cliff sections. White areas are pre-Quaternary bedrock, in places overlain by eolian deposits, alluvium or colluvium. All mapping done by the authors except some of the “Qto” delineations are slightly modified from Weaver et al. (1969). Note that unit designated as “Qtpo,” possible marine terrace platforms, may or may not have overlying marine and/or terrestrial deposits. Long, black, arcuate line shows location of Santa Rosa Island fault, taken from Weaver et al. (1969).

inherited ^{230}Th from detrital minerals. Modern seawater $^{234}\text{U}/^{238}\text{U}$ activity values average ~ 1.149 (Delanghe et al., 2002) and back-calculated initial $^{234}\text{U}/^{238}\text{U}$ activity values of the San Miguel Island corals (Table 2) are only slightly higher than this. When viewed on an isotopic evolution diagram, the measured $^{234}\text{U}/^{238}\text{U}$ values show that there is probably very little age bias from post-mortem, diagenetic additions of ^{230}Th or ^{234}U . Isotopic values for the San Miguel Island corals fall close to those of corals dated from terrace 2a (~ 120 ka) on San Nicolas Island and are clearly much older than those from terrace 1 (~ 80 ka) on that island (Fig. 13a). The San Miguel Island corals are also similar in age to colonial corals from the Key Largo Limestone of the Florida Keys (Fig. 13b). Hence, the ages are regarded as robust and the terrace is considered to date to ~ 120 ka, MIS 5.5. The single coral analyzed from the 2nd terrace on Santa Rosa Island (SRI-5F, Figs. 8 and 9) also likely dates to this same high sea stand, although there is somewhat less confidence in the apparent age of ~ 121 ka (Table 2). The U content, Th content, and $^{230}\text{Th}/^{232}\text{Th}$ activity values are all within the ranges of values indicating no U gain or loss or inherited ^{230}Th . Nevertheless, the

back-calculated initial $^{234}\text{U}/^{238}\text{U}$ activity value of ~ 1.20 is well above the value for modern seawater, indicating that the apparent age is likely biased old.

Uranium-series ages of corals from an emergent, but low-elevation terrace in western Santa Cruz Island, studied by Pinter et al. (1998a), were updated with the new half-lives for ^{230}Th and ^{234}U given by Cheng et al. (2013) and are also presented in Table 2. These corals have U concentrations within the range typically found in fossil corals from California and have low concentrations of Th, but have $^{230}\text{Th}/^{232}\text{Th}$ values that are not quite as high as the San Miguel Island samples reported here. Although the new half-lives do not change the ages significantly from those given in Pinter et al. (1998a), it is worth pointing out that the lower $^{230}\text{Th}/^{232}\text{Th}$ values (indicating some inherited ^{230}Th from detrital minerals) and the higher-than-modern, back-calculated initial $^{234}\text{U}/^{238}\text{U}$ values probably bias the samples to somewhat older apparent ages (Gallup et al., 1994; Thompson et al., 2003). If this interpretation is correct, then the true ages of the Santa Cruz Island corals are likely similar to those of San Miguel Island (i.e., ~ 120 ka).

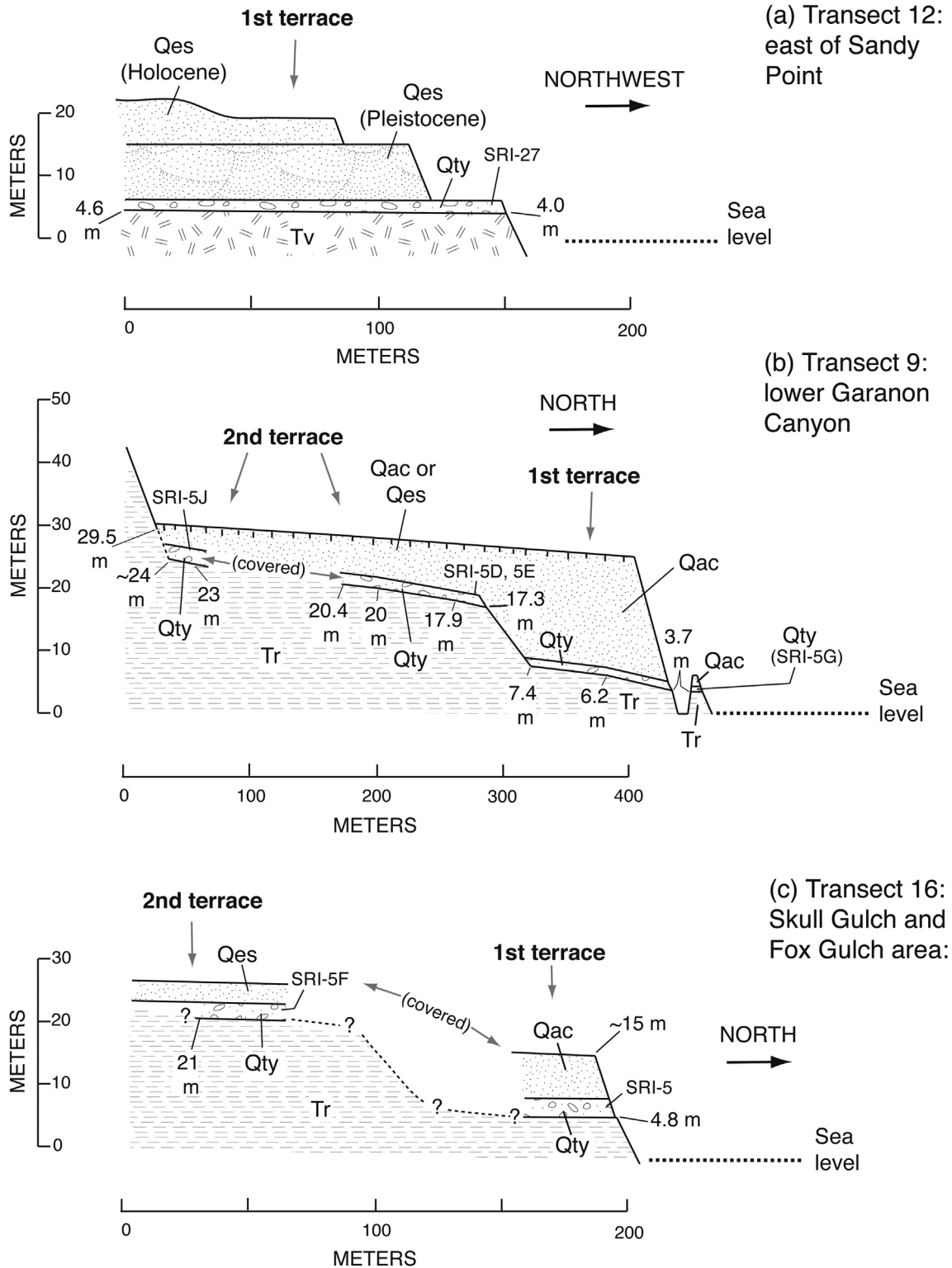


Fig. 9. Shore-normal transects 12, 9, and 16 (Fig. 8) of northwestern Santa Rosa Island, showing marine terraces, elevations from GPS surveys, overlying deposits, and fossil localities. Qac, alluvium and/or colluvium; Qes, eolian sand; Qty, marine terrace deposits, younger; Tr, Rincon Formation; Tv, Tertiary volcanic rocks.

3.4. Aminostratigraphy of marine terrace deposits

Amino acid analyses of fossil *Chlorostoma* (formerly *Tegula*) and *Epilucina* allow correlation of marine terrace deposits on Santa Rosa Island with localities on other islands or on the California mainland

that have been dated by U-series methods on coral. Low-elevation suites of marine terraces dating to the Last Interglacial complex are found at a number of localities along the Pacific Coast of North America, from central California to northern Baja California. Previous work (Muhs et al., 1994, 2002a, 2006, 2012) demonstrates

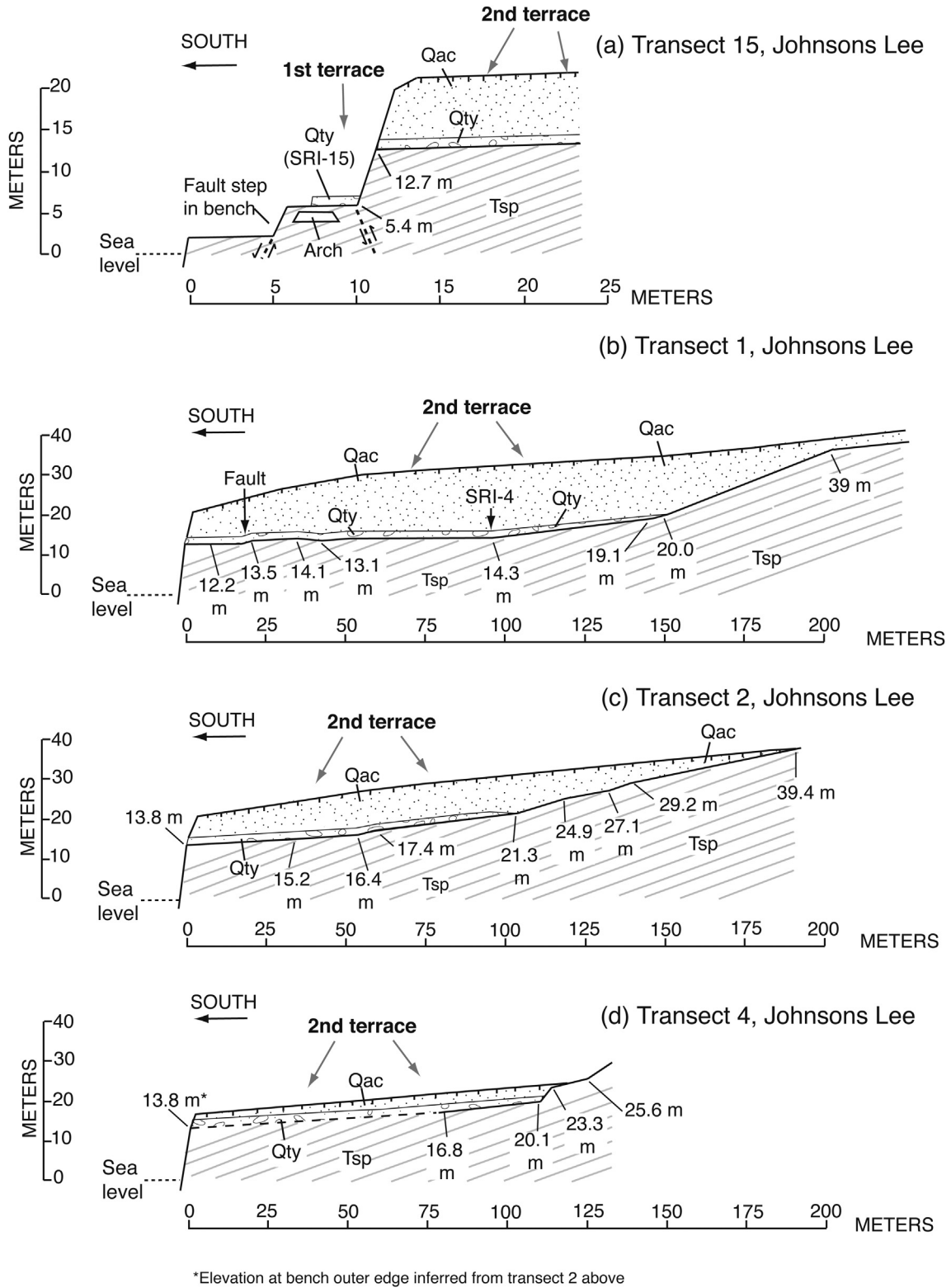


Fig. 10. Shore-normal transects 15, 1, 2, and 4 in the Johnsons Lee area (Fig. 8) of southern Santa Rosa Island, showing marine terraces, elevations from GPS surveys, overlying deposits, and fossil localities. Qac, alluvium and/or colluvium; Qty, marine terrace deposits, younger; Tsp, South Point Formation.

that in some low-elevation terrace pairs, there is an upper terrace that hosts corals dating either to MIS 5.5 (~120 ka) or dating to both MIS 5.5 and MIS 5.3 (~120 ka and ~100 ka), and a lower terrace dating to MIS 5.1 (~80 ka). Such terrace pairs are found at Punta

Banda, Baja California; Point Loma, San Diego County; and the Palos Verdes Hills, Los Angeles County (Figs. 2 and 3). On San Nicolas Island, there are three low-elevation terraces, with the uppermost terrace hosting corals dating solely to ~120 ka (MIS 5.5), the

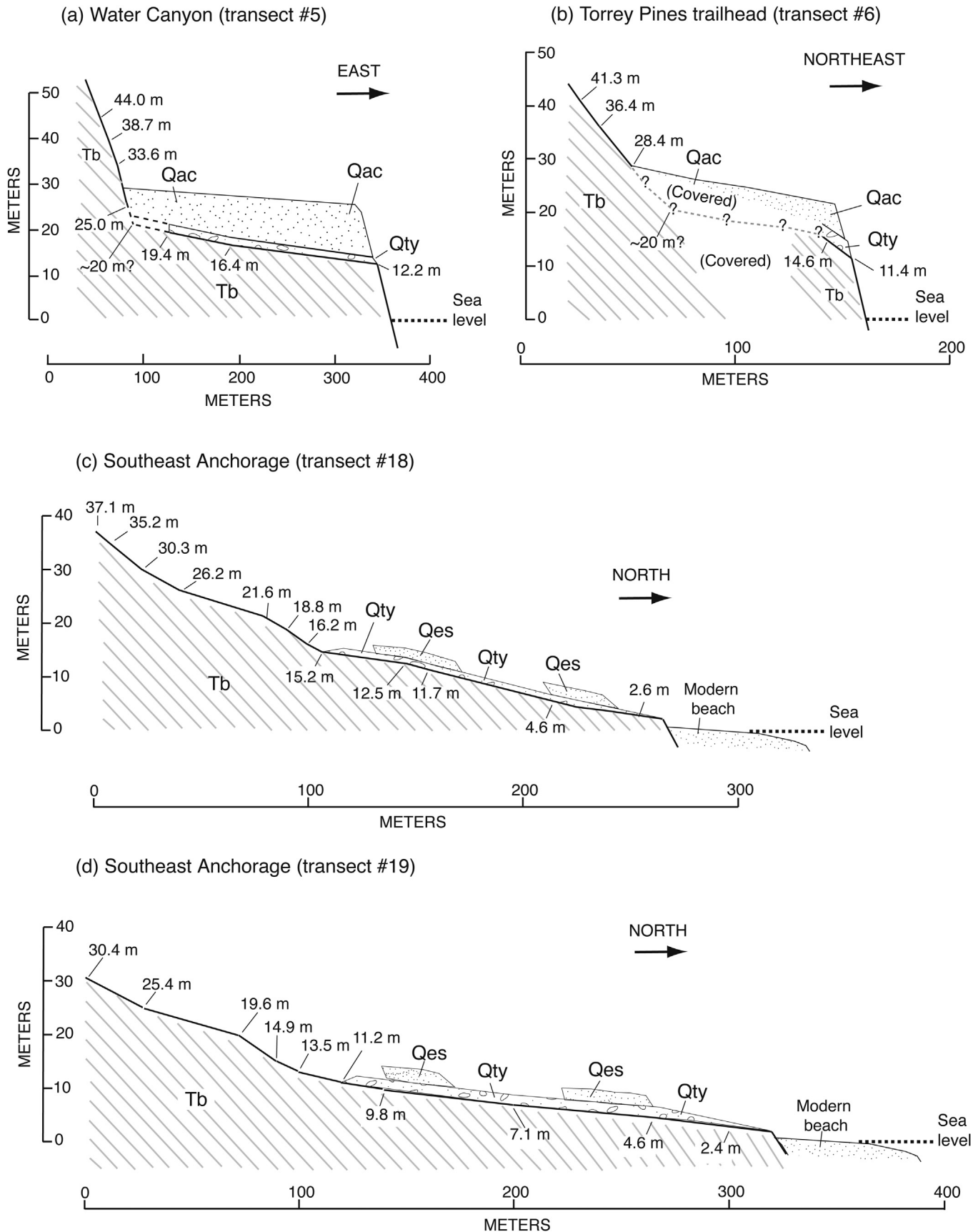


Fig. 11. Shore-normal transects 5, 6, 18, and 19 in the Bechers Bay area of Santa Rosa Island, showing marine terraces, elevations from GPS surveys, and overlying deposits. Qac, alluvium and/or colluvium; Qes, eolian sand; Qty, marine terrace deposits, younger; Tb, Bechers Bay (informal) formation.

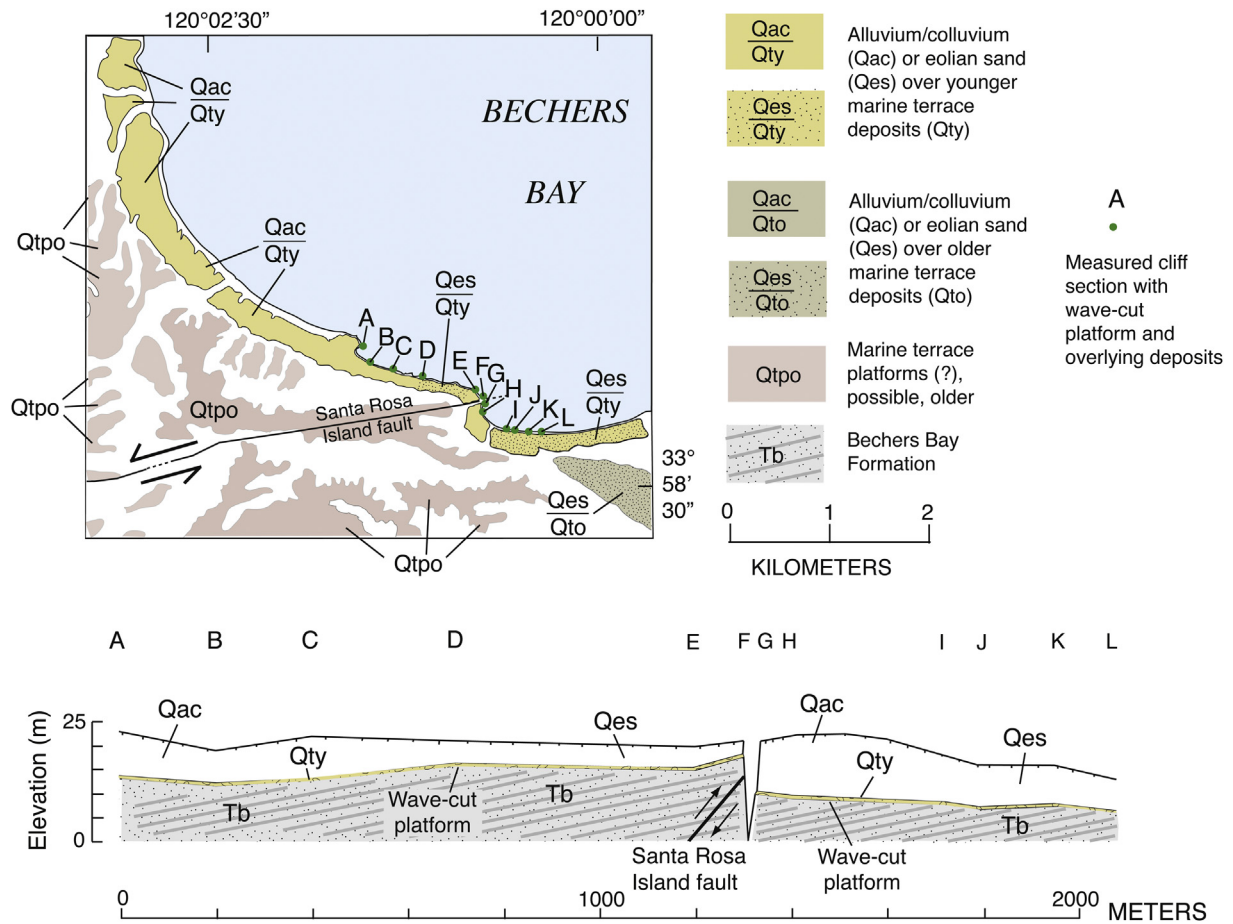


Fig. 12. Shore-parallel transect of outer wave-cut platform exposed in sea cliff (measurement points shown as upper-case letters in geologic map in upper part of figure) in the Bechers Bay area of Santa Rosa Island, showing variable elevations as a function of proximity to the Santa Rosa Island fault. Qac, alluvium and/or colluvium; Qes, eolian sand; Qty, marine terrace deposits, younger; Tb, Bechers Bay (informal) formation. Opposing arrows next to the Santa Rosa Island fault (lower diagram) indicate inferred dip-slip component of fault movement.

intermediate one hosting corals dating to both ~120 ka and ~100 ka (MIS 5.5 and 5.3), and the lower one dating solely to ~80 ka, or MIS 5.1 (Muhs et al., 2012). These localities, along with some others (Point San Luis and Cayucos, San Luis Obispo County) that have been dated to MIS 5.5 or to both MIS 5.5 and 5.3, form the basis for generating amino acid isochron “bands.” Such isochron bands are defined by amino acid ratios in fossils of the same age (dated independently) that decrease as one moves from warmer to cooler regions (see discussion in Wehmiller, 1982, 2013a, 2013b).

Amino acid ratios in fossil *Chlorostoma* from independently dated terrace pairs (120 ka and 80 ka), collected in the present study, do indeed show good relative age discrimination, consistent with earlier studies of this genus (Wehmiller et al., 1977; Muhs, 1983, 1985; Muhs et al., 1992). D/L values for glutamic acid (Fig. 14a) and valine (Fig. 14b) both show clear separations for terrace pairs dated to the ~80 ka high-sea stand and the ~120 ka (or combined ~120 ka and ~100 ka) high-sea stand at Punta Banda, Point Loma, the Palos Verdes Hills, and San Nicolas Island. Furthermore, independently dated ~120 ka or ~120 ka/100 ka marine terrace sites north of San Nicolas Island (San Miguel Island, Point San Luis, and Cayucos) show that amino acid ratios for both valine and glutamic acid decrease northward at these cooler localities.

With evidence that *Chlorostoma* can provide relative age discrimination and allow correlation to dated localities, it is possible to assess ratios in fossils of this genus from undated

localities. On Santa Rosa Island, the northern side of the island is exposed to the cool California Current, whereas the more protected southern side of the island has less exposure to these cool waters. Thus, D/L values in amino acids from fossils at localities from southern Santa Rosa Island are plotted separately from those on northern Santa Rosa Island. Two fossil-bearing localities on the 2nd terrace on southern Santa Rosa Island (SRI-4 at Johnsons Lee and SRI-25 at China Camp; Figs. 8 and 10) have nearly identical D/L values for both glutamic acid and valine (Fig. 14). These values lie between D/L values for these amino acids in *Chlorostoma* from the Paseo del Mar terrace of the Palos Verdes Hills and terrace “2a” on San Nicolas Island, correlating these deposits. Both the Paseo del Mar terrace on the Palos Verdes Hills and terrace “2a” on San Nicolas Island host corals dated to ~120 ka (Muhs et al., 2006). Thus, we infer from the *Chlorostoma* amino acid data that the 2nd terrace on the south side of Santa Rosa Island could be ~120 ka.

Consistent with the assumption of a cooler temperature history, D/L values in *Chlorostoma* from the 2nd terrace on northwestern Santa Rosa Island (SRI-5F; Fig. 9c) are somewhat lower than those in *Chlorostoma* from the 2nd terrace at Johnsons Lee and China Camp (Fig. 14). Nevertheless, D/L values for both valine and glutamic acid from SRI-5F fall well within the latitudinal band of amino acid ratios defined by fossils collected from terraces that have coral U-series ages of ~120 ka (or mixes of ~120 ka and ~100 ka ages). Thus, the amino acid ratios in *Chlorostoma* are in agreement with the apparent U-series age of ~121 ka on the coral from SRI-5F. In

Table 2
U and Th concentrations, isotopic activity ratios (AR) and U-series ages of corals, California (CA) and Baja California Sur (BCS).

Sample#	Location	Species	Aragonite (wt. %)	U (ppm)	²³² Th (+/–) ppm	²³⁴ U/ ²³⁸ U (+/–) AR	²³⁰ Th/ ²³⁸ U (+/–) AR	²³⁰ Th/ ²³² Th (+/–) AR	²³⁰ Th/ ²³⁸ U (+/–) age (ka) ^a	²³⁴ U/ ²³⁸ U initial AR (+/–)
IV-1 ^b	Isla Vista, Goleta, CA	<i>Balanophyllia elegans</i>	≥95	6.20	0.4259	1.1349	0.0040	18.9	49.4	1.1551
SMI-236- A ^c	San Miguel Island, CA	<i>Balanophyllia elegans</i>	100	3.87	0.0073	1.1108	0.0016	1204	118.4	1.1548
SMI-236- B ^c	San Miguel Island, CA	<i>Balanophyllia elegans</i>	100	3.92	0.0140	1.1094	0.0012	642	121.2	1.1541
SMI-236- C ^c	San Miguel Island, CA	<i>Balanophyllia elegans</i>	100	3.81	0.0165	1.1114	0.0015	513	113.8	1.1536
SMI-236- D ^c	San Miguel Island, CA	<i>Balanophyllia elegans</i>	100	3.65	0.0066	1.1143	0.0029	1261	119.8	1.1602
SMI-236- E ^c	San Miguel Island, CA	<i>Balanophyllia elegans</i>	100	3.68	0.0119	1.1173	0.0016	531	119.9	1.1645
SRI-5F ^c	Santa Rosa Island, CA	<i>Balanophyllia elegans</i>	≥95	4.59	0.0164	1.1417	0.0014	675	125.5	1.2019
Scri-1 ^d	Santa Cruz Island, CA	<i>Balanophyllia elegans</i>	≥95	3.03	0.2824	1.1270	0.0036	27	135.9	1.1864
Scri-2 ^d	Santa Cruz Island, CA	<i>Balanophyllia elegans</i>	≥95	4.01	0.0747	1.1340	0.0020	130	128.0	1.1923
Scri-3 ^d	Santa Cruz Island, CA	<i>Balanophyllia elegans</i>	≥95	3.38	0.12	1.1819	0.0030	46	138.6	1.1733
PC ^e	Punta Chivato, BCS	<i>Porites californica</i>	99	3.31	0.11	1.059	0.0016	1195	117.7	1.1476
IC ^e	Isla Coronados, BCS	<i>Pavona gigantea</i>	97	3.19	0.0078	1.1212	0.0016	980	127.2	1.1735

All samples analyzed in laboratories of the U.S. Geological Survey, Denver, Colorado USA; all uncertainties are two-sigma.

^a Ages calculated with new half-lives of ²³⁰Th = 75,584 and ²³⁴U = 245,620 (Cheng et al., 2013).

^b Age reported by Gurtola et al. (2014), but isotopic data reported for the first time in the present study.

^c Isotopic data and ages reported for the first time in the present study.

^d Isotopic data also reported by Pinter et al. (1998a), but ages and initial ²³⁴U/²³⁸U values recalculated using half-lives of Cheng et al. (2013) in the present study.

^e Ages reported by Johnson et al. (2007), but isotopic data reported here for the first time; ages and initial ²³⁴U/²³⁸U values recalculated using half-lives of Cheng et al. (2013) in the present study.

contrast, amino acid ratios in *Chlorostoma* collected from the 1st terrace on northern Santa Rosa Island (SRI-27; Figs. 8 and 9), are significantly lower than those in shells of this genus from SRI-5F on the 2nd terrace (Fig. 14). Amino acid ratios in *Chlorostoma* shells from SRI-27 on the 1st terrace fall well within the latitudinal band of amino acid ratios from dated, ~80 ka terraces elsewhere in southern California and northern Baja California.

In the Bechers Bay area of eastern Santa Rosa Island, there is only a single fossil locality that yielded a sufficient number of *Chlorostoma* shells for amino acid analyses, at SRI-1 (Figs. 7d and 8). For both glutamic acid and valine, *Chlorostoma* shells from this locality give D/L values that are intermediate between those of fossil locality SRI-5F (~120 ka) and locality SRI-27 (interpreted to be ~80 ka). The *Chlorostoma* shells from SRI-1 have D/L values that are similar to those of locality SMI-236 on San Miguel Island, where corals are dated to ~120 ka (Fig. 14). San Miguel Island is, however, influenced even more by the cool California Current. It is possible, therefore, that fossils in the deposit at SRI-1 date to the ~120 ka high-sea stand or perhaps the ~100 ka high-sea stand, but it is unlikely they date to the ~80 ka high-sea stand. U-series analyses of corals from SRI-1 may shed greater light on the age of these terrace deposits.

Consistent with past studies (Wehmiller et al., 1977; Muhs, 1983, 1985; Muhs et al., 1992), *Epilucina* does not seem to be as effective an age discriminator as *Chlorostoma* (Fig. 15). Nevertheless, the relative age difference between the 1st terrace (SRI-27) and the 2nd terrace (SRI-5F, ~120 ka) on northwestern Santa Rosa Island is also apparent from the *Epilucina* amino acid data. Furthermore, at two localities of the 1st terrace on southern Santa Rosa Island (SRI-12 and SRI-14), where we were unable to find *Chlorostoma* fossils, *Epilucina* shells have amino acid ratios that confirm correlation of this terrace to the ~80 ka high-sea stand. *Epilucina* shells from the 2nd terrace at Johnsons Lee (SRI-4), however, give D/L values somewhat lower than do *Chlorostoma* shells from this locality.

Overall, the amino acid data from Santa Rosa Island, particularly those from *Chlorostoma*, indicate that the 2nd terrace, on both the north and south sides of the island, likely correlates to the ~120 ka high sea stand and the 1st terrace likely correlates to the ~80 ka high-sea stand. It is worth noting, however, that amino acid data from the 2nd terrace on both San Miguel Island and Santa Rosa Island permit an interpretation that this terrace may be a composite feature, with initial formation during the ~120 ka high-sea stand and later reoccupation by the ~100 ka high-sea stand, as is the case with some of the terraces found elsewhere in California (Cayucos, San Nicolas Island, and Point Loma; see Muhs et al., 2002a, 2012). One possible interpretation for the 2nd terrace at SRI-4, based on the amino acid data, is that the *Chlorostoma* shells date from the ~120 ka high-sea stand and the *Epilucina* shells date from the ~100 ka high-sea stand.

3.5. Paleozoogeography of San Miguel Island and Santa Rosa Island fossil faunas

The terrace deposits at fossil locality SMI-236 on San Miguel Island, where the ~120 ka corals were collected, contain molluscan species with both southern (warmer) and northern (cooler) affinities. Deposits at SMI-236 contain four southward-ranging species of mollusks. These include *Chione* sp., *Ceratostoma* cf. *Ceratostoma nuttalli*, *S. squamigeris*, and *Zonaria spadicea* (Swainson, 1823) (Fig. 16). Although the *Chione* specimens were not identified to species, all species of this genus residing in the eastern Pacific Ocean at present live no farther north than the Goleta–Santa Barbara area (Coan et al., 2000). *S. squamigeris* ranges into central California, but generally only as individuals; the occurrence of this species as twisted masses of multiple individuals (as at SMI-236) is

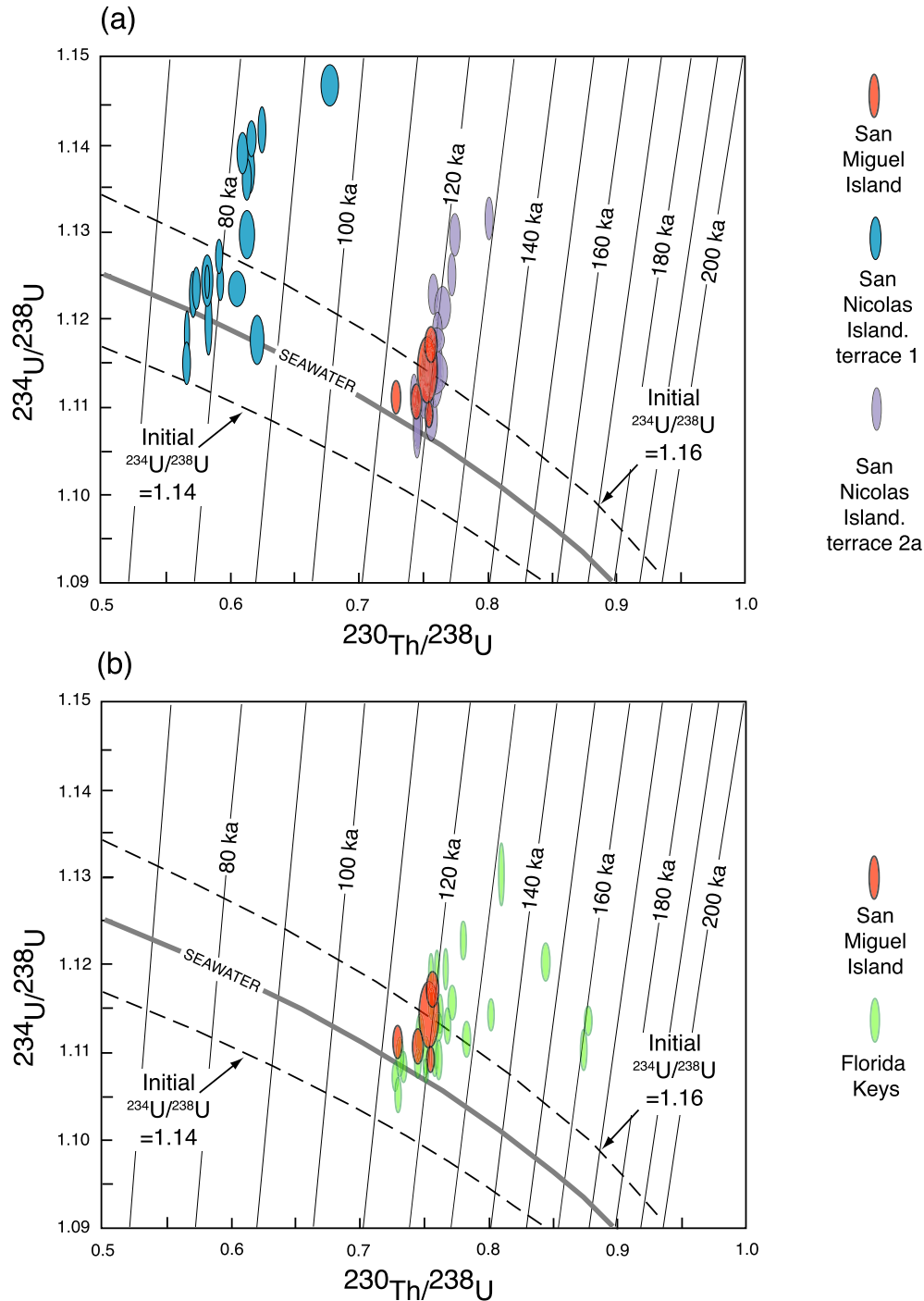


Fig. 13. Isotopic evolution curves (dashed lines) showing sympathetic variation in $^{230}\text{Th}/^{238}\text{U}$ and $^{234}\text{U}/^{238}\text{U}$ activity ratios over time in materials with no initial ^{230}Th and with different initial $^{234}\text{U}/^{238}\text{U}$ activity ratios that define the bounds of modern seawater. Age in thousands of years (ka) is shown by isochrons (thin solid lines). Reddish-brown ellipses define the measured values and 2-sigma uncertainties, as calculated using Isoplot/Ex software (Ludwig, 2001) for fossil corals (*Balanophyllia elegans*) from locality SMI-236 on San Miguel Island (Fig. 5). Also shown for comparison are (a) measured values of fossil corals (also *Balanophyllia elegans*) from the lowest two marine terraces on western San Nicolas Island (data from Muhs et al., 2006) and (b) measured values from fossil corals of the Key Largo Limestone, Florida (data from Muhs et al., 2011). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

limited to the region south of Point Conception (McLean, 2007). Although *C. nuttalli* (Conrad, 1837) and *Z. spadicea* currently range somewhat north of San Miguel Island, their occurrence north of Point Conception (Fig. 1) is rare and they live dominantly in warmer waters to the south (McLean, 1978).

In addition, however, locality SMI-236 also contains five northward-ranging species of mollusks and one extralimital

northern species. *Calliostoma ligatum* (Gould, 1849) *Chlorostoma brunnea* (Philippi, 1849), *H. rufescens* (Swainson, 1822), *Ocenebrina lurida* (Middendorff, 1848) and *Cryptochiton stelleri* Middendorff, 1847 all have modern ranges that extend somewhat south of Point Conception (Figs. 1 and 16), but their occurrences south of this major faunal boundary are very rare (McLean, 1978; Abbott and Haderlie, 1980; Haderlie and Abbott, 1980). Furthermore, SMI-236

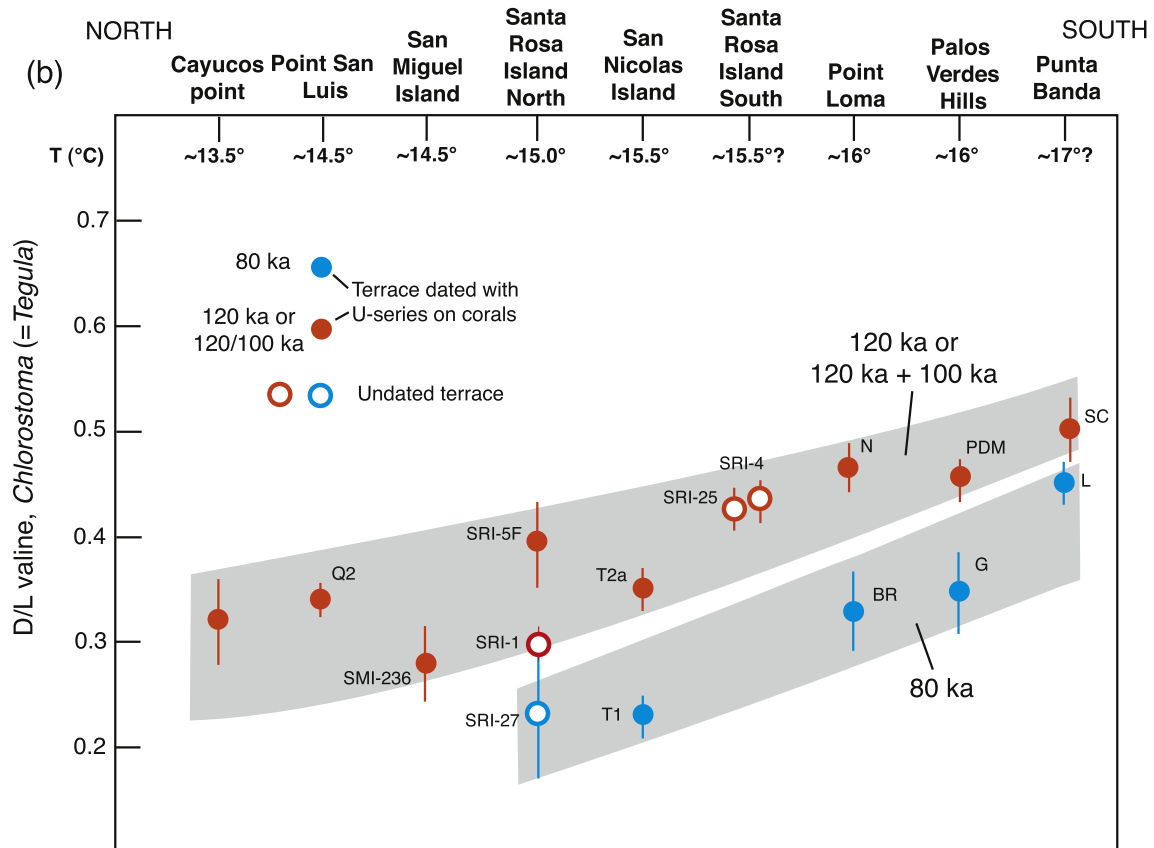
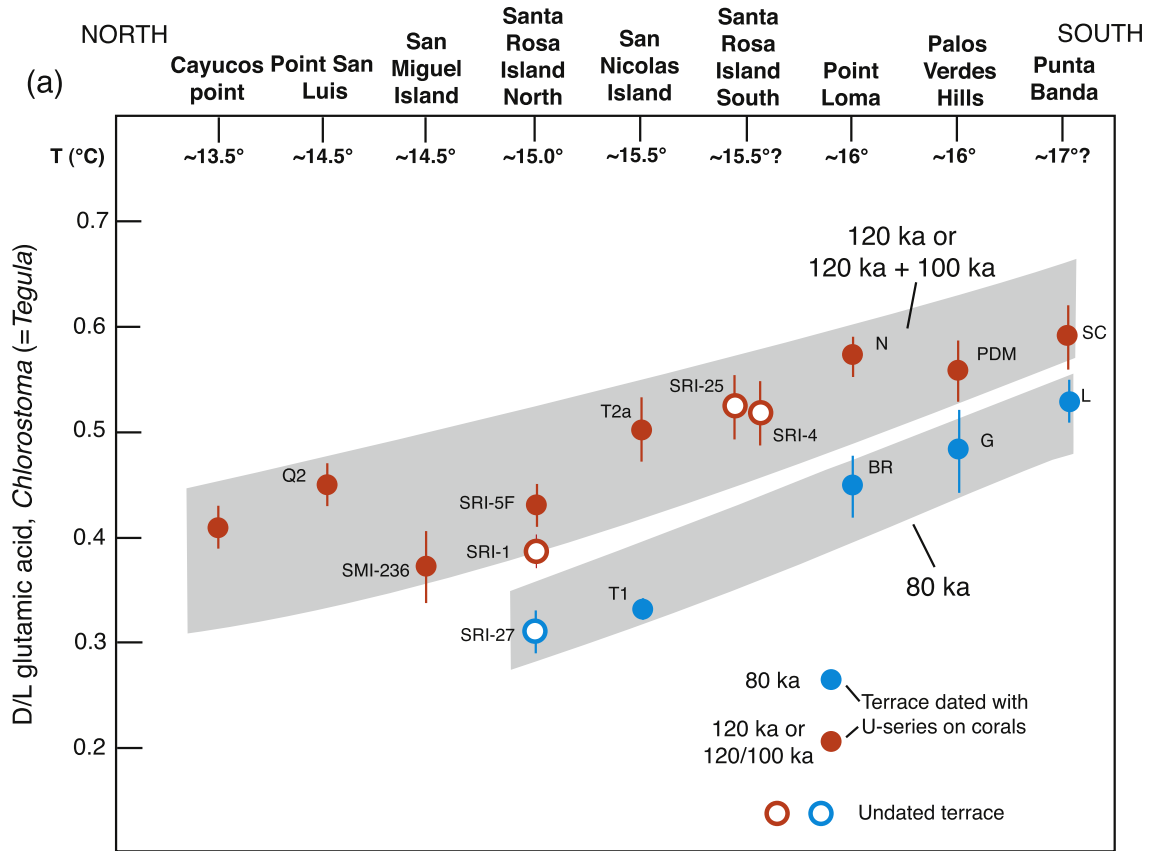


Fig. 14. (a) Plot of mean D/L values in glutamic acid (vertical axis) in fossil *Chlorostoma* (formerly *Tegula* (McLean, 2007)) from dated (filled circles) and undated (open circles) marine terraces on the California and Baja California coast, shown as a function of approximate present mean annual air temperature (horizontal axis). Error bars are ± 1

includes specimens of the extralimital northern gastropod *Harfordia harfordi* (Stearns, 1871). This species has a modern distribution from Hope Island, British Columbia (Abbott, 1974) south only to Cormorant Cove, Mendocino County, California (Fig. 1), based on records of the Natural History Museum of Los Angeles County (Los Angeles County Museum, or LACM 94-4.30).

On Santa Rosa Island, Orr (1960, 1968) reported a fauna from the 2nd terrace, collected at or very close to our fossil localities SRI-5-D, E, F, and J, based on records obtained through the courtesy of Dr Paul Valentich-Scott of the Santa Barbara Museum of Natural History. An examination of this fossil list with updated, modern zoogeography reveals that the 2nd terrace on Santa Rosa Island also contains a mix of species with differing thermal aspects. Southward-ranging species include *Astraea undosa* (= *Megastraea undosa* (Wood, 1828)) and *Aletes squamigeris* (= *S. squamigeris*), both of which have present ranges that occur no farther north than Point Conception (McLean, 2007) or San Luis Obispo County (LACM collections) but extend well into central Baja California. Orr (1960, 1968) also reports *Acmaea conus* (= *Lottia conus* (Test, 1945)), which ranges from Point Conception to as far south as southern Baja California (McLean, 1978). Also present is a chiton, *Stenoplax conspicua* (= *Stenoplax conspicua* (Pilsbry, 1892)) that, according to Keen (1971), has Santa Barbara as its modern northern range endpoint and lives as far south as Bahía Sebastián Vizcaino, Baja California (Fig. 1). *Siphonaria brannani* Stearns, 1873 is a limpet whose modern distribution is no farther north than Santa Barbara and whose southern range limit is Santa Catalina Island (Abbott, 1974) or possibly Cabo San Lucas, Baja California Sur (Fig. 1), based on information in Keen (1971). On the other hand, according to Orr (1960, 1968), deposits of the 2nd terrace also host *C. stelleri*, which presently is rare south of Monterey Bay and *H. rufescens*, which is uncommon south of Point Conception, as discussed above. In addition, Orr (1960, 1968) reports that the 2nd terrace hosts an extralimital northern gastropod, *Stylidium eschrichtii* (Middendorff, 1849), which ranges from the Kenai Peninsula of Alaska or possibly Ketchikan, Alaska [LACM 165048] to only as far south as San Luis Obispo County, California [LACM 16052]. Finally, Orr (1960, 1968) reports a fossil sea urchin in deposits of the 2nd terrace, *Strongylocentrotus droebachiensis* (Müller, 1776), which presently lives from Arctic Alaska only as far south as southern Oregon (O'Clair and O'Clair, 1998; Pearse and Mooi, 2007).

Overall, the marine terrace faunas from the 2nd terraces on both San Miguel Island and Santa Rosa Island show about equal numbers of species with northern affinities and southern affinities (Fig. 16). Thus, by analogy with similar “thermally anomalous” fossil assemblages reported elsewhere in southern California (Muhs et al., 2002a, 2012, 2014), it cannot be assumed that deposits of the 2nd marine terraces on these two islands contain only ~120 ka fossils, despite the U-series ages of 120 ka for corals from both islands. Initial terrace formation at ~120 ka (with a warm-water fauna), followed by terrace reoccupation at ~100 ka (with a cool-water fauna), must be considered as a possible scenario in interpretation of the marine terrace record of the northern Channel Islands.

3.6. Late Quaternary uplift rates on the northern Channel Islands

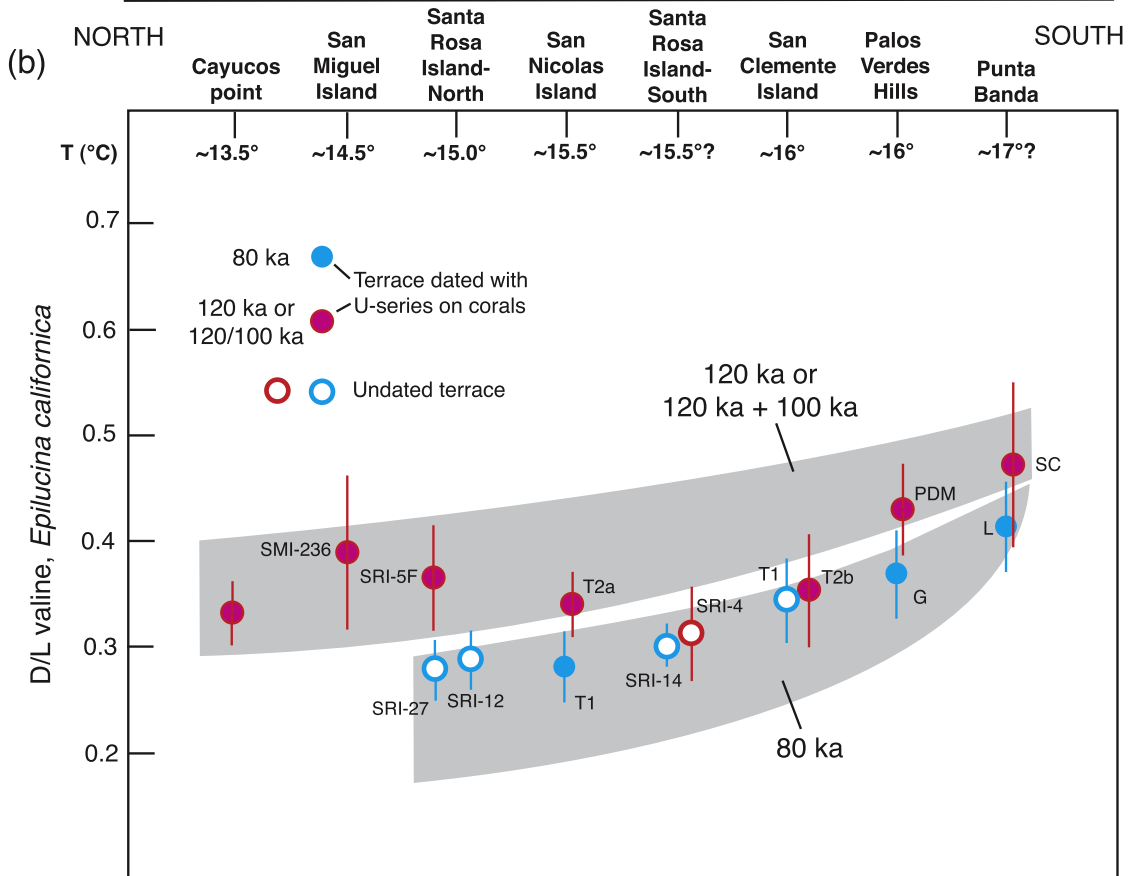
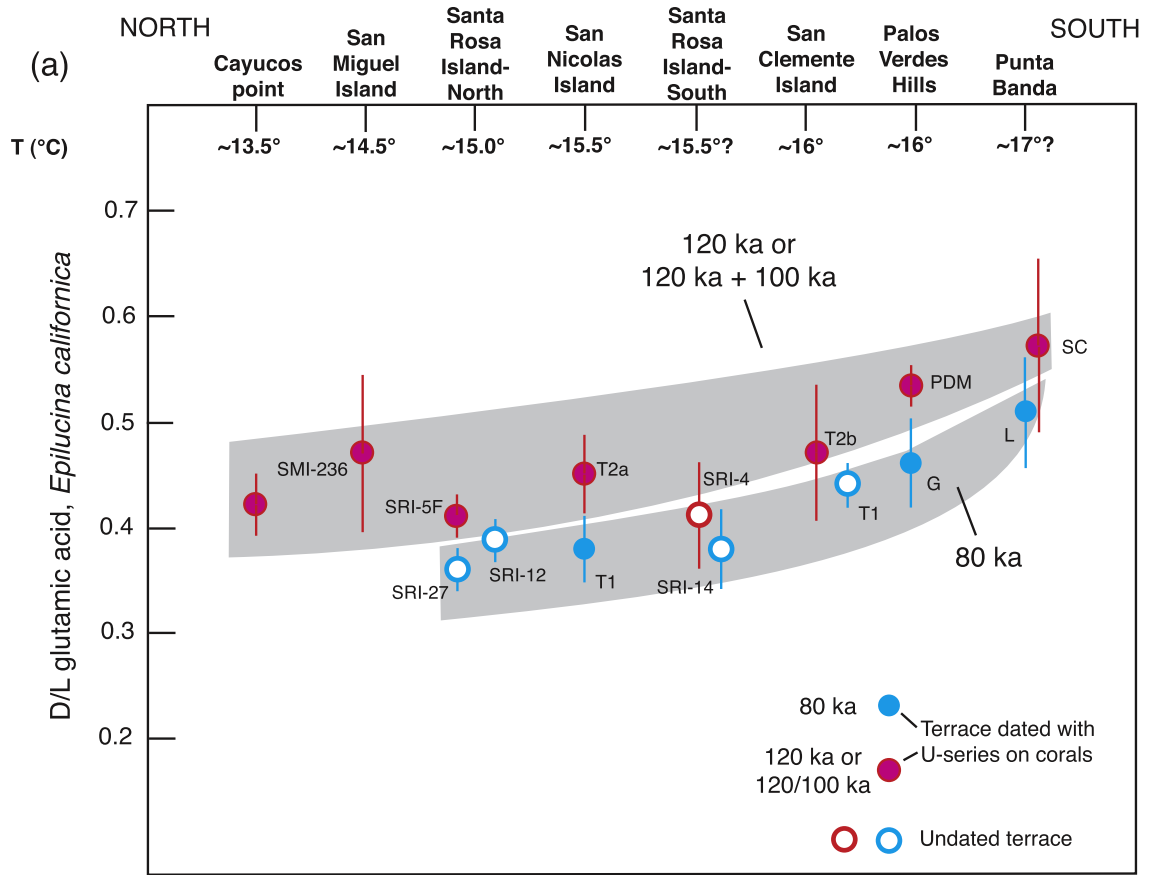
Three measurements are required for calculation of late Quaternary uplift rates on the northern Channel Islands, including marine terrace elevations, terrace ages, and paleo-sea level at the time of terrace formation. Here, measured or estimated shoreline

angle elevations from the 2nd terrace of southern San Miguel Island and both northern (Garañon Canyon area) and southern (Johnsons Lee) Santa Rosa Island are used. Ages are those from U-series dating of corals (~120 ka for both islands), supported by aminostratigraphic correlation of the 2nd terraces to U-series-dated, ~120 ka terraces elsewhere.

For estimates of paleo-sea level at the time of terrace formation at ~120 ka, it is necessary to use elevations of well-dated marine deposits of this age from tectonically stable coastlines that are distant from active plate boundaries. Murray-Wallace and Woodroffe (2014) point out that most neotectonic studies use a value of about +6 m for a paleo-sea level estimate during the peak of the Last Interglacial period at ~120 ka. These authors note, however, that this value is simply a rough average of emergent reef elevation measurements ranging from about +2 m to about +9 m in tectonically stable areas, taken largely from a pioneering study by Veeh (1966). Murray-Wallace and Woodroffe (2014) point out that the apparent magnitude of paleo-sea level rise at ~120 ka will vary geographically with the nature of the sea-level record and the relative importance of a suite of glacial isostatic adjustment (GIA) processes. In order to provide the best estimate of the magnitude of paleo-sea level at ~120 ka for the present study, measurements from tectonically stable parts of North America are considered here. Muhs et al. (2011) report reef elevation measurements of +3 m to +5 m and therefore derive paleo-sea level estimates of +6 m to +8 m (assuming water depths of at least 3 m) for the ~120 ka Key Largo Limestone of the Florida Keys, an island chain found in a tectonically stable region of North America. Closer to the Channel Islands, marine deposits on Isla Guadalupe, off Baja California (Fig. 1), also contain corals with U-series ages of ~120 ka (Muhs et al., 2002a). Lindberg et al. (1980) report that emergent marine deposits on Isla Guadalupe have elevations of 1–8 m above sea level, with most localities described as 1–6 m above sea level, in good agreement with the measurements of the ~120 ka Key Largo Limestone. Isla Guadalupe is attractive as a reference locality for estimating paleo-sea level at ~120 ka in California because it is distant from any plate boundary, has no active faults nearby, has no active volcanoes on it 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). Paleo-sea level estimates at ~120 ka from both the Florida Keys (+6 m to +8 m) and Isla Guadalupe (reported maximum elevations of +6 to +8 m) are consistent with global estimates of the eustatic component of sea level at this time (+5.5 m to +9 m) from compilations done by Kopp et al. (2009) and Dutton and Lambeck (2012). Both of these global compilations include considerations of glacial isostatic adjustment (GIA) effects.

Using the measurements described above, calculated late Quaternary uplift rates on San Miguel Island and Santa Rosa Island do not differ significantly from one another and both are relatively low. On San Miguel Island, shoreline angle elevation estimates range from ~21 to ~24 m and average ~22 m (Fig. 6). Subtracting 6 m (paleo-sea level at ~120 ka) from these elevations average yields about 15–18 m of uplift in ~120 ka (U-series ages; Table 2) for uplift rates of 0.12–0.15 m/ka. If the youngest permissible age from San Miguel Island (~114 ka) is used along with an assumption of the same +6 m paleo-sea level, the uplift rate increases only slightly, to 0.13–0.16 m/ka. Use of +8 m as a paleo-sea level at ~120 ka would lower uplift rate estimates to 0.11–0.13 m/ka. At Garañon Canyon, on northern Santa Rosa Island, the 2nd terrace has a shoreline angle

standard deviation, based on D/L values in 4–6 individual shells from the same deposit. Gray bands indicate correlation between fossil localities of the same age based on U-series dating of corals. Terrace name abbreviations: SMI, San Miguel Island, SRI, Santa Rosa Island (localities keyed to Figs. 5 and 8); N, Nestor; BR, Bird Rock; PDM, Paseo del Mar; G, Gaffey; SC, Sea Cave; L, Lighthouse; see Muhs et al. (1994, 2002a, 2006) for terrace stratigraphic names and U-series ages. (b) Same as in (a), but for mean D/L values in valine.



elevation that is estimated to be ~24 m (Fig. 9). Thus, assuming an age of ~120 ka from the U-series age at SRI-5F and the same +6 m paleo-sea level yields an uplift rate of 0.15 m/ka for northern Santa Rosa Island. The shoreline angle elevations of the 2nd terrace at Johnsons Lee range from ~19 m to ~21 m and average ~20 m. Assuming a +6 m paleo-sea level at ~120 ka yields a late Quaternary uplift rate of ~0.12 m/ka. A similar uplift rate can be calculated for the low-elevation marine terrace north of the Santa Rosa Island fault at Bechers Bay (transects #5 and #6 on Figs. 8 and 11), if this terrace dates to the ~120 ka high-sea stand. In Water Canyon and at Torrey Pines, a shoreline angle of ~20 m is estimated, yielding an uplift rate identical to that at Johnsons Lee. Nevertheless, south of the Santa Rosa Island fault, in the Southeast Anchorage area, the terrace at Bechers Bay has a shoreline angle elevation estimated to be 13–15 m (transects #18 and #19 on Figs. 8 and 11). If the terrace in the Southeast Anchorage area dates to the ~120 ka high-sea stand, even lower uplift rates of 0.06–0.08 m/ka are implied. As with San Miguel Island, use of +8 m for a paleo-sea level at ~120 ka would lower all uplift rate estimates for Santa Rosa Island, but only slightly.

4. Discussion

4.1. Marine terrace ages and sea-level history

U-series data from five corals indicate that the 2nd terrace on the south side of San Miguel Island correlates with the ~120 ka high-sea stand, or MIS 5.5. Based on a single coral age (and with a calculated initial $^{234}\text{U}/^{238}\text{U}$ value that is higher than modern seawater), it is likely that the 2nd terrace on Santa Rosa Island also correlates with the ~120 ka high-sea stand. Amino acid data provide further evidence that the 2nd terrace on Santa Rosa Island correlates with the ~120 ka high-sea stand, and that the 1st terrace on that island correlates with the ~80 ka high stand. A qualification noted here is that differing amino acid ratios in *Chlorostoma* and *Epilucina* from the 2nd terrace on the southern side of Santa Rosa Island permit interpretation of a mixture of ~120 ka and ~100 ka mollusks, similar to dated localities in California that have mixtures of ~120 ka and ~100 ka corals. Furthermore, the molluscan faunas from the 2nd terrace on San Miguel Island and the 2nd terrace on Santa Rosa Island contain both southern and northern forms. On Point Loma, San Nicolas Island, and Cayucos, terraces that contain both southern and northern species of fossil mollusks also have corals that yield two groups of U-series ages, ~120 ka and ~100 ka. Muhs et al. (2002a, 2012) hypothesized that the mollusks with warm-water (southern) affinities date to the ~120 ka high-sea stand and mollusks with cool-water (northern) affinities date to the ~100 ka high-sea stand.

A major question that arises in these observations is that based on sea level history from uplifted reefs on New Guinea and Barbados, paleo-sea levels during the high-sea stands at ~80 ka and ~100 ka are estimated to be –15 m to –20 m, relative to present (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; see also Murray-Wallace and Woodroffe (2014), pp. 288–292). New Guinea and Barbados are, however, distant from where Northern Hemisphere ice sheets were located and are considered to be “far field” (New Guinea) or

“intermediate field” (Barbados) localities with respect to GIA effects. Muhs et al. (2012) report that the relative sea levels of both the ~80 ka and the ~100 ka high-sea stands on the California coast were significantly higher (–11 to –12 m at ~80 ka and +2 m to +6 m at ~100 ka, relative to present sea level) compared to New Guinea and Barbados. Because of the closer proximity of California to Northern Hemisphere ice sheets of the Pleistocene, Muhs et al. (2012) inferred that the higher relative sea levels on the California coast are due to GIA processes, and their modeling supports that interpretation. On the tectonically stable Atlantic Coast of the United States (Wehmiller et al., 2004) and Bermuda (Muhs et al., 2002b), marine deposits dated to ~80 ka are found at elevations of 1 m to as much as ~7.5 m above modern sea level. These higher-than-expected elevations have also been explained by GIA effects (Potter and Lambeck, 2003).

If GIA effects have been important on the California coast, then before much uplift of the ~120 ka terrace could take place, the ~100 ka high-sea stand could have overtaken at least the seaward portion of the ~120 ka platform. Mixing of ~120 ka and ~100 ka fossils could have resulted. As with other localities in California with low uplift rates, the faunas in deposits of the 2nd terraces on San Miguel Island and Santa Rosa Island seem to represent mixing of fossils from these two high-sea stands. This explanation, while plausible, could benefit from additional testing, with both U-series geochronology and paleontology.

4.2. Implications for previous estimates of late Quaternary uplift rates of the northern Channel Islands platform

As discussed earlier, there have been highly divergent estimates of late Quaternary uplift rate for the northern Channel Islands platform (Sorlien, 1994; Pinter et al., 1998a, 1998b, 2003; Chaytor et al., 2008). Marine terrace elevations reported here indicate that late Quaternary uplift rates on the northern Channel Islands platform are modest. Uplift rates calculated for San Miguel Island are 0.12–0.15 m/ka and similar uplift rates are calculated for Santa Rosa Island (0.15 m/ka on the north side of the island and 0.12 m/ka on the south side of the island). The uplift rates for San Miguel Island and Santa Rosa Island are very close to those estimated for western Santa Cruz Island, based on data in Pinter et al. (1998a, 1998b, 2003). On western Santa Cruz Island, the lowest terrace, dated to ~120 ka (Table 1; see also Pinter et al. (1998a)) has shoreline angle elevations ranging from ~6 m to ~8 m in the extreme northwestern part of the island and shoreline angle elevations ranging from ~10 m to ~17 m farther to the southeast (Pinter et al., 1998a, 1998b, 2003). These data indicate that the highest uplift rate on Santa Cruz Island would be on the order of 0.09 m/ka. Northwestern Santa Cruz Island may not have experienced any uplift at all in the past ~120 ka, based on shoreline angle elevations of ~6 m–~8 m reported in Pinter et al. (2003).

Thus, late Quaternary uplift rates for San Miguel Island, Santa Rosa Island, and western Santa Cruz Island are all much lower than those proposed for the Channel Islands platform by Chaytor et al. (2008). Using Chaytor et al.'s (2008) uplift rates of 0.9–2.0 m/ka, a marine terrace on San Miguel Island or Santa Rosa Island dating to ~120 ka should now be at elevations of ~114 m (assuming an uplift rate of 0.9 m/ka, plus 6 m for a higher paleo-sea level) to ~246 m (assuming an uplift rate of 2.0 m/ka, plus 6 m for a higher paleo-sea

Fig. 15. (a) Plot of mean D/L values in glutamic acid (vertical axis) in fossil *Epilucina californica* from dated (filled circles) and undated (open circles) marine terraces on the California and Baja California coast, shown as a function of approximate present mean annual air temperature (horizontal axis). Error bars are ± 1 standard deviation, based on D/L values in 4–6 individual shells from the same deposit. Gray bands indicate correlation between fossil localities of the same age based on U-series dating of corals. Terrace name abbreviations: SMI, San Miguel Island, SRI, Santa Rosa Island (localities keyed to Figs. 5 and 8); PDM, Paseo del Mar, G, Gaffey; SC, Sea Cave; L, Lighthouse. See Muhs et al. (1994, 2002a, 2006) for terrace stratigraphic data and U-series ages. (b) Same as in (a), but for mean D/L values in valine.

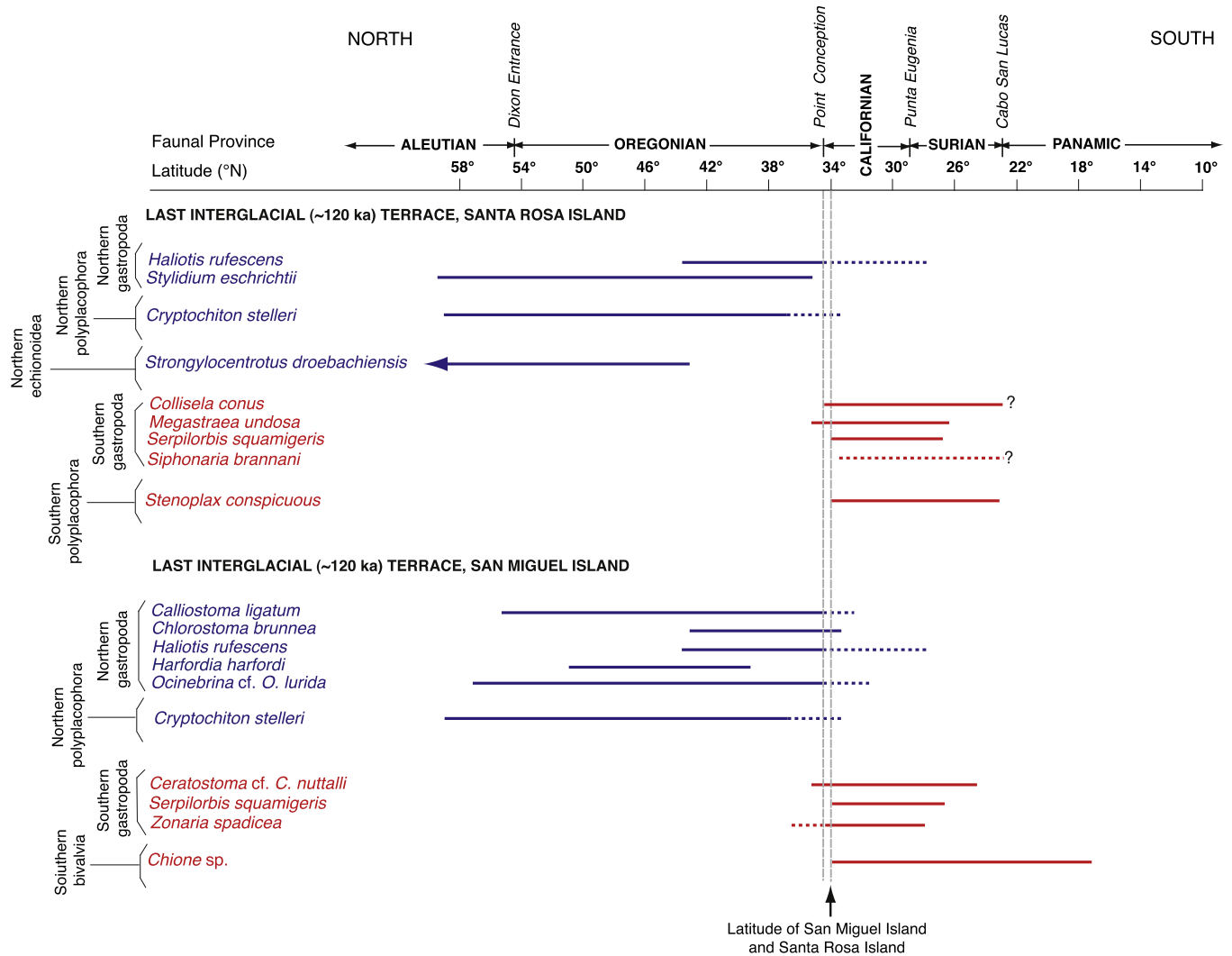


Fig. 16. North–south latitudinal plot showing marine invertebrate faunal provinces (Valentine, 1966) and modern ranges of fossils with paleozoogeographic significance found in the ~120 ka 2nd terraces on Santa Rosa Island and San Miguel Island (ages from Table 2; fossils from Santa Rosa Island are from Orr (1960, 1968); and fossils from San Miguel Island are from this study). Modern geographic ranges are from Coan et al. (2000) for bivalves; Abbott (1974), McLean (1978, 2007), Abbott and Haderlie (1980) and O’Clair and O’Clair (1998), and collections in the Natural History Museum of Los Angeles County for gastropods; and Pearse and Mooi (2007) for echinoids.

level). Terrace mapping and elevation data, combined with U-series and amino acid data presented here, indicate that terraces dating to the ~120 ka high sea stand are at much lower elevations (~20–24 m).

There are a number of possible explanations that can be considered for the apparent differences in uplift rates reported here compared to Chaytor et al. (2008). One possibility is that there is an east-west gradient in uplift rate along the northern Channel Islands, with higher uplift rates to the east, near eastern Santa Cruz Island and Anacapa Island, where Chaytor et al. (2008) made most of their measurements. However, a much better case actually could be made for the opposite trend, with lower uplift rates being apparent on western Santa Cruz Island (Pinter et al., 1998a, 1998b, 2003) and slightly higher uplift rates on Santa Rosa Island and San Miguel Island, farther west. Another possibility is that late Quaternary uplift of San Miguel Island, Santa Rosa Island, and Santa Cruz Island was extremely slow or nonexistent until the LGM. In this scenario, a terrace dating to ~120 ka would form at +6 m, relative to present (Kopp et al., 2009; Muhs et al., 2011; Dutton and Lambeck, 2012), remain at this elevation for ~100 ka, and then experience uplift at a rate of 0.9 m/ka for the

past ~23 ka (using the most conservative uplift rate presented by Chaytor et al. (2008)). Such a terrace would now be at an elevation of ~27 m. This value is only slightly higher than the observed terrace shoreline angle elevations on San Miguel and Santa Rosa Islands, indicating that in principle, such a sequence of events is possible. It is difficult to imagine what geologic scenario might permit tectonic quiescence for ~100 ka and then abruptly bring about rapid uplift for ~23 ka afterward, but there is a more obvious problem with this hypothesis. The presence of marine terraces at higher elevations on all four of the northern Channel Islands indicates that uplift has been in progress throughout much or all of the Quaternary. Thus, a hypothesis of a recent change from absolutely no uplift for ~100 ka to very rapid uplift in the past ~23 ka does not seem likely.

It is proposed that the order-of-magnitude difference between the uplift rates reported in the present study and by Pinter et al. (1998a, 1998b, 2003) versus those of Chaytor et al. (2008) can be explained by different estimates of GIA effects on the California coast. Chaytor et al. (2008) recognized the possibility of GIA effects on the California coast at the time of their study. Nevertheless, the significance of these effects over the course of the Last

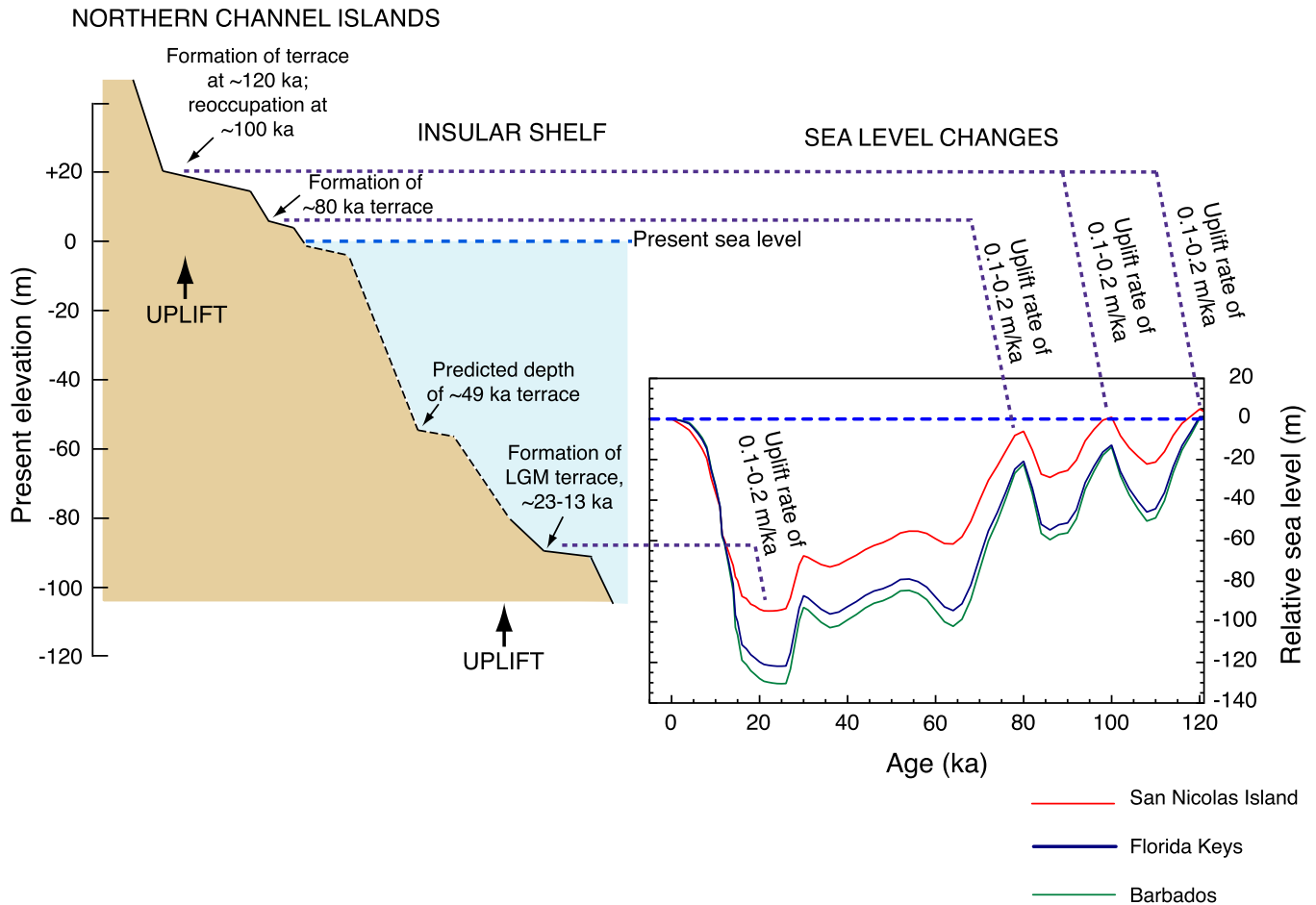


Fig. 17. Model of marine terrace formation (left portion of diagram) on the Channel Islands over the past ~120 ka, assuming a relatively constant uplift rate of 0.1–0.2 m/ka (based on data presented herein) and sea level fluctuations according to glacial isostatic adjustment (GIA) model given in Muhs et al. (2012). Depth and age of Last Glacial maximum (LGM) terrace taken from Chaytor et al. (2008); subaerially exposed higher, older terraces taken from data in the present study. Note that with this model, a terrace dating to ~49 ka should be found off the northern Channel Islands at a present depth of ~55 m (see text for Discussion).

Interglacial–Glacial cycle was only recently modeled (Muhs et al., 2012) and appears to be more significant than Chaytor et al. (2008) assumed. Results by Muhs et al. (2012) show that relative paleo-sea level during the LGM on San Nicolas Island, also on the southern California coast (Fig. 2), was on the order of about –95 m, compared to present sea level (Fig. 17). This is much shallower than the value of –140 m, relative to present, the LGM paleo-sea level assumed by Chaytor et al. (2008). When the shallower LGM paleo-sea level of –95 m is used, the amount of uplift over the past ~23 ka has been minimal, which is consistent with the low, long-term uplift rate presented here and the age (~23 ka) and depth (about 90–110 m below sea level) of the submerged terrace studied by Chaytor et al. (2008). There do not appear to be any problems with the mapping, depth measurements, or ages of the submarine terrace studied by Chaytor et al. (2008). The apparent differences in uplift rate estimates can be reconciled by the new estimates of GIA-influenced paleo-sea level at the LGM (Fig. 17). Using the sea level history of the past ~120 ka presented by Muhs et al. (2012) and the uplift rate for the easternmost Santa Cruz Island ~120 ka locality (at ~12 m), the minor high-sea stand of –62 m at ~49 ka (recorded as an emergent terrace at Isla Vista in Goleta, Fig. 2; see also Table 2) should be recorded as a submarine terrace at ~60 m below present sea level (Fig. 17). It is interesting to note that Chaytor et al. (2008) mapped what they interpret to be a submarine terrace (NCI-S4 on their Fig. 5) near this depth around Santa Cruz Island.

The relatively low rates of uplift of San Miguel Island and Santa Rosa Island in the western Santa Barbara Channel are consistent with GPS measurements. GPS studies indicate a northeast-to-southwest convergence rate in the vicinity of eastern Santa Barbara Channel of ~6 mm/yr (Larson and Webb, 1992; Larson, 1993). These observations are consistent with a picture of rapid, north-south convergence in the Quaternary south of the San Andreas Big Bend and can explain the high uplift rates apparent along the coast at Isla Vista (Goleta) and Ventura (Fig. 2). However, Larson and Webb (1992) and Larson (1993) report little deformation, based on GPS data, in the western Santa Barbara Channel region. This is consistent with the lower uplift rates reported here for San Miguel Island and Santa Rosa Island, compared to those for Isla Vista (Goleta) and Ventura. Further, all of these observations are consistent with a far lower frequency of historical seismicity around the northern Channel Islands compared to the northeastern part of the Santa Barbara Channel, just offshore from the Santa Barbara–Ventura reach of coastline (Hill et al., 1990).

4.3. Cause of slow tectonic uplift of the northern Channel Islands in the late Quaternary

It is pertinent to consider the possible causes of uplift of the northern Channel Islands. Crustal uplift can be the result of any one of a number of isostatic, volcanic, or tectonic processes or a

combination of several such processes (Keller and Pinter, 2002; Murray-Wallace and Woodroffe, 2014). Long-term, slow isostatic rise of a coast, due to erosion of sediments from a landmass, does not seem to be a likely cause of uplift for relatively small islands of low relief over the timescale considered here (~120 ka). Short-term isostatic uplift, due to glacial ice removal, or uplift due to ongoing volcanic processes are not relevant to the northern Channel Islands. Tectonic processes that could be responsible for uplift can occur at various spatial and temporal scales and include: (1) uplift of the forearc margin of a tectonic plate overriding a subduction zone; (2) uplift adjacent to a restraining bend of a strike-slip fault; (3) upward movement on an actively growing anticline, including such folds that form above, or in the tip region of an active reverse or thrust fault; (4) the vertical component of movement along an oblique-slip fault; or (5) uplift in the footwall block of a normal fault, due to dip-slip movement. The uplift-generating processes enumerated here are not mutually exclusive. For example, a coastline may be experiencing regional uplift of marine terraces due to subduction beneath a forearc complex, but have differential uplift rates along the coast due to superposed deformation along local structures (e.g., Taylor and Mann, 1991; Kelsey et al., 1996).

Several investigators have suggested that uplift of the Channel Islands could be the result of Quaternary movement along a blind (buried) thrust fault (Seeber and Sorlien, 2000; Pinter et al., 2001, 2003; Chaytor et al., 2008). This inference is based on interpretation of seismic reflection survey data in the eastern part of Santa Barbara Channel (Fig. 2) by Shaw and Suppe (1994). The latter investigators proposed that a blind, north-dipping thrust fault is present beneath the Santa Barbara Channel and Santa Cruz Island, with the base of the overriding plate at depths of ~18 km (in the northern part of the channel) to ~8 km (beneath Santa Cruz Island). Shaw and Suppe (1994) referred to this structure as the Channel Islands thrust. Keller et al. (2007) infer that this structure and the Santa Barbara fold belt to the north of it are a result of crustal contraction, linked to roughly north-south convergence at the Big Bend of the San Andreas Fault to the north (Figs. 1 and 2). Elsewhere in southern California, blind thrusts have also been proposed as mechanisms for uplift (Grant et al., 1999; Rivero et al., 2000).

In addition to the mechanisms of uplift described above, Mueller et al. (2009) recently proposed an intriguing hypothesis for explaining low rates of marine terrace uplift in southernmost California and northern Baja California. In their model, uplift in this region is caused primarily by upwelling beneath the Peninsular Ranges of southern California and the northern Gulf of California (Mexico), due to upper-mantle heating and thinning. The mantle upwelling model proposed by Mueller et al. (2009) for southernmost California and northern Baja California may not be applicable to the present study, however, as the Channel Islands are well north of the area for which their model was considered.

The primary cause of uplift on the northern Channel Islands needs more investigation, but the low rates reported here suggest it differs from the mechanism of crustal shortening near the Big Bend, the origin of the higher rates of uplift in the Isla Vista (Goleta) and Ventura areas. Alternatively, uplift on the northern Channel Islands may be driven by the same mechanism, but at a lower degree of intensity, given the more southerly location of the islands. In an extensive review, Brown (1990) pointed out that the San Andreas Fault system is dominated by strike-slip motion over most of its length and width (outside the Big Bend area), with amounts of horizontal motion exceeding other deformation processes (such as vertical displacement, or uplift) by an order of magnitude. It is inferred here that small dip-slip, or vertical components of movement along faults of this system may explain the relatively low but measurable rates of late Quaternary uplift found over much of

coastal California, including the northern Channel Islands, in areas not immediately adjacent to the Big Bend region. Wehmler et al. (1979) proposed this concept to explain marine terrace uplift in California more than three decades ago.

4.4. Role of a local structure: the Santa Rosa Island fault

Local structures can explain differential uplift of marine terraces. A major structure on Santa Rosa Island is the Santa Rosa Island fault, a left-lateral, strike-slip fault that spans the width of the island (Fig. 8). Studies indicate that the fault may have a complex slip history during the Quaternary (Minor et al., 2012). Although the fault's movement is predominantly horizontal (Weaver et al., 1969; Dibblee et al., 1998), a question that arises is whether vertical components of movement have resulted in differential uplift on opposite sides of the fault. Results presented here show that the 2nd marine terrace to the south of the fault, at Johnsons Lee, has a shoreline angle elevation (~20–21 m) that is slightly lower than that of the 2nd terrace at Garañon Canyon (~24 m), on the north side of Santa Rosa Island and north of the fault. It is recognized, however, that the apparent terrace elevation differences at Garañon Canyon and Johnsons Lee are within the natural range of variability of shoreline angle elevations for this terrace. In contrast, on the eastern side of the island at Bechers Bay, the elevations of the outer wave-cut platform differ by ~7 m on opposite sides of the fault (~17.3 m on the north side of the fault; ~10 m on the south side of the fault), implying a greater amount of cumulative dip slip in that area (Figs. 7b and 12). Furthermore, the shoreline angle elevation of what we interpret to be the ~120 ka marine terrace is estimated to be ~20 m at localities in the Bechers Bay area north of the fault (Water Canyon and Torrey Pines areas) and ~13 m–~15 m at localities to the south of the fault (Southeast Anchorage area; Fig. 11). These observations imply cumulative dip slip movement of about 5–7 m. Such an interpretation is consistent with the findings reported by Schumann et al. (2014) that drainage density is high in the northeastern part of Santa Rosa Island, implying very recent or ongoing uplift. The results reported here do not support the proposal by Seeber and Sorlien (2000) that uplift of the Channel Islands is characterized by tectonic tilt to the north, at least during the late Quaternary.

Overall, the relatively low uplift rates presented here are consistent with primarily strike-slip movement along the Santa Rosa Island fault during the late Quaternary. The geomorphology of Santa Rosa Island indicates that left-lateral, strike-slip movement along the Santa Rosa Island fault has exerted a strong influence on landscape development in the Quaternary, superimposed on slow uplift. The broad peninsula between Skunk Point and East Point (south of the fault) implies eastward movement, while immediately north of the fault, the configuration of Bechers Bay itself is consistent with westward movement of this portion of the island's crustal block (Fig. 8). Elsewhere on the island, the peninsula ending at Sandy Point (north of the fault) also implies westward movement, whereas the northwest-to-southeast orientation of the coast between Sandy Point and South Point (south of the fault) implies eastward movement. In effect, the island's geography gives the appearance of the landmass becoming elongated in an eastward direction (southern half of the island) and westward direction (northern half of the island) due to horizontal movement on the Santa Rosa Island fault (Dibblee and Ehrenspeck, 1998). Finally, valleys of north-flowing streams on Santa Rosa Island are offset along the Santa Rosa Island fault, easily visible on topographic maps and aerial photographs (Dibblee and Ehrenspeck, 1998; Schumann et al., 2014), indicating that long-term, left-lateral movement along the fault has exerted a strong effect on Quaternary stream valley development.

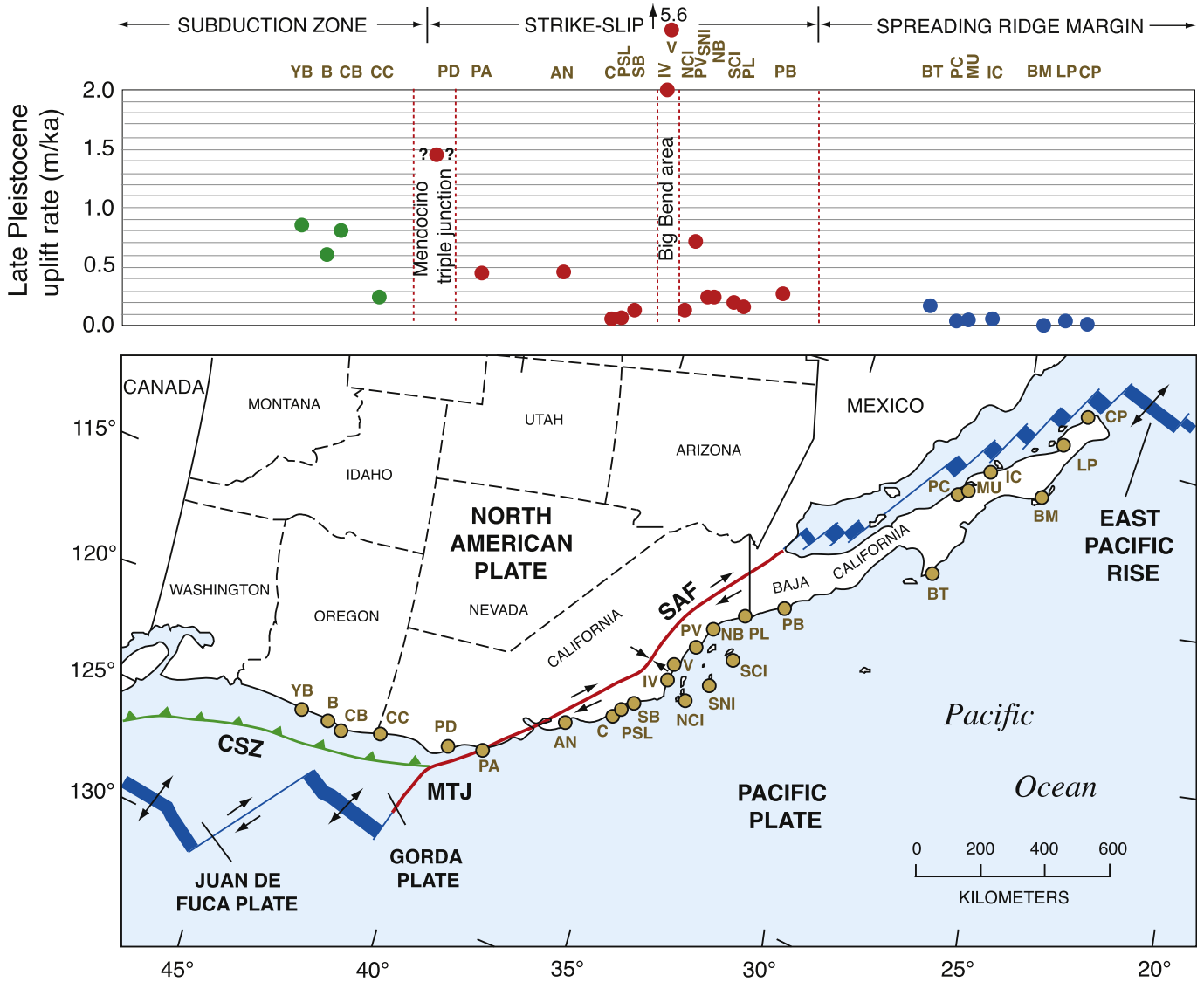


Fig. 18. Map showing the plate tectonic setting of western North America (simplified from Drummond (1981) and Simkin et al. (2006)). SAF, San Andreas Fault; MTJ, Mendocino Triple Junction; CSZ, Cascadia subduction zone. Also shown are marine terrace localities with reliably dated ~120 ka, ~80 ka, or ~49 ka terraces, and elevation data that allow calculations of late Quaternary uplift rates. Paleo-sea levels, relative to present, used for uplift rate calculations are +6 m (~120 ka), -11 m (~80 ka), and -62 m (~49 ka), derived from data in Muhs et al. (2012). Abbreviations and sources of data, south to north: CP, Cabo Pulmo (Muhs et al., 2002a); LP, La Paz (Sirkin et al., 1990); BH, Bahía Magdalena (Omura et al., 1979); IC, Isla Coronados and PC, Punta Chivato (Johnson et al., 2007; see also Table 2); MU, Mulegé (Ashby et al., 1987); BT, Bahía de Tortugas (Emerson et al., 1981); PB, Punta Banda (Rockwell et al., 1989; Muhs et al., 2002a); PL, Point Loma (Kern, 1977; Muhs et al., 2002a); SCI, San Clemente Island (Muhs et al., 2002a, 2014); NB, Newport Bay (Grant et al., 1999); SNI, San Nicolas Island (Muhs et al., 2012); PV, Palos Verdes Hills (Muhs et al., 2006); NCI, Northern Channel Islands (this study); V, Ventura (Lajoie et al., 1979; Kennedy et al., 1982; Wehmiller, 1982); IV, Isla Vista (Gurrola et al., 2014; see also Table 2); SB, Shell Beach (Stein et al., 1991; Hanson et al., 1994); PSL, Point San Luis (Hanson et al., 1994; Muhs et al., 1994); C, Cayucos (Stein et al., 1991; Muhs et al., 2002a); AN, Año Nuevo (Muhs et al., 2006); PA, Point Arena (Muhs et al., 2006); PD, Point Delgada (McLaughlin et al., 1983a, 1983b; Merritts and Bull, 1989); CC, Crescent City (Kennedy et al., 1982; Polenz and Kelsey, 1999); CB, Cape Blanco (Kelsey, 1990; Muhs et al., 1990); B, Bandon (McInelly and Kelsey, 1990; Muhs et al., 1990, 2006); YB, Yaquina Bay (Kennedy et al., 1982; Kelsey et al., 1996).

4.5. Comparison of Channel Islands uplift rates with other localities along the northeastern margin of the Pacific Rim

The late Quaternary uplift rates inferred here for the northern Channel Islands can be compared to those derived from emergent marine terraces elsewhere around the northeastern Pacific Rim, where there is a diversity of tectonic settings (Fig. 18). Emphasis here is on well-studied localities with precise elevation measurements and reliable U-series ages on coral dated to MIS 5.5 (~120 ka) or amino acid data on mollusks that allow correlation to U-series-dated corals nearby. In a few places (Año Nuevo, Point Arena,

Crescent City, Cape Blanco, and Bandon), probable ~120 ka terraces are undated, but lower-elevation terraces, dated to ~80 ka (MIS 5.1) by U-series on coral or amino acids on mollusks, are present. Uplift rates for these localities are therefore based on the age and elevations of the ~80 ka terraces. At three localities (Ventura, Isla Vista/Goleta, and Point Delgada), the only dated Pleistocene terraces are 45–50 ka (MIS 3) and uplift rates are based on terraces of this younger, interstadial high-sea stand. For all terraces dating to MIS 5.5, an age of ~120 ka is assumed and a paleo-sea level of +6 m, relative to present, is used in uplift rate calculations, the same as for calculations of uplift rate for San Miguel Island and

Santa Rosa Island. For the younger high-sea stands of MIS 5.1 (~80 ka) and MIS 3 (~45–50 ka) GIA effects result in wide geographic variations in relative paleo-sea level from region to region, as shown by Potter and Lambeck (2003). Thus, in the comparisons presented here, it is appropriate to use estimates of paleo-sea level from the Pacific Coast of North America. These estimates are –11 m, relative to present, for the ~80 ka high-sea stand, and –62 m, relative to present, for the ~45–50 ka high-sea stand (Muhs et al., 2012).

Baja California, Mexico is situated on the western margin of the East Pacific Rise spreading center, and evolved to its present location as a peninsular landmass as seafloor spreading rifted it away from mainland Mexico (Fig. 18). In the past several decades, a number of studies of emergent MIS 5.5 terraces have been generated, such that there is now a fairly consistent picture of late Quaternary uplift in this region. At Bahía Magdalena and Cabo Pulmo, elevations of ~6 m for the ~120 ka terrace indicate no measurable uplift at all in the late Quaternary (Omura et al., 1979; Muhs et al., 2002a). Elsewhere, studies by Ashby et al. (1987), Sirkin et al. (1990) and Johnson et al. (2007) at Mulegé, La Paz, Isla Coronados, and Punta Chivato (see Table 2 for U-series data for the latter two localities) indicate just a few meters of uplift of the ~120 ka terrace, yielding uplift rates of less than 0.1 m/ka. Thus, although Mueller et al. (2009) proposed that there is no Quaternary coastal uplift south of Bahía de Tortugas in Baja California (Figs. 1 and 18), several localities do indicate at least modest amounts of late Quaternary uplift. A significantly higher uplift rate of as much as 0.17 m/ka is recorded at Bahía de Tortugas, where the ~120 ka terrace is found at elevations of 24–27 m (Emerson et al., 1981). Interestingly, this is the only known locality of southern Baja California where a terrace estimated to be younger than ~120 ka is found above sea level (although see Mayer and Vincent (1999)), which supports an interpretation of higher uplift rate. It is worth noting that Bahía de Tortugas is situated west of a major transform fault separating two spreading ridges (Figs. 1 and 18), whereas the more southerly localities described above are found on the margins of spreading ridges.

Localities from Punta Banda, Baja California north to Point Arena, California are all west of the San Andreas Fault (Fig. 18). Uplift rates along most of this reach of coastline bracket those of 0.12–0.15 m/ka for San Miguel Island and Santa Rosa Island, reported here, and range from as low as 0.04–0.06 at Cayucos and Point San Luis to as high as 0.44–0.46 at Año Nuevo and Point Arena. In some areas, restraining bends along strike-slip faults result in locally higher uplift rates. For example, near the Palos Verdes Hills, the Palos Verdes and Cabrillo faults strike northwest in their southern parts and bend to a west strike in their northern parts (Fig. 2). Based on the elevation, age, and paleo-sea level of the ~120 ka marine terrace (Muhs et al., 2006), the late Quaternary uplift rate in the Palos Verdes Hills area is estimated to be 0.6–0.7 m/ka, a factor of three or more higher than in most other southern California coastal areas. A restraining bend in the northern part of the Santa Maria River fault (Fig. 2) may also explain the slightly higher uplift rate at Shell Beach (0.12 m/ka) compared to lower rates (0.04–0.06 m/ka) just a short distance north at Point San Luis and Cayucos. A much more dramatic example of rapid uplift due to a restraining bend in a fault is that found near the Big Bend of the San Andreas Fault. In the Isla Vista district of the city of Goleta, Santa Barbara County (Fig. 2), the lowest emergent marine terrace is found at elevations of 14–35 m above sea level (Gurrola et al., 2014). In the earliest investigations of amino acid geochronology, fossils from this terrace gave surprisingly low amino acid ratios, implying a relatively young (older than Holocene, but younger than ~80 ka) age (Wehmiller et al., 1977). Subsequent work has confirmed this early estimate with a U-series age on coral of

~49 ka (Gurrola et al., 2014; see also isotopic data in Table 2), correlative with some part of MIS 3. The terrace probably formed ~62 m below present sea level (Muhs et al., 2012) and has been subsequently uplifted to elevations of about 14–35 m above present sea level (Trecker et al., 1998; Gurrola et al., 2014). Based on the age and elevation of this marine terrace, Gurrola et al. (2014) estimate uplift rates of 1.6–2.0 m/ka. East of Goleta, Wehmiller et al. (1978), Lajoie et al. (1979), Wehmiller (1982) and Sarna-Wojcicki et al. (1987) mapped and dated a marine terrace near Ventura, also thought to be ~49 ka, that is now about 120–210 m above present sea level, indicating even higher uplift rates of 3.7–5.6 m/ka. The latter workers also documented what is probably co-seismic uplifts of a younger, late Holocene marine terrace, to elevations of 6–35 m.

The tectonic setting is complex near Cape Mendocino, California, just east of the Mendocino triple junction (Figs. 1 and 18). Offshore Cape Mendocino, the San Andreas Fault strikes seaward in a northwesterly direction and forms the southern boundary of the Gorda subplate. Northward of this boundary, the Gorda subplate and Juan de Fuca plate are being subducted under the North American plate. On the California coast east of the Mendocino triple junction, marine terraces are common, but almost all dated, emergent terraces are of Holocene age, indicating very high uplift rates (Lajoie et al., 1991; Merritts, 1996). Indeed, the modern platform near Cape Mendocino was co-seismically uplifted ~1.4 m during a 1992 earthquake (Carver et al., 1994) and higher terraces likely record earlier Holocene earthquakes (Merritts, 1996). Few data exist, however, on possible ages of Pleistocene marine terraces, although they are present in the area (Merritts and Bull, 1989). The only dated Pleistocene terrace near the triple junction is at Point Delgada, described by McLaughlin et al. (1983a, 1983b). Here, a marine terrace deposit at ~7 m above sea level is overlain by alluvial deposits that host *Picea* cones and fossil wood ~2 m above the contact with the marine terrace deposits. One of the wood fragments gave an uncalibrated radiocarbon age of ~45 ka. Because this age is near the effective limit of radiocarbon dating, it is not known whether this apparently finite age accurately dates the deposit or is in fact considerably older (see discussion in Pigati et al. (2007)). Assuming that it does provide a relatively close minimum-limiting age for the underlying marine deposits, the marine terrace could date to the same MIS 3 high-sea stand of ~45–50 ka as the terraces found at Isla Vista and Ventura. If so, this implies an uplift rate of ~1.5 m/ka (Fig. 18). It is interesting to note that this uplift rate, although it is a maximum estimate given the age uncertainties, is actually lower than uplift rates for this area that are derived from the ages and elevations of Holocene marine terraces (Lajoie et al., 1991; Merritts, 1996).

The coastline north of Cape Mendocino is east of the Cascadia subduction zone (Figs. 1 and 18). At Yaquina Bay, Oregon, the uplift rate (~0.85 m/ka) is derived from a terrace that is correlated with the ~120 ka high-sea stand, based on amino acid ratios from Kennedy et al. (1982) and elevation data from Kelsey et al. (1996). Uplift rates at three other localities (Cape Blanco, Bandon, and Crescent City) are based on the age, elevation, and paleo-sea level of ~80 ka marine terraces. Along the southern Oregon coast at Cape Blanco and Bandon, uplift rates (~0.6–0.8 m/ka), like Yaquina Bay, are higher than most localities in California west of the San Andreas Fault, other than where restraining bends in faults have brought about locally higher uplift rates. In contrast, the uplift rate at Crescent City (~0.25 m/ka), based on age data in Kennedy et al. (1982) and elevation data in Polenz and Kelsey (1999), is similar to those of other California localities (Fig. 18).

Uyeda and Kanamori (1979) proposed a model that included a continuum of subduction zone geometries. In this continuum, low-angle subduction zones, with strongly coupled plates, characterize

one end-member (the “Chilean” type), and high-angle subduction zones, with weakly coupled plates, characterize the other end-member (the “Marianas” type). Jarrard (1986) took this concept further and the basic model is still cited as an important explanation of first-order subduction zone variability (Stern, 2002). Ota and Omura (1992) proposed that variation in uplift rates of ~120 ka marine terraces on the Ryukyu Islands of Japan could be explained by this model. The data presented by Ota and Omura (1992) do seem to fit the model fairly well, with Kikai Island (“Chilean” type of subduction) showing a very high uplift rate and Hateruma Island (“Marianas” type of subduction) showing a modest uplift rate. The Cascadia subduction zone also seems to fit the model reasonably well, as it has an intermediate type of subduction zone geometry (Jarrard, 1986) and the data presented here show variable, but generally intermediate uplift rates when compared to the two extremes of the Ryukyu Islands. Nevertheless, other subduction zones do not seem to fit the model very well (see review in Muhs et al. (1990)). For example, the uplift rate in a coastal area of north-central Chile that can be categorized (as its name implies) as a “Chilean” type of subduction zone has, in fact, a rather modest late Quaternary uplift rate of 0.16 m/ka (Leonard and Wehmiller, 1992). Interestingly, the rate of uplift from this part of Chile is similar to those reported here from San Miguel Island and Santa Rosa Island. Thus, uplift rates for different regions over the same time period of consideration can be similar, even when the plate tectonic settings are drastically different.

5. Conclusions

Marine terraces are extensive on San Miguel Island and Santa Rosa Island and new mapping shows that terraces likely related to the Last Interglacial complex of sea-level high stands (~80 ka, ~100 ka, and ~120 ka) are found around the perimeters of both islands. Uranium-series dating of terrace corals from the 2nd marine terraces on San Miguel Island and Santa Rosa Island show that sediments and fossils from these terraces likely were deposited during the ~120 ka high sea stand. Amino acid ratios in fossil mollusks from these terraces further support a correlation to the ~120 ka high sea stand, but also permit the possibility of mixing of fossils from both the ~120 ka and ~100 ka high sea stands. Paleozoogeographic evidence from mollusks on the 2nd terraces of both islands also permits an interpretation of fossil mixing, with faunas showing both northern (cool waters, ~100 ka?) and southern (warm waters, ~120 ka?) forms. Amino acid data from both *Chlorostoma* and *Epilucina* show that the 1st terrace on Santa Rosa Island correlates with the ~80 ka high sea stand of the Last Interglacial complex.

Uplift rates on San Miguel Island and Santa Rosa Island, based on the elevations and age of the 2nd (~120 ka) terrace, range from 0.12 to 0.15 m/ka. These rates are lower, by an order of magnitude, than those proposed in a recent study that used the age and elevation of a terrace offshore from the northern Channel Islands, and dating to the Last Glacial period. The latter study was conducted before glacial isostatic adjustment effects were modeled for the area, indicating that local paleo-sea level during the Last Glacial period could have been much higher than previously supposed. Modest late Quaternary uplift for the northern Channel Islands, similar to that reported for other parts of coastal California, is likely due to small vertical components of dominantly strike-slip faults of the greater San Andreas fault system. Compared to other localities around the northeastern Pacific Rim, late Quaternary uplift rates on the northern Channel Islands are slightly higher than those on coastal localities adjacent to the East Pacific Rise spreading center and somewhat lower than those coastal localities adjacent to the Cascadia subduction zone. With the exception of locally higher

uplift rates caused by restraining bends of faults, Channel Islands uplift rates are similar to many other coastal localities in California west of the San Andreas Fault zone.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.quascirev.2014.09.017>.

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