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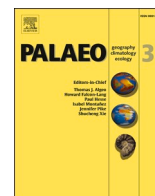


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A complex record of last interglacial sea-level history and paleozoogeography, Santa Rosa Island, Channel Islands National Park, California, USA

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ABSTRACT

Studies of marine terraces and their fossils can yield important information about sea level history, tectonic uplift rates, and paleozoogeography, but some aspects of terrace history, particularly with regard to their fossil record, are not clearly understood. Marine terraces are well preserved on Santa Rosa Island, California, and the island is situated near a major marine faunal boundary. Two prominent low-elevation terraces record the ~80 ka (marine isotope stage [MIS] 5a) and ~120 ka (MIS 5e) high-sea stands, based on U-series dating of fossil corals and aminostratigraphic correlation to dated localities elsewhere in California and Baja California. Low uplift rates are implied by an interpretation of these ages, along with their elevations. The fossil assemblage from the ~120 ka (2nd) terrace contains a number of northern, cool-water species, along with several southern, warm-water species, a classic example of what has been called a thermally anomalous fauna. Low uplift rates in the late Pleistocene, combined with glacial isostatic adjustment (GIA) processes, could have resulted in reoccupation of the ~120 ka (MIS 5e), 2nd terrace during the ~100 ka (MIS 5c) high-sea stand, explaining the mix of warm-water (~120 ka?) and cool-water (~100 ka?) fossils in the terrace deposits. In addition, however, sea surface temperature (SST) variability during MIS 5e may have been a contributing factor, given that Santa Rosa Island is bathed at times by the cold California Current with its upwelling and at other times is subject to El Niño warm waters, evident in the Holocene SST record. Study of an older, high-elevation marine terrace on the western part of Santa Rosa Island shows more obvious evidence of fossil mixing. Strontium isotope ages span a large range, from ~2.3 Ma to ~0.91 Ma. These analyses indicate an age range of ~500 ka at one locality and ~600 ka at another locality, interpreted to be due to terrace reoccupation and fossil reworking. Consideration of elevations and ages here also yield low, long-term uplift rates, which in part explains the potential for terrace reoccupation in the early Pleistocene. In addition, however, early Pleistocene glacial-interglacial cycles were of much shorter duration, linked to the ~41 ka obliquity cycle of orbital forcing, a factor that would also enhance terrace reoccupation in regions of low uplift rate. It is likely that other Pacific Coast marine terrace localities of early Pleistocene age, in areas with low uplift rates, also have evidence of fossil mixing from these processes, an hypothesis that can be tested in future studies.

1. Introduction

The composition of shallow-water marine invertebrate communities, worldwide, is to a great extent a function of ocean water temperatures. The importance of water temperature on marine ecosystems has long been recognized and is the foundation for what are referred to as marine invertebrate provinces (Valentine, 1966) or biogeographic units

(Fig. 1a). In a global study of marine invertebrate provinces, Belanger et al. (2012) found that the geographic structure of such provinces is controlled, with 89–100% accuracy, by three variables, temperature, salinity, and productivity. Of these, temperature alone can predict 53–99% of the contemporary marine biogeographic structure along the world's coastlines.

Under almost any scenario, climate models project not only a

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substantially higher global sea level in the coming decades (Church et al., 2013), but also warmer sea surface temperatures (SST) over much of the globe (Alexander et al., 2018). Thus, with the prospect of global ocean warming, it is expected that the composition of what are now regarded as traditional marine invertebrate provinces could change, with migration of species in poleward directions. For example, disjunct populations of gastropods on the Pacific Coast of North America have been reported to be the result of northward migrations within the past few decades, and are hypothesized to have occurred in warm, El Niño years (Lindberg and Lipps, 1996). Similarly, there has been substantial documentation of migration of marine bivalves beyond what were previously regarded as their northern limits on the Pacific Coast of North America, also likely during warm, El Niño years (Coan et al., 2000). More recently, Sanford et al. (2019) have documented northern range extensions of a wide variety of northern California marine taxa during prolonged and intense marine heatwaves in the eastern Pacific Ocean. As a result of such findings, considerable effort is currently underway to study geologic records of past times when ocean waters were warmer than present.

Studies of Quaternary fossil faunas in marine terrace deposits offer one method for estimating past SSTs. Most commonly, such studies have been undertaken on marine deposits dating to the last interglacial period (LIG). The LIG is recorded in the foraminiferal oxygen isotope record of deep-sea cores as either all of marine isotope stage (MIS) 5 (LIG, *sensu lato*) or the warmest part of this period, MIS 5e (LIG, *sensu stricto*). Murray-Wallace and Woodroffe (2014) provide an excellent review of how this important interglacial period has left geomorphic and sedimentary records along the world's shorelines. Along the Pacific Coast of North America, the primary record of the LIG takes the form of fossiliferous deposits of emergent marine terraces (see Muhs, 2022 for a

recent review). Within the fossil record of marine terrace deposits, examples can be found for both cooler-than-present waters, during MIS 5a at 80 ka (Muhs et al., 2006), and warmer-than present waters, during MIS 5e at ~120 ka (Lindberg et al., 1980; Muhs et al., 2002).

A recurring question of the fossil record along the Pacific Coast of North America has been the origin of what are called “thermally anomalous” faunas. Such fossil assemblages are characterized by extant species, but contain extralimital fossil taxa that indicate both warmer (southern, for the Pacific Coast of North America) and cooler (northern) taxa coexisting in a given deposit. Thermally anomalous faunas are common in marine deposits along the Pacific Coast that date to the late Pleistocene (e.g., Muhs et al., 2002, 2012, 2014a), but can be found in deposits as old as early Pleistocene and even Pliocene (e.g., Groves, 1991; Woodring and Bramlette, 1950; Woodring et al., 1946). The origin of these mixes of faunas has generated debate for more than eight decades. Explanations, summarized by Muhs et al. (2014b) and Muhs and Groves (2018) include the following: (1) northward and southward shifts in marine isotherms throughout the Pleistocene (Smith, 1919); (2) reworking of fossils from older marine deposits into younger ones; (3) non-temperature-related factors that govern the composition of a marine community, such as species competition; (4) the presence of a cold-water upwelling cell adjacent to a protected, warm embayment (Valentine, 1955); (5) storm wave and longshore current transportation of fossils from deeper waters or from another locality (Woodring et al., 1946); (6) changes in coastal geography between the time of fossil deposition and the present; (7) changes in physiology that would alter tolerances of species to different temperature ranges; (8) local and temporary current changes that bring extralimital taxa into regions where they do not usually live (Zinsmeister, 1974); (9) individualistic species response to climate change (Roy et al., 1995); and (10) greater

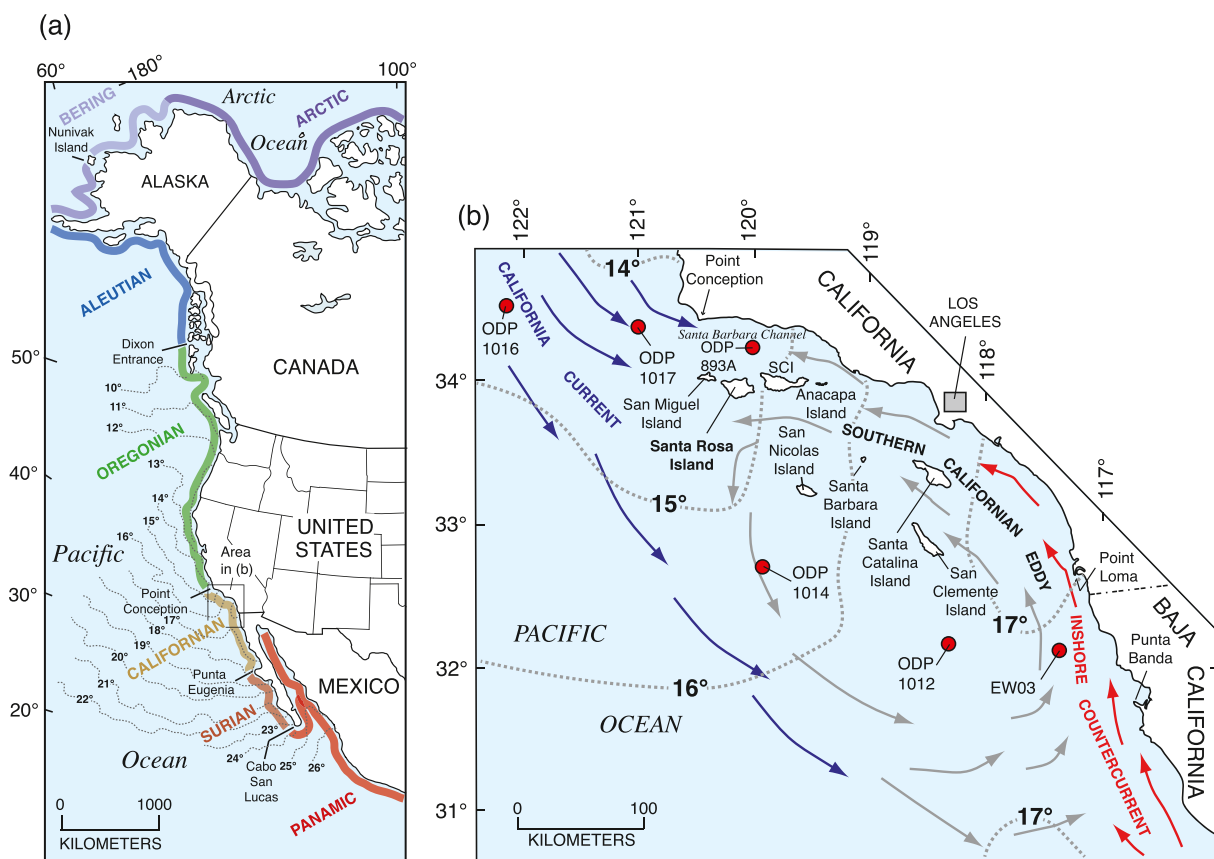


Fig. 1. (a) Map of a part of the Pacific Coast of North America, showing coastal faunal zones of Valentine (1966) and mean annual sea surface temperatures (SSTs) for the period 1955–2012 CE (from Seidov et al., 2017). (b) Map of the California Channel Islands, including Santa Rosa Island, adjacent parts of the mainland, location of Ocean Drilling Project (ODP) core sites, and ocean currents, redrawn from Hendy (2010); mean annual SSTs are from Seidov et al. (2017). SCI, Santa Cruz Island.

seasonality, due to orbital forcing, in past interglacial periods compared to the present (Kennedy, 2000). Some of these mechanisms are not mutually exclusive and allow for the possibility of complex explanations of the fossil record.

Unfortunately, no one of these explanations is completely satisfactory in explaining the thermally anomalous aspects of many Pacific Coast fossil faunas that have been studied to date. For example, Valentine (1955) and Zinsmeister (1974) pointed out that hypothesis (1) does not explain the co-existence of warm-water and cool-water faunas within the same deposit. Hypothesis (2) can easily explain some thermally anomalous faunas, but requires some method of age determination to differentiate older from younger fossils. Species competition [hypothesis (3)] is well documented, such as diminution or elimination of sea urchin populations with increases in sea otter populations (Estes and Palmisano, 1974). However, such a process would not seem to favor the co-existence of both cold-water and warm-water taxa at a number of localities. Hypothesis (4) can conceivably explain some thermally anomalous faunas, but cannot explain them at localities where upwelling cells and warm-water embayments are not adjacent to one another. Storm wave transport from deeper waters into shallower waters [part of hypothesis (5)] was rejected by Roy et al. (1995), because many extralimital species are shallow-water forms. Hypothesis (6) does not explain thermally anomalous faunas in many areas because the coastal geography has changed very little from high-sea stand to high-sea stand, as evidenced by shore-parallel arrays of marine terraces. Hypothesis (7) is virtually impossible to test, as soft parts of emergent marine fossils are almost never preserved, thus precluding any documentation of physiological changes. Roy et al. (1995) rejected hypothesis (8) on the grounds that some extralimital species lack a planktotrophic larval stage and thus could not take advantage of short-term fluctuations in water temperature. The excellent study by Roy et al. (1995), hypothesis (9), focused largely on extraprovincial species, but not all extralimital species in the Pleistocene fossil record were taxa who crossed provincial boundaries. Hypothesis (10), greater seasonality, is not supported by examinations of modern marine communities, where studies in widely separated parts of the globe show that strongly seasonal environments tend to have lower species diversity (Blanchette et al., 2009).

A partial explanation for what were once thought to be some thermally anomalous faunas on the Pacific Coast of North America came with the development of amino acid geochronology in combination with new paleontological investigations (Wehmiller et al., 1977; Kennedy et al., 1982; Wehmiller, 1982, 1992). In the absence of numerical dating methods, some early marine terrace studies in California assumed that many of the lowest-elevation marine terrace deposits were at least roughly the same age from place to place (e.g., Valentine, 1961; Valentine and Meade, 1961). As a consequence, a low-elevation terrace locality with a cool-water fossil fauna and a terrace locality elsewhere at the same elevation but with a warm-water fossil fauna could be described as a thermally anomalous situation, based on the simple assumption that similar elevations meant similar ages. Aminostratigraphic studies coupled with detailed paleontological characterization showed that the assumption of an identical age for the lowest marine terrace all along the Pacific Coast is not valid (Wehmiller et al., 1977; Kennedy et al., 1982; Wehmiller, 1982, 1992). This work demonstrated that many marine terrace faunas that included cool-water species correlated to MIS 5a (~80 ka) or possibly MIS 5c (~100 ka). In contrast, fossil faunas with thermally “neutral” species assemblages (neither warm nor cold), on exposed coasts, or those with or warm-water species (on protected coasts) correlated to MIS 5e (~120 ka). Subsequent U-series dating of corals from a number of these terraces has confirmed many of the paleozoogeographically based age interpretations (Muhs et al., 2002, 2006).

There are, however, still challenges in interpreting the paleozoogeography of Pacific Coast marine terrace deposits. For example, while many ~120 ka marine terrace deposits on the Pacific Coast do indeed contain warm-water taxa, it is also true that a number of such

localities host both warm-water and cool-water species. Muhs et al. (2012), studying such fossil assemblages on San Nicolas Island, California (Fig. 1) proposed that glacial isostatic adjustment (GIA) processes resulted in a higher paleo-sea level at ~100 ka than has been characterized for lower-latitude regions, due to the presence of large ice sheets on North America during glacial periods. Thus, in areas with modest uplift rates, such as San Nicolas Island, the ~100 ka high stand could have captured at least the outer parts of ~120 ka terraces, mixing fossils of both ages. It is therefore possible that within the same terrace deposits, warm-water mollusks date to the ~120 ka high-sea stand and cool-water mollusks date to the ~100 ka high-sea stand. Put in the context of the hypotheses outlined above, this is essentially a combination of hypothesis (1), latitudinal changes in water temperatures over the Pleistocene, and hypothesis (2), reworking of older fossils (e.g., from a warmer period) into deposits with younger fossils (e.g., from a cooler period). On a shorter timescale, however, a combination of hypotheses (1) and (8) is also possible, whereby temperature changes within an interglacial period could vary over time because of the changing strengths of cold and warm currents that both affect a given locality. Finally, changes in water temperature over time (but within the same interglacial period) due to orbital forcing may be possible. Such an explanation was offered for the co-existence of extralimital northern (Mediterranean) species and extralimital southern (Senegalese) species in ~120–130 ka marine terrace deposits of the Canary Islands, Spain (Muhs et al., 2014c). All three of these combined hypotheses can, in theory, be accommodated with the hypothesis of individualistic species response to climate change [hypothesis (9) given above], as outlined by Roy et al. (1995).

Santa Rosa Island, in Channel Islands National Park, is just southeast of Point Conception, at the boundary between the Oregonian and Californian faunal provinces (Fig. 1). The island is, therefore, in a sensitive location with regard to temporal shifts in marine faunal provinces. Santa Rosa Island is bathed by the innermost part of the cold, southward-moving California Current (and the upwelling associated with it) but is also just west of the warm, northward-flowing Inshore Countercurrent (Fig. 1b). An initial marine terrace study on Santa Rosa Island indicated that the late Quaternary uplift rate on this island could be modest (Muhs et al., 2014a). Thus, as is the case with San Nicolas Island to the south, Santa Rosa Island could therefore host thermally anomalous faunas due to terrace reoccupation as a result of GIA effects. Previous studies of marine terraces on this island indicate that the 1st emergent terrace likely dates to MIS 5a and the 2nd terrace could date to MIS 5e (Muhs et al., 2014a, 2015), but only a single U-series age on coral is available for the 2nd terrace. Nevertheless, Muhs et al. (2014a) conducted a zoogeographic analysis of the fossils from this terrace, reported by Orr (1960), with the conclusion that there is likely a mix of warm-water and cool-water species, a classic thermally anomalous fauna. In the present study, new U-series analyses, a reexamination of amino acid geochronological data, and new fossil faunal analyses from numerous localities on Santa Rosa Island are reported. These data provide the basis for evaluating the hypothesis that if this island has a modest uplift rate, terrace reoccupation and faunal mixing could have taken place and/or that a thermally anomalous fauna may be due to interglacial SST variability. In addition, these hypotheses are tested for an older, pre-LIG marine terrace record on Santa Rosa Island, anchored by new Sr isotope geochronology.

2. Methods

Marine terraces on Santa Rosa Island have been previously mapped in whole or in part by Orr (1960), Sonneman et al. (1969), Dibblee et al. (1998), Pinter et al. (2001), and Muhs et al. (2014a, 2015). All of these studies are in broad agreement with one another that marine terraces are prominent landforms at low and intermediate elevations around much of the island. In the present study, marine terrace mapping was conducted using large-scale colour and black-and-white stereoscopic aerial

photography and 1:24,000-scale U.S. Geological Survey topographic maps as bases. Initial mapping on these bases was refined with extensive field checking. Elevations of terrace wave-cut platforms and shoreline angles (junction of the wave-cut platform with the base of the sea cliff) were measured from sea cliff and canyon exposures, some of which have already been reported by Muhs et al. (2014a, 2015). Stratigraphy of marine terrace deposits and overlying sediments for many fossil localities are also given in those papers, but similar data for new localities are presented here.

Elevations of most localities studied were determined using differential Global Positioning System (GPS) measurements. Latitude and 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 software in which GPS field data were differentially corrected against one to six 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.

Fossils were collected from marine terrace deposits at all localities where they could be found. Initial collections were made by “high-grading” easily attainable specimens by hand. This was followed by removal of bulk terrace sediment and passing the material through a 2-mm sieve in the field. Fossils retained by the sieve were then hand-picked and the process repeated. Because marine terrace deposits on Santa Rosa Island are thin, poorly sorted, and lack sedimentary structures, all fossil collections represent what is found in the entire vertical extent of each exposed deposit. All fossil specimens were identified in the Department of Malacology at the Natural History Museum of Los Angeles County, where extensive reference collections of northeastern Pacific mollusks are housed. Almost all of the fossil taxa examined are extant species, so the paleozoogeographic significance of the faunas was assessed by examining the modern ranges of the species using the latest available sources. These references include Keen (1971), McLean (1978, 2007), Abbott and Haderlie (1980), Coan et al. (2000), Jackson (2001), Coan and Valentich-Scott (2012), Bertsch and Aguilar Rosas (2016), Calloman and Snyder (2017), Alf (2019), Collin (2019), deMaintenon (2019), Geiger and Owen (2019), Groves (2019), Houart et al. (2019), and collections in the Department of Malacology, Natural History Museum of Los Angeles County. Fossil locality numbers (with an “LACMIP” prefix) given in the text, tables, and figures are for the Department of Invertebrate Paleontology, Natural History Museum of Los Angeles County. Coordinates given for these localities in this paper and in the museum records use the WGS84 datum.

For geochronology of younger marine terraces, the method of choice is uranium-series (U-series) dating of fossil corals. Corals are suitable for U-series geochronology because during growth, these organisms take up U in isotopic equilibrium from seawater. In California, the most common species in marine terrace deposits is the solitary coral *Balanophyllia elegans* Verrill, 1864. On Santa Rosa Island, only well-preserved specimens of this taxon (i.e., those with no macroscopic evidence of recrystallization) were sampled for U-series geochronology. Corals were cleaned mechanically, washed in distilled water and X-rayed to determine aragonite purity. After cleaning of corals, sample preparation followed methods outlined by Ludwig et al. (1992). Cleaned corals were dissolved in HNO₃, spiked with ²²⁹Th, ²³³U, and ²³⁶U and purified with ion exchange methods. Purified U and Th were loaded with colloidal graphite on separate Re filaments and isotopic abundances were determined by thermal ionization mass spectrometry (TIMS). The U—Th spike is calibrated against a solution of uranium ore from the Schwartzwalder Mine, Colorado, that has yielded concordant U/Pb ages (Ludwig et al., 1985) and sample-to-sample agreement of ²³⁴U/²³⁸U and ²³⁰Th/²³⁸U (Ludwig and Paces, 2002). In addition, an in-house, carefully

homogenized, aragonitic fossil coral of last interglacial age (~120 ka) was used for routine, run-to-run checks. Ages were calculated using a half-life of 75,584 yr for ²³⁰Th and a half-life of 245,620 yr for ²³⁴U (Cheng et al., 2013). All data are given in Table 1 and are also reported in a U.S. Geological Survey database: <https://doi.org/10.5066/P9KDKAB9>.

For marine deposits that lack corals, amino acid geochronology of mollusks provides an appropriate method for correlation to dated deposits elsewhere. Wehmiller (1982, 1992, 2013a, 2013b), Wehmiller and Miller (2000), and Miller and Clarke (2007) review the method in detail. Relative abundances (using peak heights or peak areas on chromatograms) of D and L enantiomers of the amino acids valine and glutamic acid were measured in fossil specimens of the gastropod *Tegula* (*T. funebris* and/or *T. gallina*) using reverse-phase liquid chromatography (Kaufman and Manley, 1998) at the Amino Acid Geochronology Laboratory at the University of Colorado, Boulder, Colorado. Inter-laboratory comparisons of this facility with others can be found in Wehmiller (2013c).

Muhs et al. (2014a) presented amino acid data for a number of marine terrace fossil localities along the Pacific Coast of North America, including Santa Rosa Island. In that earlier study, age interpretations for the island’s terraces were made based primarily on D/L peak height ratios, although peak area ratios were reported in a supplementary data file. Muhs and Groves (2018) and Muhs et al. (2021) updated the graphical presentation of the earlier study with additional peak height data from U-series-dated deposits on nearby Santa Cruz Island. In the present study, aminostratigraphic results for Santa Rosa Island and other localities are revisited with an examination of peak area D/L values. The supplementary data for Santa Rosa Island given in Muhs et al. (2014a) are used for this purpose, along with previously unpublished peak area D/L values for U-series-dated terrace localities from Santa Cruz Island (Table 2).

For age estimates of older (pre-LIG) fossils from marine terrace deposits, Sr isotope geochronology was applied. Strontium isotopes can be utilized for assessing ages of fossil carbonate marine organisms because Sr is taken up from seawater as a substitute for Ca in both calcitic and aragonitic skeletons. Although Sr is taken up by marine organisms in isotopic equilibrium with seawater, the isotopic composition of Sr dissolved in seawater has varied over geologic time. Thus, ⁸⁷Sr/⁸⁶Sr values in unaltered fossil carbonate skeletons reflect the ⁸⁷Sr/⁸⁶Sr isotopic composition of seawater at the time of precipitation. Since ~37 Ma, the ⁸⁷Sr/⁸⁶Sr isotopic composition of seawater has become increasingly radiogenic (Howarth and McArthur, 1997; McArthur et al., 2001, 2012, 2020).

For Sr isotope analyses, fossil mollusks were cleaned mechanically and washed in distilled water. After cleaning, each specimen was checked for aragonite purity by X-ray diffraction (XRD). Only specimens that were 99–100% aragonite were selected for analysis. Because of the small changes in ⁸⁷Sr/⁸⁶Sr values over the course of the Quaternary (Howarth and McArthur, 1997; McArthur et al., 2020), analyses consisted of: (1) multiple shells (two to five individuals) from each locality; (2) two species where it was possible to do so (SRI-13C); (3) multiple chemical extractions of the same homogenized shell where sample size permitted it; and (4) multiple runs using the same filament from each split done for chemical extraction.

Cleaned samples were dissolved in 5 M acetic acid to minimize Sr contamination from any remaining detrital, non-carbonate material. The soluble fraction was then centrifuged and separated by standard ion-exchange techniques. Strontium was loaded on an oxidized Ta filament. Isotopic ratios were measured on a VG54 sector multi-collector mass spectrometer in dynamic mode. Average ⁸⁷Sr/⁸⁶Sr values were computed for each shell using the multiple extractions and multiple runs on the same filament for each extraction. Mean values for each shell, therefore, were computed from 8 to 16 runs (mean of 11 runs per shell). Uncertainties are given at the 95% confidence level. SRM-987 from the U.S. National Institute of Standards and Technology (<https://www-sist>

Table 1
Marine terraces, Natural History Museum of Los Angeles County Invertebrate Paleontology (LACMIP) locality number, coordinates, elevations, aragonite contents, U and Th concentrations, isotopic activity ratios (AR), and U-series ages of corals.

Location, marine terrace	LACMIP loc.	Latitude (°)	Longitude (°)	Fossil locality/SLA* elevation (m)	Aragonite (%)	U ppm	U error	²³² Th ppm	²³⁰ Th/ ²³² Th AR	²³⁴ U/ ²³⁸ U AR*	+/-	²³⁰ Th/ ²³⁸ U AR*	+/-	²³⁰ Th/ ²³⁸ U Age (ka)**	+/-	²³⁴ U/ ²³⁸ U initial AR*	+/-
Santa Rosa Island: 1st terrace																	
SRI-27-A***	42957	34.00868333	-120.2388333	4/8	100	4.66	0.11	0.0041	2016	1.1139	0.0019	0.5846	0.0021	79.9	0.5	1.1427	0.0023
SRI-27-C***	42957	34.00868333	-120.2388333	4/8	99	4.17	0.12	0.0061	1218	1.1226	0.0016	0.5908	0.0017	80.1	0.4	1.1537	0.0019
SRI-27-D***	42957	34.00868333	-120.2388333	4/8	100	4.49	0.14	0.003	2636	1.1173	0.0015	0.5817	0.0023	78.9	0.5	1.1466	0.0018
SRI-27-E***	42957	34.00868333	-120.2388333	4/8	100	3.18	0.11	0.0039	1471	1.1136	0.002	0.5996	0.0021	82.9	0.5	1.1436	0.0024
SRI-27-B***	42957	34.00868333	-120.2388333	4/8	100	3.70	0.11	0.0028	2485	1.1251	0.0025	0.6107	0.0025	83.8	0.6	1.1585	0.0030
SRI-27-G***	42957	34.00868333	-120.2388333	4/8	100	3.86	0.13	0.0034	2007	1.1234	0.003	0.5839	0.0022	78.6	0.5	1.1541	0.0036
SRI-12-A	42948	33.9887	-120.2229333	2	100	4.21	0.12	0.0044	1754	1.1683	0.002	0.5997	0.0068	76.9	1.3	1.2091	0.0025
SRI-12-C	42948	33.9887	-120.2229333	2	100	3.95	0.11	0.0037	1969	1.1809	0.0031	0.6122	0.0031	77.9	0.6	1.2254	0.0036
SRI-12-D	42948	33.9887	-120.2229333	2	100	4.73	0.11	0.0068	1344	1.1972	0.0016	0.6397	0.0017	81.2	0.4	1.2480	0.0019
SRI-12-E	42948	33.9887	-120.2229333	2	100	4.59	0.11	0.0058	1579	1.2042	0.0018	0.6582	0.0018	83.8	0.4	1.2587	0.0022
SRI-12-F	42948	33.9887	-120.2229333	2	99	4.51	0.11	0.0158	563	1.1957	0.002	0.649	0.0022	83.1	0.5	1.2474	0.0024
SRI-5-1	42937	34.00393333	-120.19605	4.8/7.4	100	4.52	0.11	0.0136	718	1.1879	0.0019	0.7099	0.0025	96.1	0.6	1.2465	0.0023
SRI-5-2	42937	34.00393333	-120.19605	4.8/7.4	99	4.60	0.11	0.0111	809	1.1641	0.0019	0.6452	0.0015	86.0	0.4	1.2092	0.0023
Santa Rosa Island: Carrington Point terrace																	
SRI-1-B***	42930	34.03098333	-120.0452333	6	100	4.19	0.11	0.0027	3424	1.1163	0.0018	0.7303	0.0026	112.7	0.8	1.1599	0.0023
SRI-1-B dup																	
#1***	42930	34.03098333	-120.0452333	6	100	4.19	0.11	0.0027	3416	1.1166	0.0019	0.7318	0.0031	113.1	0.9	1.1604	0.0025
SRI-1-C***	42930	34.03098333	-120.0452333	6	100	4.11	0.11	0.01	903	1.1164	0.0019	0.7219	0.0021	110.5	0.6	1.1590	0.0024
SRI-1-D***	42930	34.03098333	-120.0452333	6	100	3.41	0.12	0.006	1258	1.1206	0.0019	0.7347	0.0017	113.1	0.6	1.1659	0.0025
SRI-1-E	42930	34.03098333	-120.0452333	6	100	4.29	0.11	0.0036	2716	1.1160	0.0018	0.75	0.0031	118.1	0.9	1.1619	0.0024
Santa Rosa Island: 2nd terrace																	
North side of island																	
SRI - 5F***	42940	34.00298333	-120.1928	21/24	95–100	4.59	0.11	0.0164	675	1.1417	0.0014	0.796	0.0024	125.5	0.8	1.2019	0.0018
SRI - 5D - 1	42938	34.00405	-120.2009167	17.6/24	99	4.07	0.11	0.0103	1109	1.1667	0.0019	0.9252	0.0033	160.8	1.4	1.2624	0.0026
SRI - 5D - 2	42938	34.00405	-120.2009167	17.6/24	99	4.62	0.11	0.0105	1107	1.1608	0.0017	0.8314	0.0033	131.3	1.1	1.2330	0.0023
SRI - 5D - 3	42938	34.00405	-120.2009167	17.6/24	100	4.48	0.11	0.0196	593	1.1711	0.0018	0.8569	0.003	136.4	1	1.2515	0.0024
SRI - 5D - 5	42938	34.00405	-120.2009167	17.6/24	100	4.12	0.11	0.0148	748	1.1128	0.003	0.8868	0.0052	165.5	2.5	1.1799	0.0043
SRI - 5D - 6	42938	34.00405	-120.2009167	17.6/24	100	4.77	0.11	0.0278	426	1.1595	0.0024	0.8183	0.0037	127.8	1.2	1.2288	0.0032
SRI - 5 J - 1	42942	34.00253333	-120.2020833	23/24	100	4.65	0.11	0.0063	1773	1.1666	0.0016	0.7973	0.0028	120.4	0.8	1.2340	0.0021
SRI - 5 J - 2	42942	34.00253333	-120.2020833	23/24	99	4.69	0.11	0.0038	3070	1.1903	0.0015	0.8252	0.003	123.0	0.8	1.2692	0.0020
SRI - 5 J - 3	42942	34.00253333	-120.2020833	23/24	99	4.02	0.11	0.0197	521	1.1859	0.0017	0.8402	0.0035	128.0	1	1.2668	0.0022
SRI - 5 J - 4	42942	34.00253333	-120.2020833	23/24	99	3.90	0.12	0.0117	946	1.1911	0.0014	0.9355	0.0066	156.4	2.4	1.2972	0.0027
SRI - 5 J - 5	42942	34.00253333	-120.2020833	23/24	100	5.05	0.10	0.0063	2075	1.2222	0.0024	0.8558	0.0036	124.4	1.1	1.3157	0.0031
SRI - 5 J - 6	42942	34.00253333	-120.2020833	23/24	98–99	4.09	0.11	0.0196	526	1.1702	0.0016	0.8285	0.0049	128.3	1.4	1.2444	0.0023
SRI - 5 J - 7	42942	34.00253333	-120.2020833	23/24	100	4.82	0.13	0.0131	902	1.1778	0.0058	0.808	0.0108	121.0	3.1	1.2501	0.0076
South side of island																	
SRI - 4 - A	42936	33.90541667	-120.1062	14.3/20.0	100	4.42	0.11	0.0197	522	1.1811	0.0021	0.7683	0.0036	110.4	0.9	1.2472	0.0027
SRI - 4 - B	42936	33.90541667	-120.1062	14.3/20.0	100	5.55	0.11	0.0182	761	1.1913	0.0014	0.8212	0.0027	121.7	0.8	1.2697	0.0019
SRI - 4 - C	42936	33.90541667	-120.1062	14.3/20.0	100	4.96	0.11	0.0326	354	1.1633	0.0021	0.7664	0.0052	113.1	1.4	1.2247	0.0028

(continued on next page)

Table 1 (continued)

Location, marine terrace	LACMIP loc.	Latitude (°)	Longitude (°)	Fossil locality/SLA*	Aragonite (%)	U ppm	error	²³² Th ppm	AR	²³⁰ Th/ ²³² Th	AR*	²³⁴ U/ ²³⁸ U	AR*	²³⁰ Th/ ²³⁸ U	Age (ka)**	+/-	²³⁴ U/ ²³⁸ U	initial AR*	+/-	
				elevation (m)																
SRI - 4 - D	42936	33.90541667	-120.1062	14.3/20.0	100	5.04	0.12	0.0344	353	0.0039	0.7922	0.0042	1.1892	0.0039	114.7	1.3	1.2616	0.0050		
SRI - 4 - E	42936	33.90541667	-120.1062	14.3/20.0	100	4.69	0.12	0.0158	752	0.0032	0.8358	0.0039	1.1813	0.0032	127.8	1.3	1.2600	0.0041		
SRI - 4 - F	42936	33.90541667	-120.1062	14.3/20.0	100	4.29	0.11	0.0065	1541	0.0018	0.7752	0.003	1.1436	0.0018	119.3	0.9	1.2010	0.0024		
SRI - 4 - G	42936	33.90541667	-120.1062	14.3/20.0	100	4.42	0.11	0.0084	1285	0.0018	0.8004	0.0034	1.1701	0.0018	120.5	1	1.2390	0.0023		
SRI - 4 - H	42936	33.90541667	-120.1062	14.3/20.0	100	4.55	0.11	0.0055	2024	0.0023	0.8011	0.0070	1.1903	0.0023	116.7	1.8	1.2646	0.0031		
SRI - 4 - I	42936	33.90541667	-120.1062	14.3/20.0	100	4.06	0.11	0.0089	1083	0.0021	0.7839	0.0055	1.1592	0.0021	118.4	1.5	1.2224	0.0028		
SRI - 4 - J	42936	33.90541667	-120.1062	14.3/20.0	100	5.24	0.11	0.0098	1293	0.0027	0.7942	0.0040	1.1792	0.0027	117.1	1.2	1.2494	0.0035		
SRI - 4 - K	42936	33.90541667	-120.1062	14.3/20.0	100	4.58	0.12	0.0076	1456	0.0018	0.7920	0.0034	1.1716	0.0018	118.1	1	1.2395	0.0023		
SRI - 4 - L	42936	33.90541667	-120.1062	14.3/20.0	100	4.89	0.10	0.0111	1100	0.0022	0.8262	0.0029	1.1602	0.0022	129.9	1	1.2311	0.0029		
SRI - 4 - M	42936	33.90541667	-120.1062	14.3/20.0	100	5.26	0.10	0.0202	624	0.0025	0.7907	0.0019	1.1863	0.0025	114.9	0.7	1.2576	0.0031		
SRI - 4 - N	42936	33.90541667	-120.1062	14.3/20.0	100	5.47	0.11	0.0164	822	0.0024	0.8142	0.0041	1.2014	0.0024	117.9	1.1	1.2810	0.0031		
SRI - 4 - O	42,936	33.90541667	-120.1062	14.3/20.0	100	4.90	0.11	0.0122	954	0.0019	0.7812	0.0026	1.1948	0.0019	111.1	0.7	1.2665	0.0024		
San Miguel Island: 2nd terrace, south side of island																				
SMI-236-F	42929	34.019883	-120.316267	21.3/22.0	98-99	3.84	0.12	0.0218	413	0.0042	0.7716	0.0045	1.1098	0.0042	125.8	1.7	1.1566	0.0056		
SMI-236-G	42929	34.019883	-120.316267	21.3/22.0	99	3.74	0.13	0.0135	624	0.0036	0.7405	0.0044	1.1182	0.0036	115.1	1.4	1.1635	0.0047		
SMI-236-H	42929	34.019883	-120.316267	21.3/22.0	100	4.07	0.11	0.0129	735	0.0028	0.7685	0.003	1.1102	0.0028	124.7	1.1	1.1567	0.0037		
SMI-236-J	42929	34.019883	-120.316267	21.3/22.0	100	4.07	0.10	0.0144	659	0.0022	0.7673	0.0133	1.1118	0.0022	122.6	3.9	1.1668	0.0034		

* SLA = shoreline angle; AR = activity ratio

** Calculated using half-lives of 75,584 yr (²³⁰Th) and 2445,620 yr (²³⁴U) from Cheng et al. (2013)

*** Data from Muhs et al. (2015)

.gov/m-smors/certificates/987.pdf) was used as a reference ⁸⁷Sr/⁸⁶Sr standard, with at least two samples of this standard in each barrel. Age estimates were made for each shell analyzed using the calibrated ⁸⁷Sr/⁸⁶Sr values of Howarth and McArthur (1997) and McArthur et al. (2001, 2020), LOWESS Version 6.

Numerous studies, summarized by Schneider et al. (2009), have shown that in addition to determination of primary mineralogy by XRD, there are chemical criteria useful in ascertaining the reliability of Sr isotopes in geochronology. The concentrations of certain trace elements found in marine carbonate shells (Mg, Sr, Ba) can be useful measures of whether there have been diagenetic alterations (usually element loss) of the original skeletal compositions. Concentrations of other elements (Si, Al, Fe, Mn) can be helpful in ascertaining whether there have been diagenetic gains of constituents from the surrounding sediment matrix and/or ground water. Thus, concentrations of Ca, Mg, Sr, Ba, Si, Al, K, Fe, and Mn were determined on identical splits of the samples analyzed for Sr isotopic composition. Powdered, homogenized splits of cleaned shell material were digested using sodium peroxide fusion at ~1050 °C and concentrations were determined by inductively coupled plasma-optical emission spectroscopy (ICP-OES). Detection limits for Ca, Mg, Si, Al, K, and Fe are 0.01% and those for trace elements are as follows: Sr (0.1 ppm), Ba (0.5 ppm), and Mn (10 ppm). All Sr isotope and geochemical data are given in Table 3 and are also reported in a U.S. Geological Survey database: <https://doi.org/10.5066/P9KDKAB9>.

3. Results

3.1. Geomorphology of Santa Rosa Island

The geomorphology of Santa Rosa Island has been described previously by Orr (1960), Pinter et al. (2001), Schumann et al. (2014), and Muhs et al. (2014a, 2015), but a generalized description is given here. The south-central part of the island has the highest elevations, up to ~480 m, and is characterized by highly dissected terrain, with steep-sided valleys cut into Tertiary sedimentary rocks (Fig. 2). Quaternary deposits, other than alluvium in valley bottoms, and colluvium on valley sides, are largely absent. Seaward of this part of the island, in all directions, there are planar surfaces on Tertiary sedimentary rocks. Shoreline angles of these possible marine terraces are rarely exposed, and the platforms commonly have elevations of ~150 m to ~270 m, but range as low as ~70 m to as high as ~300 m. They are mapped as Qtpo in Figs. 2-5. Most of these surfaces lack marine deposits, but Muhs et al. (2014a) interpreted them to be ancient wave-cut platforms whose overlying sediments have been stripped away. Commonly, these surfaces slope gently seaward and often have what appear to be degraded, former sea cliffs at their landward edges.

Over much of the northern half of the island, largely to the north of the Santa Rosa Island fault, and between Sandy Point and Carrington Point, high-elevation marine terraces are present (mapped as Qto; Figs. 2-5). These landforms have wave-cut platforms, overlain by marine sand and gravel, and are occasionally fossiliferous. Even where fossils are lacking, gravel clasts frequently have holes produced by mollusks, specifically rock-boring pholad bivalves. The highest of these marine terraces has a shoreline angle elevation of 272 m and the lowest has an outer (seaward) edge of ~70 m (Muhs et al., 2014a). The highest documented fossil-bearing marine terrace deposits are found in the northwestern part of the island (Figs. 3, 6, 7, 8). The terrace deposits at many localities in this area host the extinct gastropod *Pusio fortis* (Carpenter, 1866) (formerly called *Calicantharus fortis*; Fig. 6c). This species has been found in deposits as old as Pliocene or early Pleistocene age (Groves, 1991). As on San Nicolas Island, Santa Barbara Island, and Anacapa Island (Muhs and Groves, 2018), the taxon serves as a marker fossil for marine terrace deposits older than the LIG period. In an elevation survey conducted from Sandy Point to ~4.5 km to the southeast, a number of high-elevation fossiliferous marine terrace deposits were observed, many of them hosting *P. fortis* (Figs. 3, 8).

Table 2

Amino acid data for fossil *Tegula*, Santa Cruz Island, California.

Locality and Field #	LACMIP locality ^a	Geomorphology and U-series age (yr)	Latitude (°N)	Longitude (°W)	Univ. of Colorado Amino Acid Laboratory (AAL) #	Sample ID	D/L glutamic acid, area	D/L valine, area	
Santa Cruz Island, Fraser Point area, SCRZI-111	42337	1st terrace (T1) ~120 ka Muhs et al. (2021)	34.061461	119.920387	<i>Tegula</i> sp.	14085	A	0.376	0.312
					<i>Tegula</i> sp.	14085	B	0.470	0.385
					<i>Tegula</i> sp.	14085	C	0.474	0.370
					<i>Tegula</i> sp.	14085	D	0.366	0.290
					<i>Tegula</i> sp.	14085	E	0.451	0.366
					Mean			0.427	0.345
			SD	0.05	0.04				
Santa Cruz Island, Fraser Point area, SCRZI-107	42335	1st terrace (T1) ~120 ka Muhs et al. (2021)	34.05866	119.917070	<i>Tegula</i> sp.	14083	A	0.442	0.376
					<i>Tegula</i> sp.	14083	B	0.491	0.434
					<i>Tegula</i> sp.	14083	C	0.490	0.408
					<i>Tegula</i> sp.	14083	D	0.464	0.376
					<i>Tegula</i> sp.	14083	E	0.422	0.330
					Mean			0.462	0.385
			SD	0.03	0.04				
Santa Cruz Island, Pozo Anchorage area, SCRZI-110	42339	1st terrace (T1) ~120 ka (Pinter et al. 1998)	33.97989	119.86541	<i>Tegula</i> sp.	14084	A	0.561	0.478
					<i>Tegula</i> sp.	14084	B	0.540	0.478
					<i>Tegula</i> sp.	14084	C	0.547	0.438
					<i>Tegula</i> sp.	14084	D	0.438	0.371
					<i>Tegula</i> sp.	14084	E	0.472	0.426
					Mean			0.512	0.438
			SD	0.05	0.04				

^a LACMIP = Natural History Museum of Los Angeles County, Department of Invertebrate Paleontology locality number

North of the Santa Rosa Island fault (Figs. 2, 3), the highest wave-cut bench elevations range from ~99 m (in the northwest, just above Sandy Point) to ~122 m at a point ~3.3 km to the southeast, adjacent to the fault. Because Pleistocene eolian sand and eolianite cover much of the landscape in this area, exposures are rare. Thus, it is not known if this range of elevations represents more than one terrace or simply a northwestward-sloping bench of the same terrace. Just south of the Santa Rosa Island fault along the southern part of topographic profile A-A' (Figs. 3, 8), the wave-cut bench and overlying marine deposits of a high terrace can be traced for ~300–400 m and elevations are relatively constant, between ~124 m and ~127 m. All elevations of the bench south of the fault are higher than all measured bench elevations that are north of the fault, supporting the conclusion made by Dibblee et al. (1998) and Minor et al. (2012) that the Santa Rosa Island fault on the westernmost part of the island has experienced up-to-the-south reverse or sinistral-reverse movement in the early Pleistocene.

The younger marine terraces (mapped as Qty on Figs. 2–5) are found at elevations lower than ~30 m and, based on previous work (Muhs et al., 2014a, 2015), likely date to high-sea stands of the LIG, *sensu lato* (all of MIS 5). These landforms rim the northwestern (Fig. 3), northeastern (Fig. 4), and south-central (Fig. 5) parts of the island. Low-elevation terraces define the coastal plain region of the island, as designated by Schumann et al. (2014), and are seaward of the outer, lower (~65 m to ~100 m) edges of the older terrace suite (Figs. 7, 8, 9). In places, the low terraces are mantled by a thin cover of alluvium and eolian sand, and in other places are overlain by thick deposits of these terrestrial sediments (Fig. 10). On both the northwestern and northeastern parts of the island, the lowest terraces are overlain by climbing (Figs. 7a, 11b) or falling (Fig. 11a) dunes, composed of eolian sand mixed with colluvium.

On the northwestern (Fig. 3) and south-central (Fig. 5) parts of the island, two low-elevation terraces are found, both mapped as Qty in Figs. 3, 5, but distinguishable in the field by a staircase geomorphology. The lowest terrace, referred to herein simply as the “1st” terrace for convenience, has a wave-cut bench that is often exposed in sea cliffs (Figs. 7a, 10b), a few meters above sea level. The next highest terrace is referred to informally as the “2nd” terrace and is broader in a shore-normal sense, typically ~100 m to ~300 m wide (Fig. 9a). Above the

2nd terrace, at least on the northern shore of Santa Rosa Island, there is an older terrace whose outer edge is ~75 m above sea level (Fig. 9).

In northeastern Santa Rosa Island there only is a single low-elevation platform with overlying marine deposits exposed in sea cliff sections and canyon sidewalls. This terrace is found exposed in the modern sea cliff almost continuously from Southeast Anchorage north along Bechers Bay, up to Carrington Point, and west to Lobo Canyon (Fig. 4). Viewed from offshore, the wave-cut platform of this terrace, overlain by eolian sediments, can be traced from Bechers Bay all the way to Carrington Point. In the southern Bechers Bay-Southeast Anchorage area, Muhs et al. (2014a) reported that the wave-cut bench of this terrace is displaced by the Santa Rosa Island fault. South of the fault, around Southeast Anchorage, these investigators reported low-terrace shoreline angle elevations of ~14 m to ~15 m, whereas just north of the fault, shoreline angle elevations of the terrace are ~20 m. Unfortunately, no fossils have yet been found in any of the exposures of this terrace in the Bechers Bay or Southeast Anchorage areas. From Corral Point north to Carrington Point and west to Lobo Canyon, however, seven fossiliferous exposures have been found (Fig. 4). Owing to a thick cover of eolian sand, shoreline angles of this terrace are not exposed in most places, with only the outer edge of the terrace still visible, at elevations from ~5 m to ~12 m above sea level (Fig. 11a). Only a single locality southwest of Carrington Point (Fig. 4) exposes a wave-cut bench with an elevation of ~12 m at its outer edge and a shoreline angle at ~16 m (Fig. 11b). Although fossils were found on this bench at nearby exposures (LACMIP locs. 42933 and 42934; Fig. 4), no corals were recovered and all mollusks were exposed on the surface and cemented into a coquina.

In summary, this single, low-elevation terrace on the eastern side of Santa Rosa Island occupies elevations that are mostly intermediate between the 1st and 2nd terraces, as these terraces have been observed elsewhere on the northwestern coast of the island and on the southern coast. Thus, it is difficult, on geomorphic grounds, to correlate it with either the 1st or 2nd terrace where both are exposed. As a consequence, this terrace is referred to simply as the “Carrington” terrace, and its age is evaluated independently of the terrace mapping done elsewhere on the island.

Where marine terrace sediments are exposed on Santa Rosa Island,

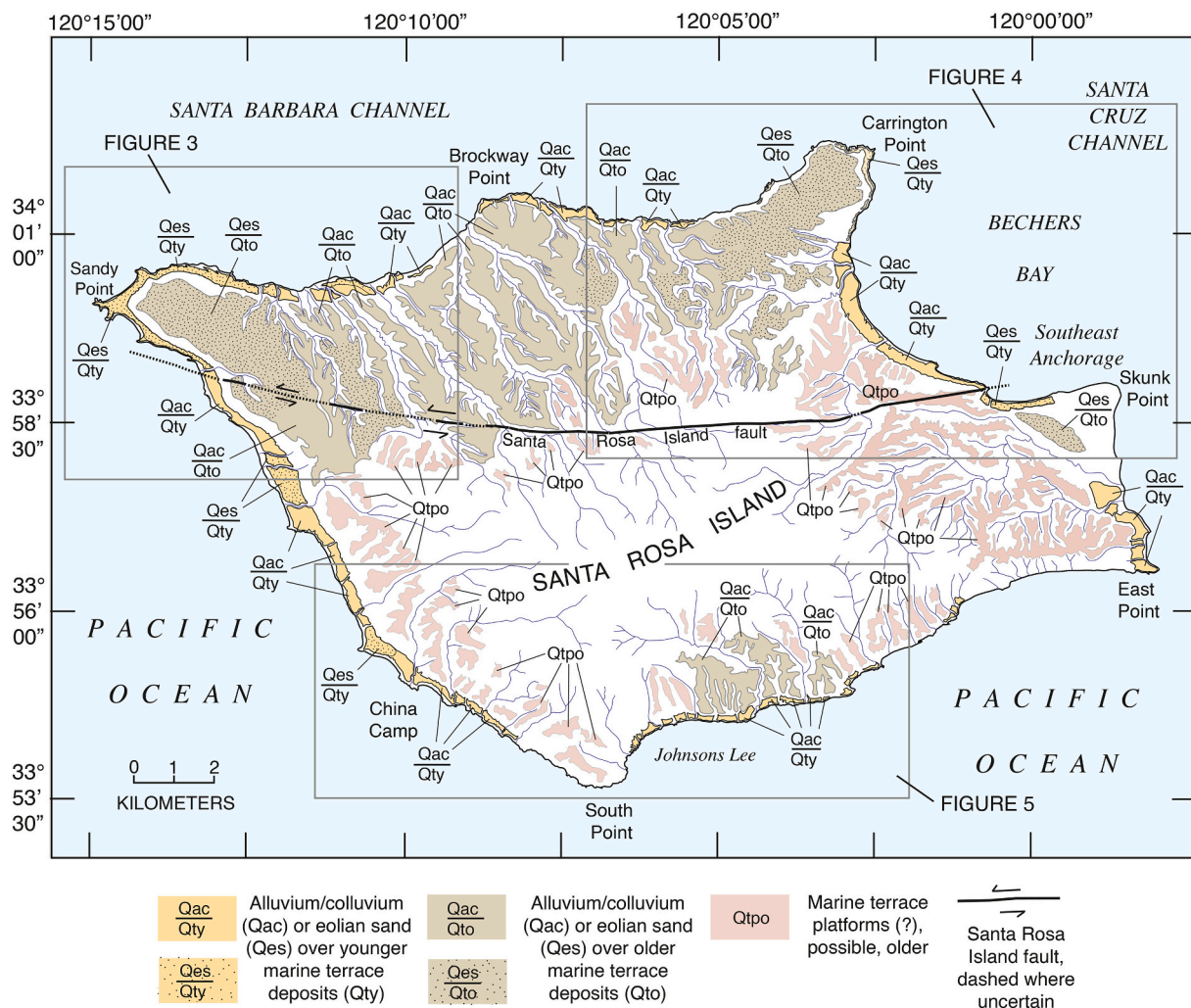


Fig. 2. Map of Santa Rosa Island, showing marine terrace deposits and other surficial deposits, drainages, and locations of detailed maps (Figs. 3, 4, 5). White areas are pre-Quaternary bedrock, in places overlain by eolian deposits, alluvium, or colluvium. Mapping is slightly modified from Muhs et al. (2014a) except some of the “Qto” delineations are slightly modified from Sonneman et al. (1969). Note that unit designated as “Qtpo” possible marine terrace platforms, may or may not have overlying marine and/or terrestrial deposits. Thick black lines show location of Santa Rosa Island fault, taken from Sonneman et al. (1969), with sense of movement indicated by opposing arrows.

for the most part they consist of thin, poorly sorted, sometimes fossiliferous deposits of gravel and sand. Primary sedimentary structures in most deposits are lacking, and consist simply of a thin (~0.5 m to ~1.0 m) mix of sand and gravel with interspersed fossils, resting on a marine bench cut on Tertiary bedrock, such as that seen for the 1st terrace near Sandy Point, at LACMIP loc. 42957 (Fig. 12a). Here, the marine terrace deposits are overlain by a pedogenic calcrete, in turn overlain by several meters of carbonate-rich eolian sand. In other localities, overlying deposits consist of alluvium, usually several meters thick. Another variation seen on Santa Rosa Island is cementation of poorly sorted marine gravel, sand, and fossils into a coquina, such as that seen for the 1st terrace at Johnsons Lee, at LACMIP loc. 42953 (Fig. 12b). At still other localities, where overlying terrestrial deposits are absent, or where they were once present but have been stripped off by erosion, a coquina cemented to a wave-cut platform can be subaerially exposed, as seen west of Carrington Point, at LACMIP loc. 42933 (Fig. 12c). Only rarely are marine deposits thick, stratified, and sorted, but one example is found south of Carrington Point, at LACMIP loc. 42930 (Fig. 12d). At this locality, approximately a meter of fossiliferous sand and gravel overlies the wave-cut bench, in turn overlain by 2 m of well-sorted, fossiliferous marine sand, in turn overlain by a paleosol and ~14 m of eolian sand. In most places, however, the marine terrace deposits are so

thin, poorly sorted, and lacking in sedimentary structures that genetic interpretations (i.e., transgressive/regressive deposits, storm deposits, etc.) are simply not possible.

Eight coastal sections (Figs. 13, 14) exposing these two terraces were described and measured (some shown previously in Muhs et al., 2014a, 2015; some described here for the first time). As noted above, on the north shore of Santa Rosa Island, at Cañada Garañon (Figs. 9, 13), the 2nd terrace has a shoreline angle elevation of ~24 m and the 1st terrace has a shoreline angle elevation of ~7 m. However, on the southern shore of the island, at Johnsons Lee, the 2nd terrace has a shoreline angle elevation of 20 m and the 1st terrace has a shoreline angle elevation of 5.4 m. In several places on the northwestern side of the island, the wave-cut bench of the 1st terrace is exposed but the shoreline angle of that terrace and all of the 2nd terrace are covered with thick deposits of eolian sand, colluvium, and/or alluvium (Fig. 7). In this area (Figs. 3, 8), the 1st terrace has a shoreline angle between ~5 m and ~12 m (estimated to be ~8 m) and the 2nd terrace has a shoreline angle between ~18 m and ~35 m (estimated to be 24 to 26 m).

3.2. Uranium-series geochronology

For the younger marine terraces, the primary method of age

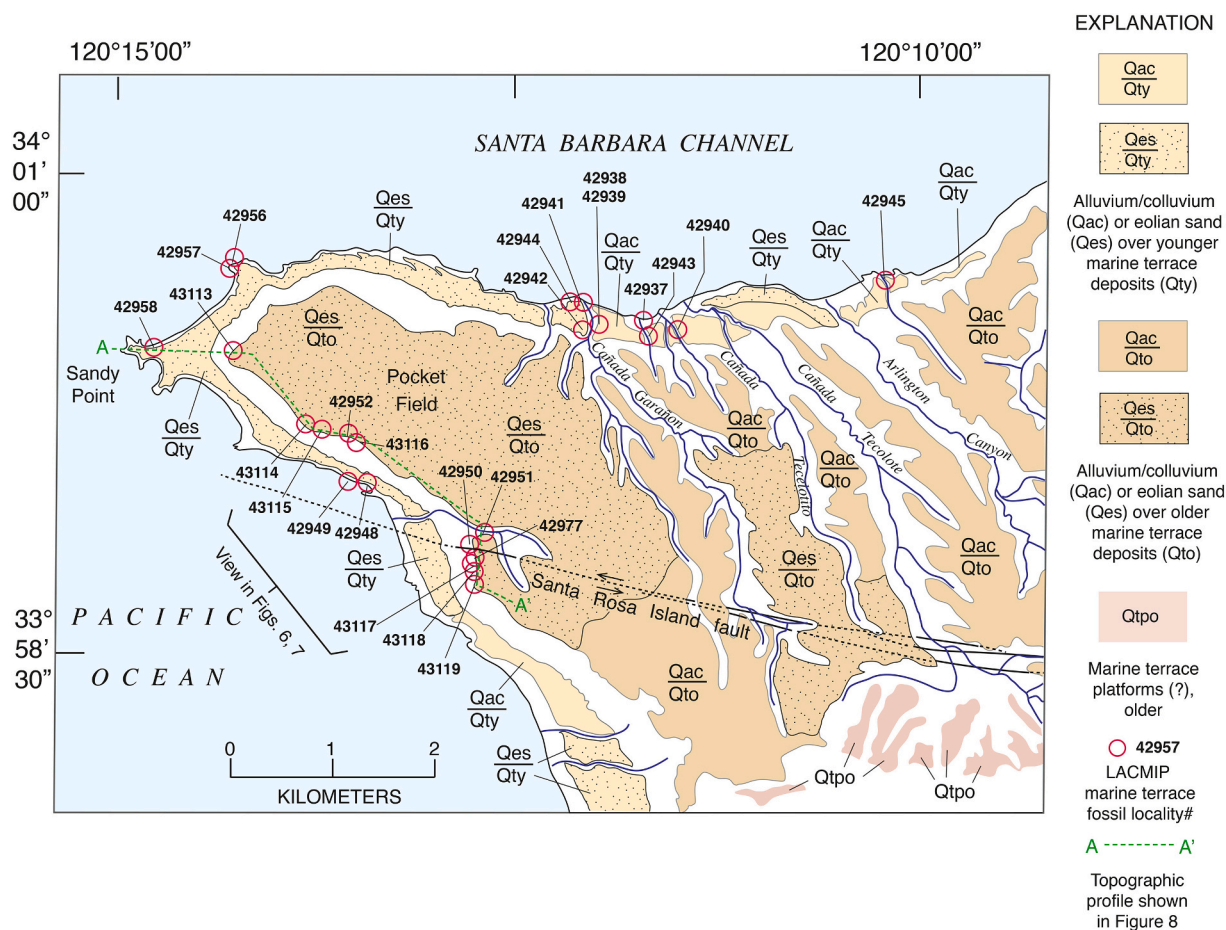


Fig. 3. Map of northwestern Santa Rosa Island (see Fig. 2 for location), showing marine terrace deposits and other surficial deposits, drainages, Natural History Museum of Los Angeles County Invertebrate Paleontology (LACMIP) fossil localities, and location of topographic profile A-A' shown in Fig. 8. Mapping is from Muhs et al. (2014a, 2015), except for the Santa Rosa Island fault, which is from Sonneman et al. (1969). For Santa Rosa Island fault, solid line where well located; dashed where uncertain or concealed.

determination reported here is uranium-series (U-series) dating of the solitary coral *Balanophyllia elegans*. Some U-series ages of corals were previously reported by Muhs et al. (2015), but most of those shown in Table 1 are reported here for the first time. In order to provide a comprehensive assessment of terrace ages, however, previously published data from Santa Rosa Island are given in Table 1 as well as the results of all new analyses.

All analyses of corals collected from three localities of the 1st terrace (SRI-5, SRI-12, SRI-27) yield ages of ~80 ka, with one exception (SRI-5-1). Taken at face value, ages range from ~86 ka to ~77 ka, which correlates this terrace with similarly aged corals from low-elevation terraces in southern Oregon, northern and central California, southern California, and northernmost Baja California, México (Muhs et al., 2002, 2006). It is clear, however, that some corals from the 1st terrace have experienced open-system conditions. This is evidenced by samples with back-calculated initial $^{234}\text{U}/^{238}\text{U}$ activity values that exceed those found in modern seawater (Table 1). Modern seawater has $^{234}\text{U}/^{238}\text{U}$ activity values that range from 1.140 to 1.155 (Chen et al., 1986; Delanghe et al., 2002). It is interesting to note that although corals from SRI-27 (LACMIP loc. 42957) have back-calculated initial $^{234}\text{U}/^{238}\text{U}$ activity values close to seawater values, those from SRI-12 (LACMIP loc. 42948) are substantially higher. Nevertheless, the apparent age ranges (78.6 ka to 83.8 ka for SRI-27; 76.9 ka to 83.8 ka for SRI-12) differ little between the two localities.

Uranium-series dating shows that corals from the 2nd terrace on Santa Rosa Island are substantially older than those from the 1st terrace (Table 1). Here it is worth noting that the 2nd terrace on Santa Rosa

Island is, in a geomorphic sense, an eastward extension of the broad, 2nd terrace found on southeastern San Miguel Island, a short distance to the west (Fig. 1b; see maps in Muhs et al., 2014a). The terrace on the south side of San Miguel Island has a shoreline angle elevation ranging from ~24 m to ~21 m, very similar to that of the 2nd terrace on the south side of Santa Rosa Island. In an earlier study, corals from the 2nd terrace on San Miguel Island gave apparent U-series ages of ~121 ka to ~114 ka, with back-calculated initial $^{234}\text{U}/^{238}\text{U}$ activity values only slightly above the range of these ratios in modern seawater, indicating a mostly closed-system history (Muhs et al., 2014a). Four more corals from this terrace were analyzed for the present study and confirm the earlier results, with apparent ages of ~126 ka to ~115 ka and again with evidence of mostly closed-system histories (Table 1; Fig. 15a). Corals from the 2nd terrace on the south side of Santa Rosa Island are limited to a single locality (SRI-4; LACMIP loc. 42936, at Johnsons Lee). At this locality, U-series analyses gave apparent ages of ~130 ka to ~110 ka, but all corals show evidence of open-system histories, based on their back-calculated initial $^{234}\text{U}/^{238}\text{U}$ activity values (Fig. 15a). On the north side of the island, three localities (SRI-5F, 5D, and 5J; LACMIP locs. 42940, 42938, and 42942, all near Cañada Garañon) yielded corals from the 2nd terrace. Three corals from the north side (SRI-5D-1, SRI-5D-5, and SRI-5J-4) gave apparent ages between ~165 ka and ~156 ka, which are not considered reliable. All other corals from the 2nd terrace on this side of the island gave apparent ages of ~136 ka to ~120 ka (Table 1). As with the corals from the south side of the island, the corals from the north side of the island also show evidence of open-system histories, in contrast with the corals from San Miguel Island (Fig. 15b). Interestingly, despite

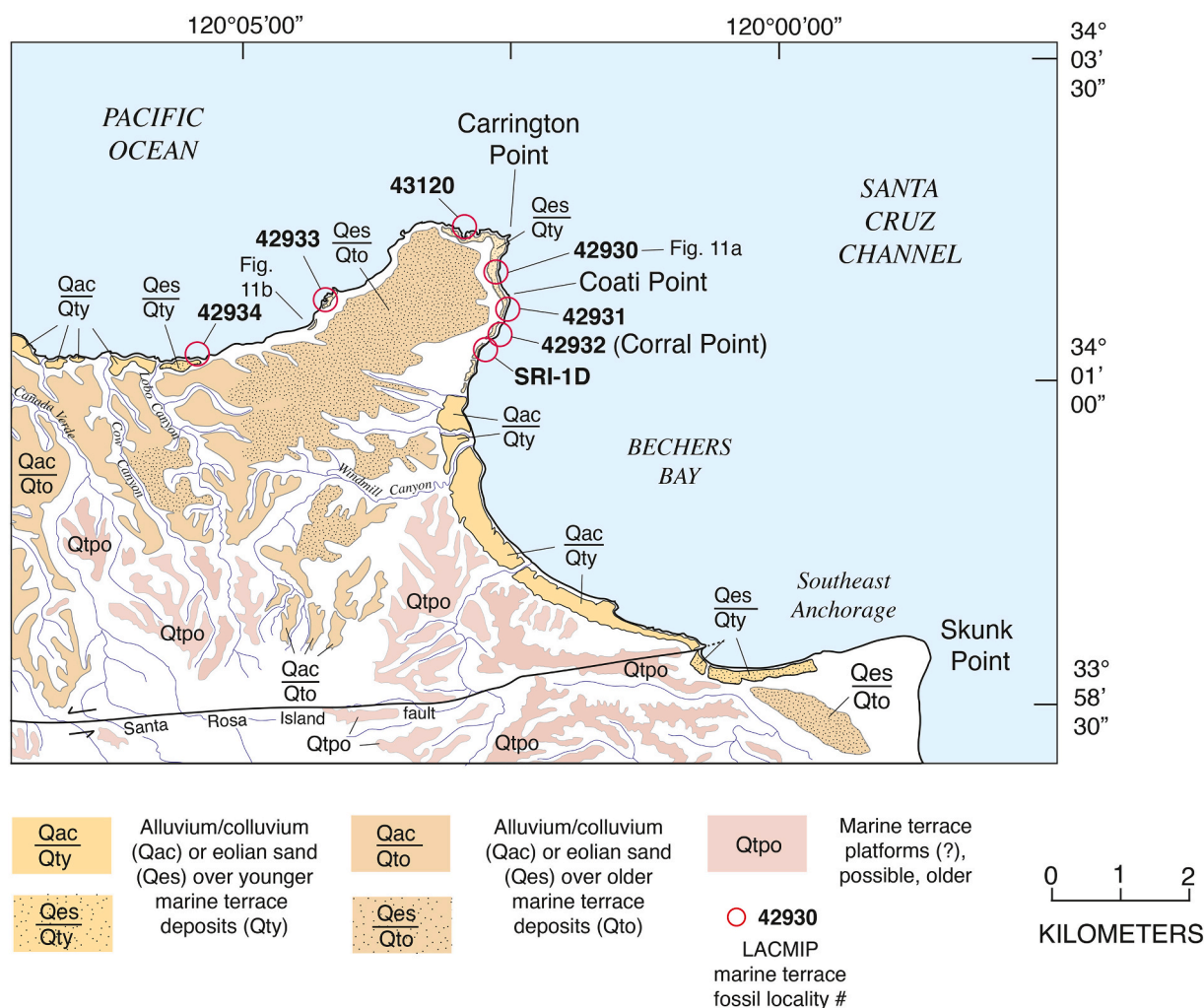


Fig. 4. Map of northeastern Santa Rosa Island (see Fig. 2 for location), showing marine terrace deposits and other surficial deposits, drainages, and Natural History Museum of Los Angeles County Invertebrate Paleontology (LACMIP) fossil localities. Mapping is from Muhs et al. (2014a, 2015). Location of Santa Rosa Island fault is from Sonneman et al. (1969).

the obvious open-system histories of the Santa Rosa Island corals, all but the three apparent oldest specimens have age ranges very similar to the San Miguel Island corals that exhibit mostly closed-system histories.

Four corals from the Carrington terrace (LACMIP loc. 42930) gave apparent ages of ~118 ka to ~110 ka (Table 1). Like the San Miguel Island corals, these specimens show only slight evidence of open-system histories. The range of ages for the Carrington terrace is similar to the age range of the majority of corals from the 2nd terrace on the south side of the island at Johnsons Lee (SRI-4; LACMIP loc. 42936).

3.3. Amino acid geochronology of low-elevation marine terrace deposits

Amino acid racemization of fossil mollusks provides a method of relative-age determination that is highly complementary to U-series dating of fossil corals. Localities that lack corals can be correlated with U-series-dated, coral-bearing localities if D/L values of amino acids in fossil mollusks are similar. Because amino acid racemization is a temperature-dependent process, latitudinal plots of D/L values provide a means of displaying “aminozones” of similar-aged fossils along north-south-trending coastlines, such as the Pacific Coast of North America (see examples in Kennedy et al., 1982 and Wehmiller, 1982). With some uncertainty apparent in interpreting the U-series ages of corals from the 1st, 2nd, and Carrington terraces on Santa Rosa Island, as discussed above, amino acid geochronology provides an independent method of

assessing the U-series ages.

For fossil *Tegula*, D/L values for glutamic acid and valine have been used for definition of aminozones in California and Baja California (Muhs and Groves, 2018; Muhs et al., 2014a, 2021). Fossil *Tegula* from the 1st, 2nd and Carrington terraces on Santa Rosa Island, previously only partially dated by U-series methods, were included in these studies. Amino acid data from those fossils indicated that the 1st terrace likely correlates with dated ~80 ka terraces and the 2nd terrace likely correlates with dated ~120 ka terraces found elsewhere. The Carrington terrace gave D/L values for both amino acids that are intermediate between these two ages of terraces, but still falling within the ~120 ka (or 120 ka and 100 ka) aminozone.

Wehmiller and Miller (2000) pointed out that D/L values in amino acids can be derived from ratios of either peak heights or peak areas on chromatograms. Both approaches have validity, depending on what the specific application might be. Although, under favorable circumstances, the difference between peak height ratios and peak area ratios should be less than ~8%, Wehmiller and Miller (2000) also noted that in principle, peak area ratios ought to be closer to the true values. In the previous studies of Santa Rosa Island cited above, all measurements were made with peak height ratios. Given the possibility of some difference in geochronological interpretation due to these methodological issues, the amino acid data for Santa Rosa Island, as well as other localities on the Pacific Coast, are reevaluated here using peak area ratios.

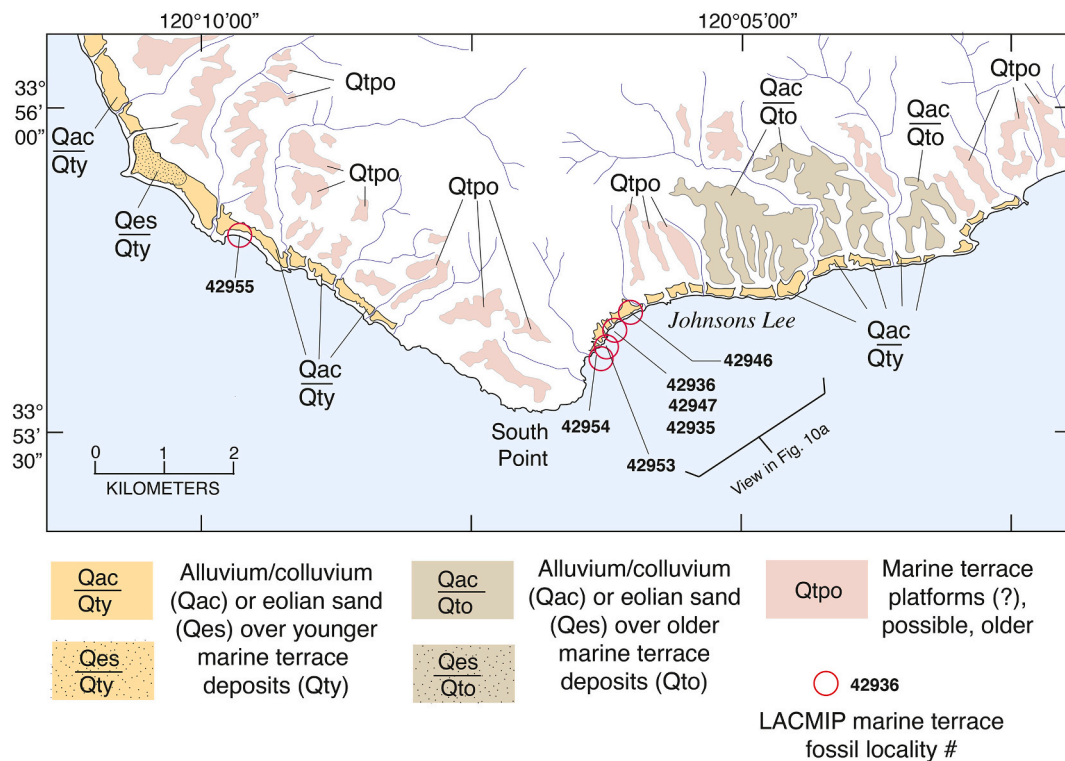


Fig. 5. Map of south-central Santa Rosa Island (see Fig. 2 for location), showing marine terrace deposits and other surficial deposits, drainages, and Natural History Museum of Los Angeles County Invertebrate Paleontology (LACMIP) fossil localities. Mapping is from Muhs et al. (2014a).

D/L values using peak areas for glutamic acid and valine in fossil *Tegula* were calculated for the three terraces on Santa Rosa Island, as well as independently dated ~80 ka and ~120 ka terrace localities from central California, southern California, and northern Baja California. Most of the data for this effort (both peak height ratios and peak area ratios) are derived from supplementary data files in Muhs et al. (2014a). In addition, however, new data for D/L values, given in Table 2, were generated for three U-series-dated localities on the lowest terrace on western Santa Cruz Island, the closest area to the eastern side of Santa Rosa Island, where the Carrington terrace is exposed. Muhs et al. (2021) reported 11 U-series ages of corals that correlated this low terrace on western Santa Cruz Island with the ~120 ka (MIS 5e) high stand of sea.

Results indicate that essentially the same aminozones identified along the Pacific Coast in Muhs and Groves (2018) and Muhs et al. (2014a, 2021) using peak height ratios also emerge using peak area ratios (Fig. 16). Temperature-controlled latitudinal aminozones are still apparent for both glutamic acid and valine D/L values, as independently dated 80 ka (MIS 5a) terrace localities with lower D/L values are clearly distinguished from independently dated ~120 ka (MIS 5e) localities. Although only one locality (LACMIP loc. 42957 or SRI-27) is available for the 1st terrace on Santa Rosa Island, D/L values in *Tegula* fall within the ~80 ka aminozone. Localities on the 2nd terrace on Santa Rosa Island, both on the north side near Cañada Garañon (SRI-5F, or LACMIP loc. 42940) and the south side at Johnsons Lee (SRI-4, or LACMIP loc. 42936) and China Camp (SRI-25, or LACMIP loc. 42955) all fall well within the ~120 ka aminozone, supporting the interpretation of an estimated ~120 ka age from the U-series data discussed above. It is worth noting that the mean D/L value for valine from the 2nd terrace at SRI-5F (LACMIP loc. 42940) at Cañada Garañon on the north side of the island is unexpectedly high, but still falls broadly within the ~120 ka aminozone. D/L values for glutamic acid in *Tegula* from this locality fall in a more central position within this aminozone.

Tegula from the Carrington terrace (SRI-1, or LACMIP loc. 42930) has D/L values for both glutamic acid and valine that fall above D/L values for the ~80 ka 1st terrace on Santa Rosa Island, indicating a somewhat

older age (Fig. 16). Interestingly, however, D/L values for glutamic acid in *Tegula* from the Carrington terrace fall slightly below those for the 2nd terrace on the north side of Santa Rosa Island and well below values for the 2nd terrace for valine. These observations indicate the possibility of an intermediate age, perhaps ~100 ka (MIS 5c), similar to what was observed for this terrace using D/L peak height values. Nevertheless, the mean values for both amino acids in *Tegula* from the Carrington terrace still fall within the older (~120 ka or ~120 ka and 100 ka) aminozone, consistent with the U-series ages of corals from this locality, and also consistent with the earlier amino acid results using peak heights.

3.4. Sr isotope age estimates of fossils from early Pleistocene marine terrace deposits

For Sr-isotope analyses of fossils from higher marine terrace deposits (those mapped as Qto and Qes/Qto on Figs. 2, 3) on northwestern Santa Rosa Island, specimens from three localities (LACMIP locs. 42950, 42977, and 42952; Figs. 3, 6, 8) were sampled, with two taxa analyzed at one of these localities. The sites at LACMIP locs. 42950 and 42977 are on the upthrown, southern side of the Santa Rosa Island fault (Figs. 6, 8) and display a bench cut on sandstone of the South Point Formation, overlain by ~1.0 m of fossiliferous marine terrace sands and gravels, in turn overlain by ~4 m of cemented, carbonate-rich, eolian sand (eolianite) with a thick Stage IV laminar calcrete in its upper part (Figs. 6, 8). No shoreline angle is exposed at either locality, but the bench is at an elevation of 127 m above sea level. The other locality (LACMIP loc. 42952) is exposed ~1.5 km to the northwest on the downthrown side of the fault, situated at an elevation of 112 m. Here, marine terrace fossils are exposed as a lag deposit right at the land surface. Based on records at the Santa Barbara Museum of Natural History, this locality is likely the same as Orr's (1960) high terrace site, referred to in museum records as "Scott's Shack."

For evaluation of the suitability of carbonate fossils in the application of Sr isotope geochronology, several criteria have been established over the past few decades. Brand and Veizer (1980) showed, on both

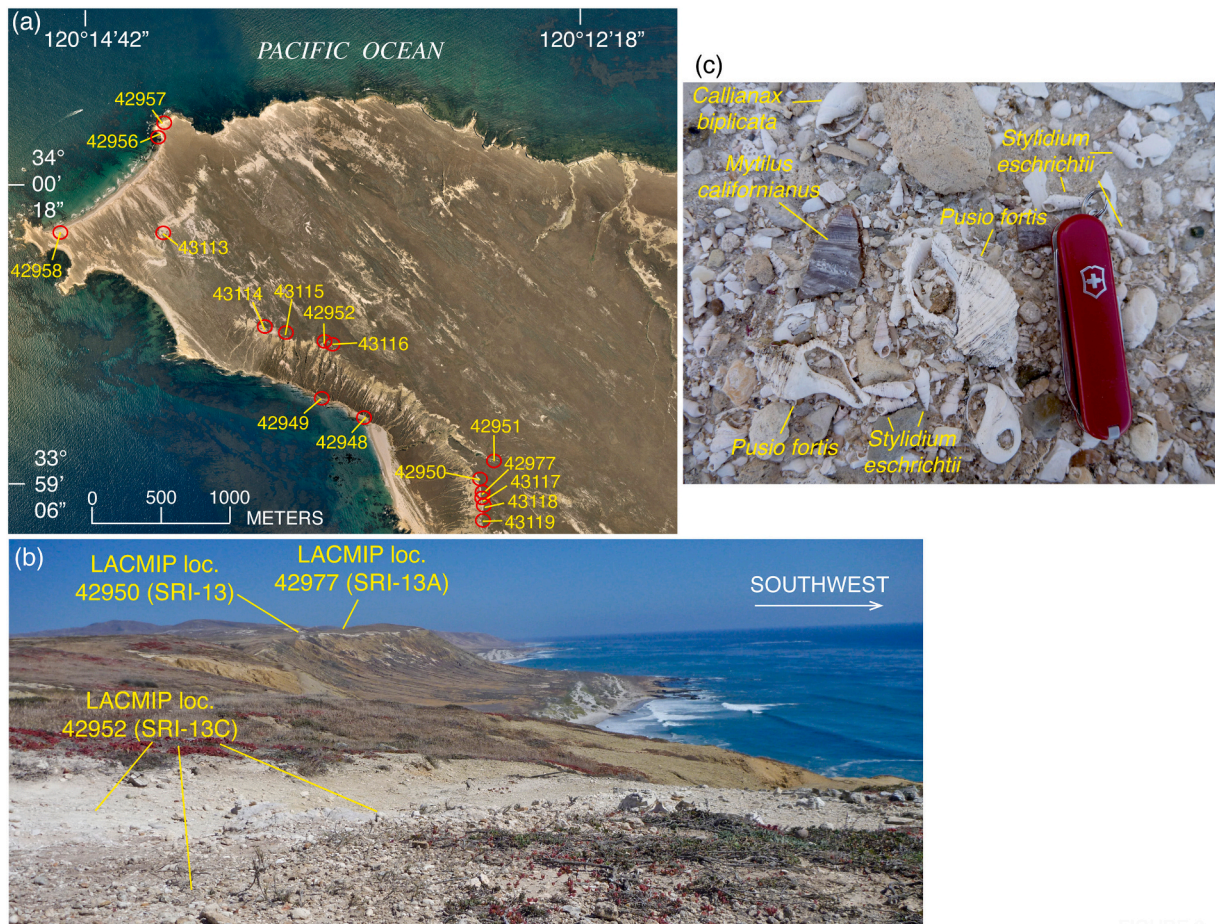


Fig. 6. (a) Aerial photograph (courtesy of the National Park Service) showing the locations of high-elevation terrace fossil localities. Linear, northwest-trending light-tan streaks are linear dunes with long axes parallel to the prevailing wind direction; (b) Ground photograph, looking southeast, of high-elevation marine terrace and fossil localities shown in (a); photograph by D.R. Muhs. (c) Photograph of marine terrace fossils at LACMIP loc. 42950; photograph by D.R. Muhs.

theoretical and empirical grounds, that through continuing diagenesis of carbonate systems, expected trace element trends through time are loss of Sr and Mg and gain of Mn and Fe. Consistent with this early study, McArthur (1994) also noted that in addition to establishment of primary mineralogy (either aragonite or high-Mg calcite) in fossils analyzed for Sr isotope geochronology, determinations of possible loss of Sr and Mg and gain of Mn and Fe are useful for assessing the integrity of original shell composition. Subsequent investigators using Sr isotopes for geochronology (e.g., McArthur et al., 2000; Schneider et al., 2009; Buczek et al., 2021) have used these same criteria and they are followed here as well.

Concentrations of trace elements that substitute for Ca in marine carbonate organisms, including Sr and Mg, are a function of both taxonomy and water temperatures at the time of shell growth (see summary in James and Jones, 2016). For the aragonite gastropod *Callianax biplicata* (G.B. Sowerby I, 1825), previously called *Olivella biplicata*, Krinsley (1960) analyzed 60 modern, dead-collected specimens from six localities in California and Washington. He reported relatively low mean Mg concentrations of ~0.008–0.039% (typical for aragonite shells) and mean Sr concentrations ranging from ~990–1750 ppm. The *Callianax* fossils studied here, from LACMIP loc. 42952, are all 99–100% aragonite, and have similarly low Mg concentrations (<0.01%), with Sr concentrations of 1490–1750 ppm (Table 3), indicating no evidence of diagenetic Sr loss. McArthur (1994) suggested that Fe and Mn concentrations greater than ~100 ppm can be indicative of diagenetic alteration in shells. The *Callianax* fossil shells analyzed here, with one exception (which is 100 ppm), all have Fe contents of <0.01% (or < 100

ppm), and Mn contents of <10 ppm, indicating no diagenetic gain of these elements.

Published data on trace element concentrations in the aragonitic bivalve *Epilucina californica* (Conrad, 1837) are lacking, so live-collected specimens from off Santa Barbara Island and modern, dead-collected specimens from San Nicolas Island were analyzed to establish some baseline values for this taxon. Although the sample size is limited ($n = 9$), results indicate that modern *E. californica* has Mg concentrations of 0.01–0.02%, and Sr concentrations of 1090–1680 ppm (Table 3). As expected, Fe contents (<0.01%, or < 100 ppm) and Mn contents (<10 ppm) are low in these modern specimens. Fossil specimens of *E. californica* studied here are 99–100% aragonite (with one exception, which is 97–98%), have Mg contents of 0.01–0.03% and Sr contents of 1530–2170 ppm, similar to modern specimens. Fe and Mn contents in these fossils are all <0.01% and < 10 ppm, respectively. Thus, collectively, both fossil *C. biplicata* and *E. californica* specimens studied here are regarded as having no substantial evidence of diagenetic alteration, from both mineralogical and geochemical points of view.

At both LACMIP locs. 42977 and 42950, *Epilucina californica* shells were collected for Sr isotope analyses. One shell from LACMIP loc. 42977 gave a mean $^{87}\text{Sr}/^{86}\text{Sr}$ value of 0.709131 ± 0.000006 (~1.11 Ma) and the other gave a mean value of 0.709125 ± 0.000003 (~1.20 Ma), resulting in ages that may not be distinguishable, considering the analytical and calibration uncertainties (Table 3; Fig. 8). Shells from LACMIP loc. 42950 yielded older ages than those from LACMIP loc. 42977. Three shells from the former locality gave ages of ~1.68 Ma to ~1.72 Ma, whereas two other shells gave substantially older ages of

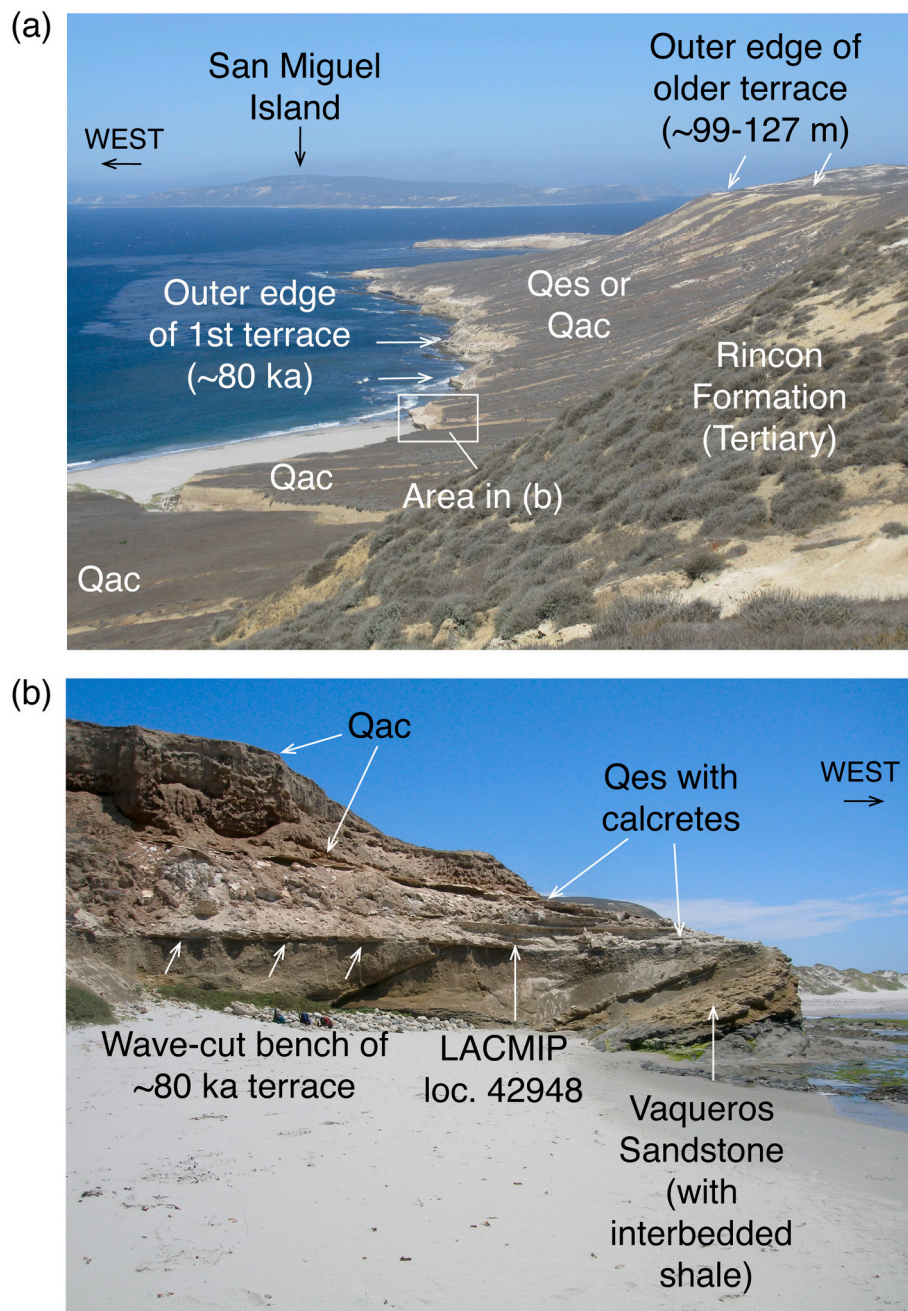


Fig. 7. Marine terrace deposits on northwestern Santa Rosa Island (see Fig. 3). (a) View to north showing outer edge of 1st terrace, overlying eolian and colluvial deposits, outer edge of higher, older terrace at ~99 to ~127 m, and underlying bedrock of the Rincon Formation (Tertiary). (b) Detail of outer edge of 1st marine terrace, LACMIP loc. 42948, and overlying eolian and alluvial deposits. Qac, alluvium or colluvium; Qes, eolian sand. Both photographs by D.R. Muhs.

~2.24 Ma to ~2.30 Ma.

The “Scott’s Shack” site (LACMIP loc. 42952) is ~1500 m northwest of LACMIP loc. 42950 and is situated at an elevation of 112 m (Fig. 8). From the deposits here, seven shells of two genera were analyzed, five *Callianax biplicata* shells and two *Epilucina californica* valves (Table 3). Results indicate significant differences between the two genera, and differences within the two genera. Four of the *C. biplicata* shells gave $^{87}\text{Sr}/^{86}\text{Sr}$ values of 0.709121 ± 0.000005 (~1.25 Ma) to 0.709123 ± 0.000004 (~1.22 Ma), while a fifth shell gave a $^{87}\text{Sr}/^{86}\text{Sr}$ value of 0.709110 ± 0.000003 (~1.40 Ma). Considering the analytical uncertainties as well as uncertainties in the age calibration, some of the *C. biplicata* shells could be roughly the same ages as the *E. californica* shells from LACMIP loc. 42977. In contrast, the *E. californica* valves from LACMIP loc. 42952 gave $^{87}\text{Sr}/^{86}\text{Sr}$ values of 0.709138 ± 0.000005

(~0.99 Ma) and 0.709142 ± 0.000005 (~0.910 Ma), both significantly younger than all five *C. biplicata* shells (Table 3; Fig. 8).

3.5. Paleontology of marine terrace faunas from low-elevation terrace deposits

3.5.1. Paleontology of the 2nd terrace deposits

Marine invertebrate fossils were collected from localities on the 2nd terrace in both the northwestern (near Cañada Garañon, Fig. 3) and south-central (near Johnsons Lee, Fig. 5) parts of the island. At least 60 species of mollusks are confirmed, including >50 gastropods and 11 bivalves (Table 4). Common to all or most all of these localities are rocky intertidal species of gastropods, typical of high-energy shores, such as *Acmaea mitra* Rathke, 1833, *Antisabia panamensis* (C.B. Adams, 1852),

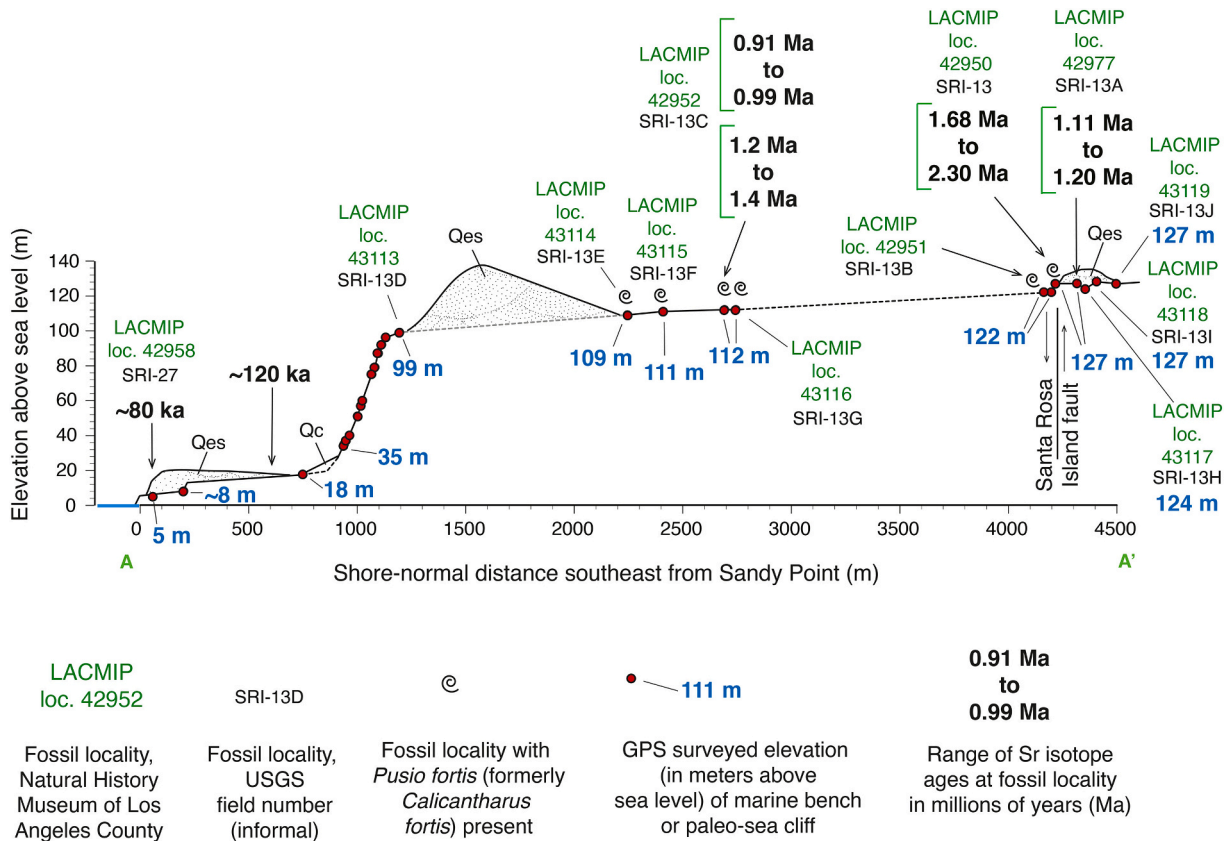


Fig. 8. Topographic profile A-A' of marine terrace benches from Sandy Point (see Fig. 3) southeast ~4.5 km, showing GPS-measured elevations, fossil localities, overlying deposits, and Sr isotope ages (Table 3), along with approximate position of the Santa Rosa Island fault. Qes, eolian sand; Qc, colluvium.

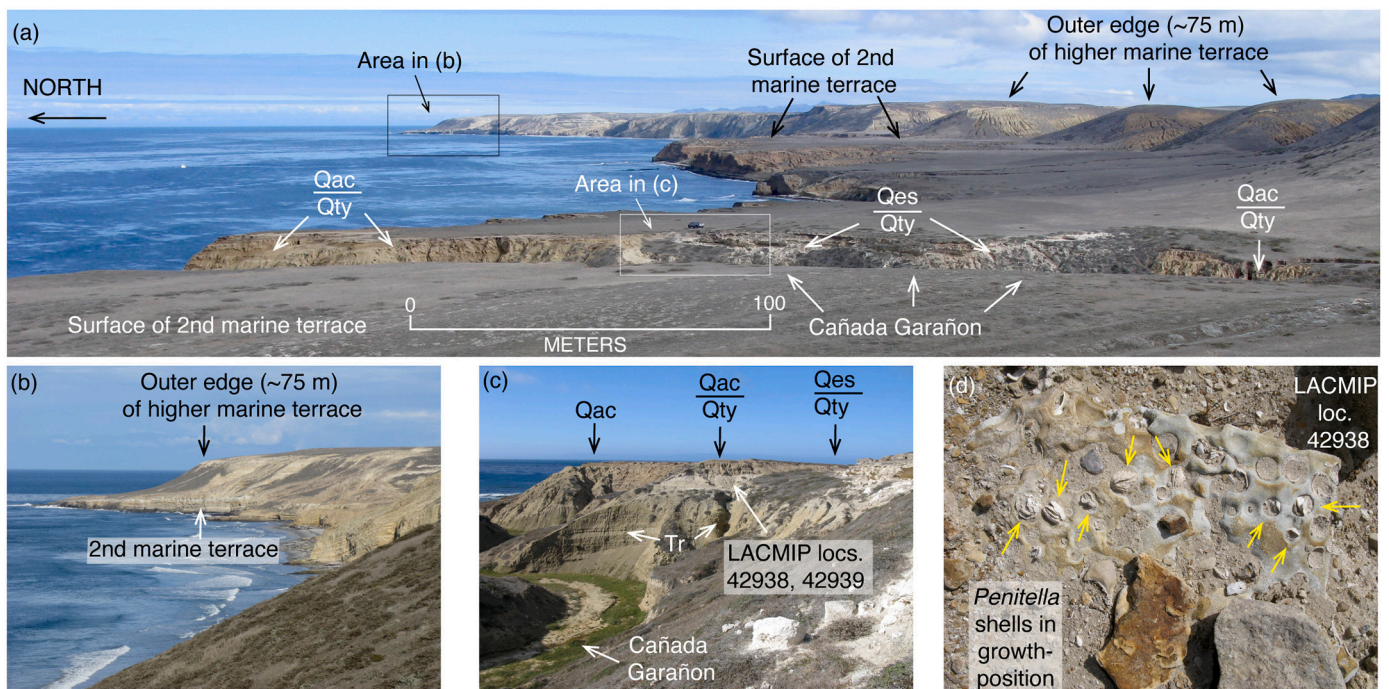


Fig. 9. Photographs of marine terraces and terrace deposits in the Cañada Garañon area of northwestern Santa Rosa Island (see Fig. 3). (a) View looking east, with Cañada Garañon in the foreground and 2nd terrace and higher terrace in background. (b) Detail of easternmost part of view in (a). (c) Cañada Garañon exposure of LACMIP locs. 42938 and 42939. (d) *Penitella* shells in growth position of marine terrace clast at LACMIP loc. 42938. Qac, alluvium or colluvium; Qes, eolian sand; Qty, marine terrace deposits, younger; Tr, Rincon Formation (shale). All photographs by D.R. Muhs.

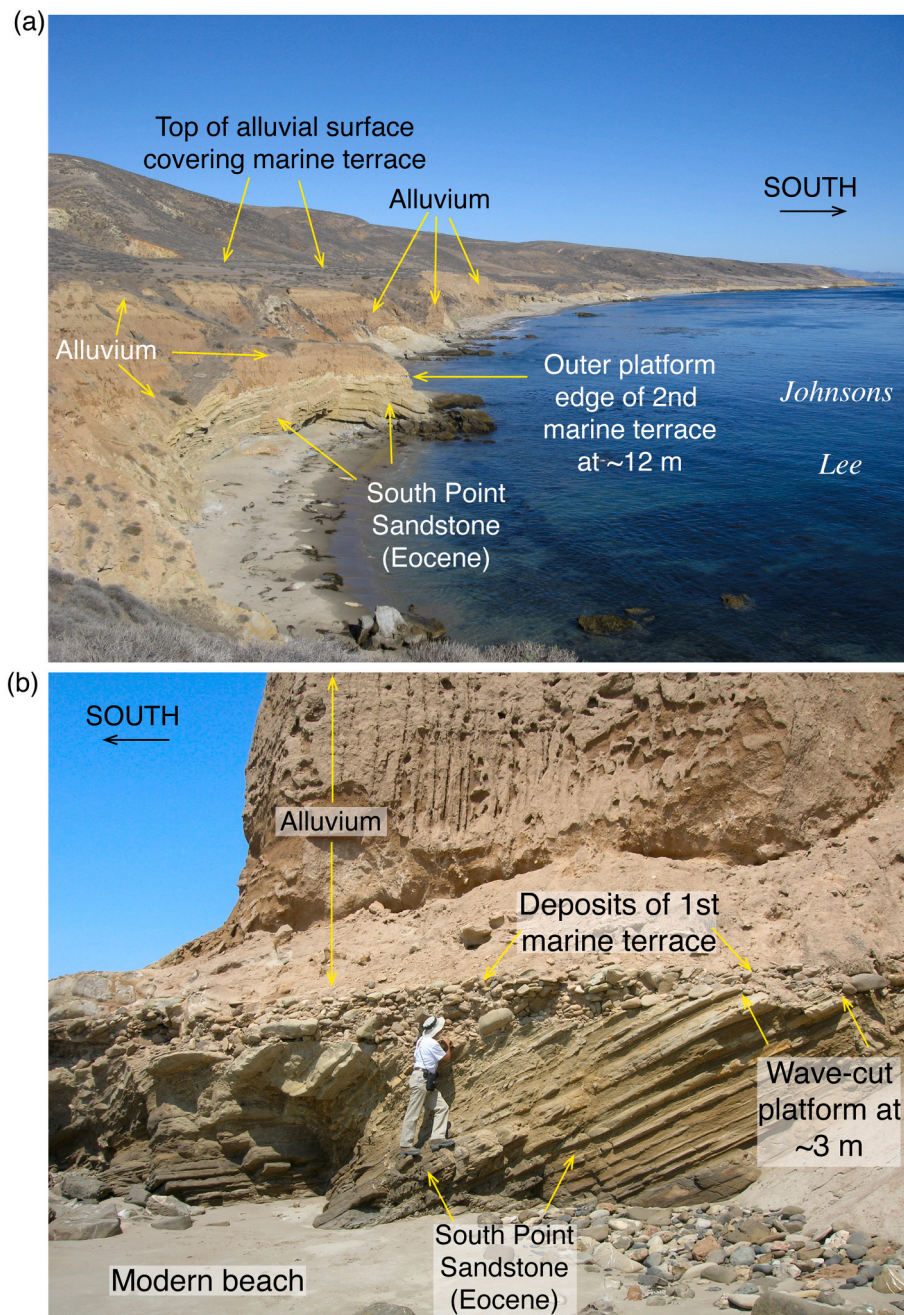


Fig. 10. Marine terrace deposits at Johnsons Lee (see Fig. 5). (a) View of outer edge of 2nd marine terrace, with overlying alluvial deposits and underlying sandstone of the South Point Formation. (b) View of outer edge of 1st marine terrace, with overlying alluvial deposits and underlying sandstone of the South Point Formation. Both photographs by D.R. Muhs.

Discurria insessa (Hinds, 1842), *Fissurella volcano* Reeve, 1849, *Haliotis cracherodii* Leach, 1814, *Homalopoma luridum* (Dall, 1885), and *Lottia scabra* (Gould, 1846), all of which live on or near Santa Rosa Island today, in addition to being found well to the north and south of the island. Consistent with the gastropod taxa, several bivalve species are found in most or all of the fossil localities of the 2nd terrace as well, again typical of rocky intertidal settings. These include *Epilucina californica* and *Glans carpenteri* (Lamy, 1922), both of which live around or near Santa Rosa Island and well to the north and south of it. In addition to the molluscan fauna, most localities also host fossil barnacles (*Balanus* sp.?) and sea urchin (*Strongylocentrotus* sp.?) plates and/or spines, also indicative of a high-energy, rocky-shore intertidal environment at the time of terrace formation.

Although a quantitative analysis of the terrace fauna is beyond the

scope of the present study, some generalizations about the most common and least abundant taxa have been made. As an example, at LACMIP loc. 42936 (=SRI-4) at Johnsons Lee, the most common species is *Callianax biplicata*, followed by *Thylacodes squamigerus* (Carpenter, 1857), *Epilucina californica*, the hoof shells *Hipponix tumens* Carpenter, 1864 and *Antisabia panamensis*, and *Fissurella volcano*. The rarest species include *Cryptochiton stelleri* Middendorff, 1847 [two disarticulated plates], *Crossata californica* (Hinds, 1843) [three fragments], *Petricola carditoides* (Conrad, 1837) [one worn valve], *Irusella lamellifera* (Conrad, 1837) [three worn fragments], and *Nucella emarginata* (Deshayes, 1839) [two juveniles and one adult].

Preservation for each species ranges from very good to poor. To illustrate the range of preservation, examples are given here of the most common gastropod (*Callianax biplicata*) and the most common bivalve

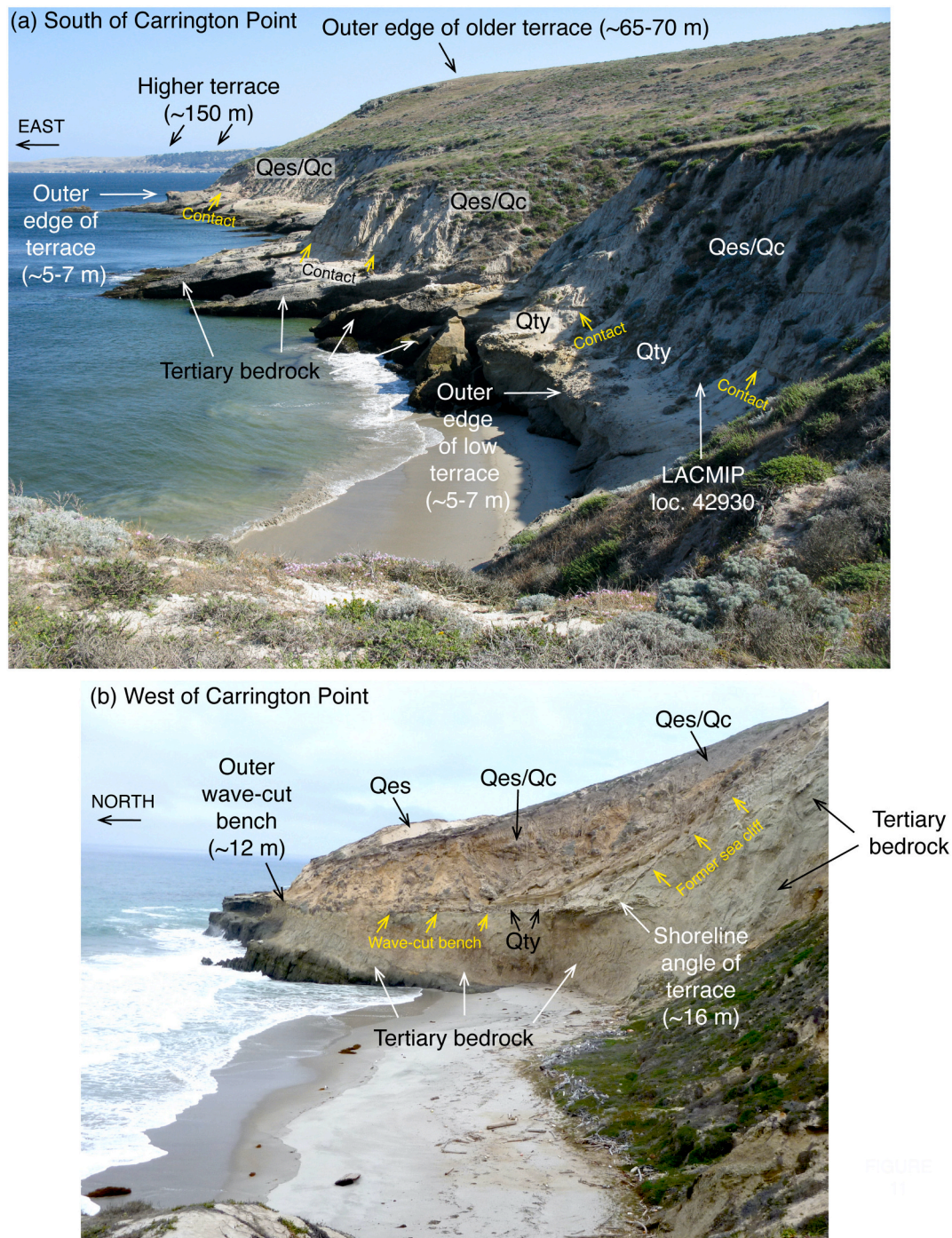


Fig. 11. (a) View of outer edge of Carrington marine terrace (see text for discussion), looking south, at LACMIP loc. 42930 (see Fig. 4) and outer edges of higher (~65 m and ~150 m) marine terraces. Qes, eolian sand; Qc, colluvium; Qty, marine terrace deposits, younger. (b) View of the shoreline angle of the Carrington marine terrace west of Carrington Point, a short distance southwest of LACMIP loc. 42933. Photographs by D.R. Muhs.

(*Epilucina californica*) from LACMIP loc. 42936 (=SRI-4). For *C. biplicata*, shells are sometimes broken and abraded, but many are also well preserved, with the external shell sculpture still apparent (Fig. 17a). In addition, this taxon also shows a very clear growth series (as that term has been used, for example, by Squires, 1981), with abundant specimens in all size ranges, from juveniles to fully mature individuals. For *E. californica*, many of the same observations can be made. No articulated valves were found, and many shells are broken and/or abraded (Fig. 17b). Nevertheless, in many specimens, the narrowly spaced, fine commarginal ribs are still apparent, indicating a history of little or no abrasion. Furthermore, as is the case with *C. biplicata*, a growth series is

apparent in the collections of *E. californica*, with abundant representatives of juveniles ranging up to fully mature individuals.

3.5.2. Paleontology of deposits from the Carrington terrace

In deposits of the Carrington terrace, extensive collections were made at a single locality (LACMIP loc. 42930; Figs. 4, 11), identical to where corals for U-series dating of this terrace were collected. Less abundant fossil-bearing deposits were also noted south of this locality, at LACMIP locs. 42931 and 42932, and to the west of Carrington Point at LACMIP locs. 42933 and 43120 (Fig. 4). At LACMIP loc. 42930, about 60 taxa were identified, including 49 gastropods and 11 bivalves (Table 4).

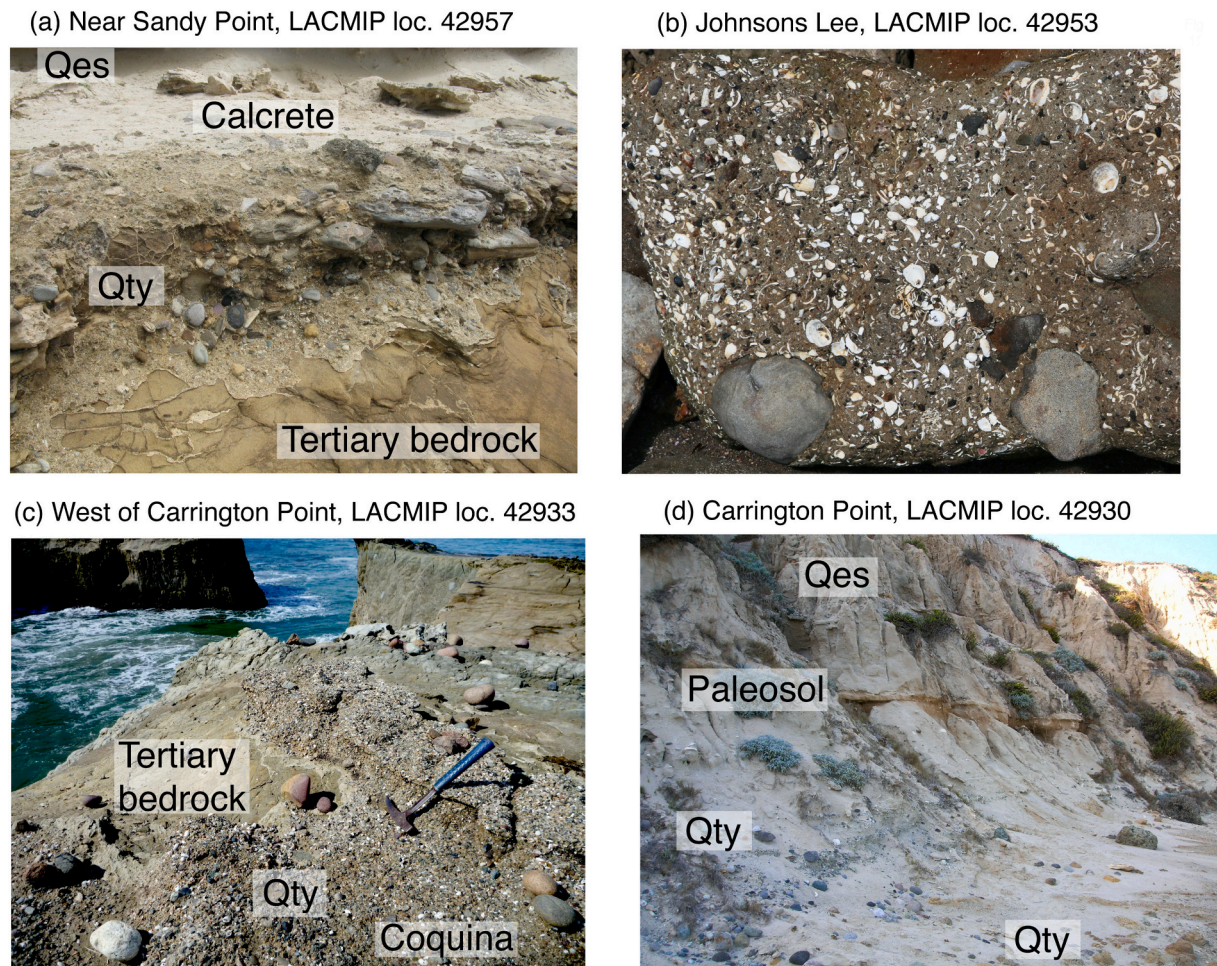


Fig. 12. Photographs showing typical examples of marine terrace deposits with fossils on Santa Rosa Island. Qes, eolian sand; Qty, marine terrace deposits, younger. All photographs by D.R. Muhs.

The high-energy, rocky-shore environment species *Acmaea mitra*, *Antisabia panamensis*, *Discurria insessa*, *Fissurella volcano*, *Haliotis cracherodii*, *Homalopoma luridum*, *Lottia scabra*, *Epilucina californica*, and *Glans carpenteri*, present in deposits of the 2nd terrace, are also found here. An interesting find at this locality was a specimen of *Penitella penita* (Conrad, 1837), still protected in a terrace clast into which it had bored.

The relative abundance of each taxon from the Carrington terrace is similar to that of the 2nd terrace at Johnsons Lee, given above. The most common species is, once again, *Callianax biplicata*, followed by *Thylacodes squamigerus*, *Epilucina californica*, the hoof shells *Hipponix tumens*, *Antisabia panamensis*, and *Crepidula adunca* G.B. Sowerby I, 1825. The rarest species are *Haliotis cracherodii* [one incomplete specimen, four fragments], *Haliotis rufescens* Swainson, 1822 [one worn specimen], *Cryptochiton stelleri* Middendorff, 1847 [one plate], *Petricola carditoides* [three worn valves], and *Tegula montereyi* (Kiener, 1850) [three fragments].

3.5.3. Paleontology of the 1st terrace deposits

In deposits of the 1st terrace, collections were made at six localities, one at Johnsons Lee in the south-central part of the island (Fig. 5), three in the northwestern part of the island, and two near Cañada Garañon, on the northern coast (Fig. 3). At least 60 species of mollusks are documented from these localities, including >50 gastropods and 9 bivalves (Table 4). As is the case with the 2nd terrace, common to most or all localities are the gastropods *Antisabia panamensis*, *Discurria insessa*, *Fissurella volcano*, *Homalopoma luridum*, and *Lottia scabra* and the bivalves *Epilucina californica* and *Glans carpenteri*. Also represented at almost all

localities on the 1st terrace are fossil barnacles (*Balanus* sp.?) and sea urchin (*Strongylocentrotus* sp.) plates and/or spines. Thus, as with the 2nd terrace, the environmental setting at the time of formation of the 1st terrace was one of a high-energy, rocky-intertidal environment.

As with the inventory of taxa from the 2nd terrace, a rigorous quantitative assessment of the species from the 1st terrace is beyond the scope of the present study. Nevertheless, a general sense of the relative abundances is given here, using the species from LACMIP loc. 42957 (=SRI-27), near Sandy Point, on the western end of Santa Rosa Island. The most common species is *Lottia scabra*, followed by *Littorina scutulata* Gould, 1849, *Antisabia panamensis*, *Epilucina californica*, and *Tegula galina* (Forbes, 1852). The rarest species include *Mytilus californianus* (Conrad, 1837) [eight fragments], *Tegula montereyi* [three fragments], *Glans carpenteri* [two worn specimens], *Homalopoma luridum* [two worn specimens], and *Discurria insessa* [one worn specimen]. Once again, preservation ranges from very good to poor.

3.6. Paleozoogeography of mollusks from marine terraces on Santa Rosa Island

3.6.1. Paleozoogeography of mollusks from the 2nd marine terrace

In an earlier study, Muhs et al. (2014a) reexamined the faunal list that Orr (1960) reported from what is called here the 2nd terrace on Santa Rosa Island. Based on records archived at the Santa Barbara Museum of Natural History, Orr's (1960) location on this terrace is very close to LACMIP locs. 42942, 42938, 42939 and 42940 of the present study, near Cañada Garañon (Fig. 3). Using updated zoogeography,

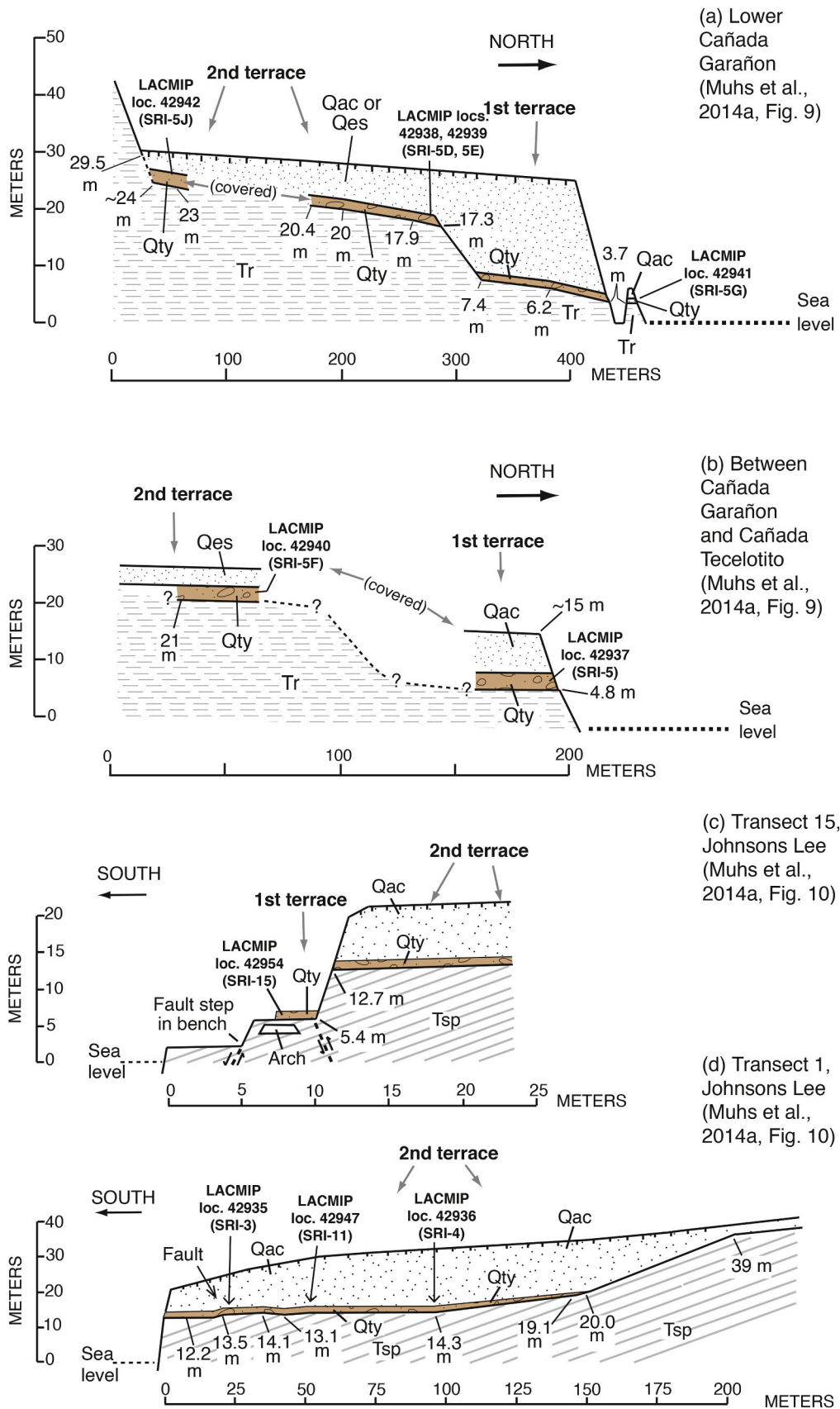


Fig. 13. Topographic profiles, geologic units, and measured elevations of the 1st and 2nd marine terraces exposed in northwestern Santa Rosa Island near Cañada Garañon (Fig. 3) and the Johnsons Lee area (Fig. 5) of southern Santa Rosa Island, and LACMIP fossil localities 42942, 42938, 42939, and 42941 (a), 42940 and 42937 (b), 42954 (c) and 42935, 42947, and 42936 (d). All elevations measured by a differential GPS instrument and are taken from Muhs et al. (2014a). Tr, Rincon Formation; Tsp, sandstone of the South Point Formation; other abbreviations as in Fig. 3.

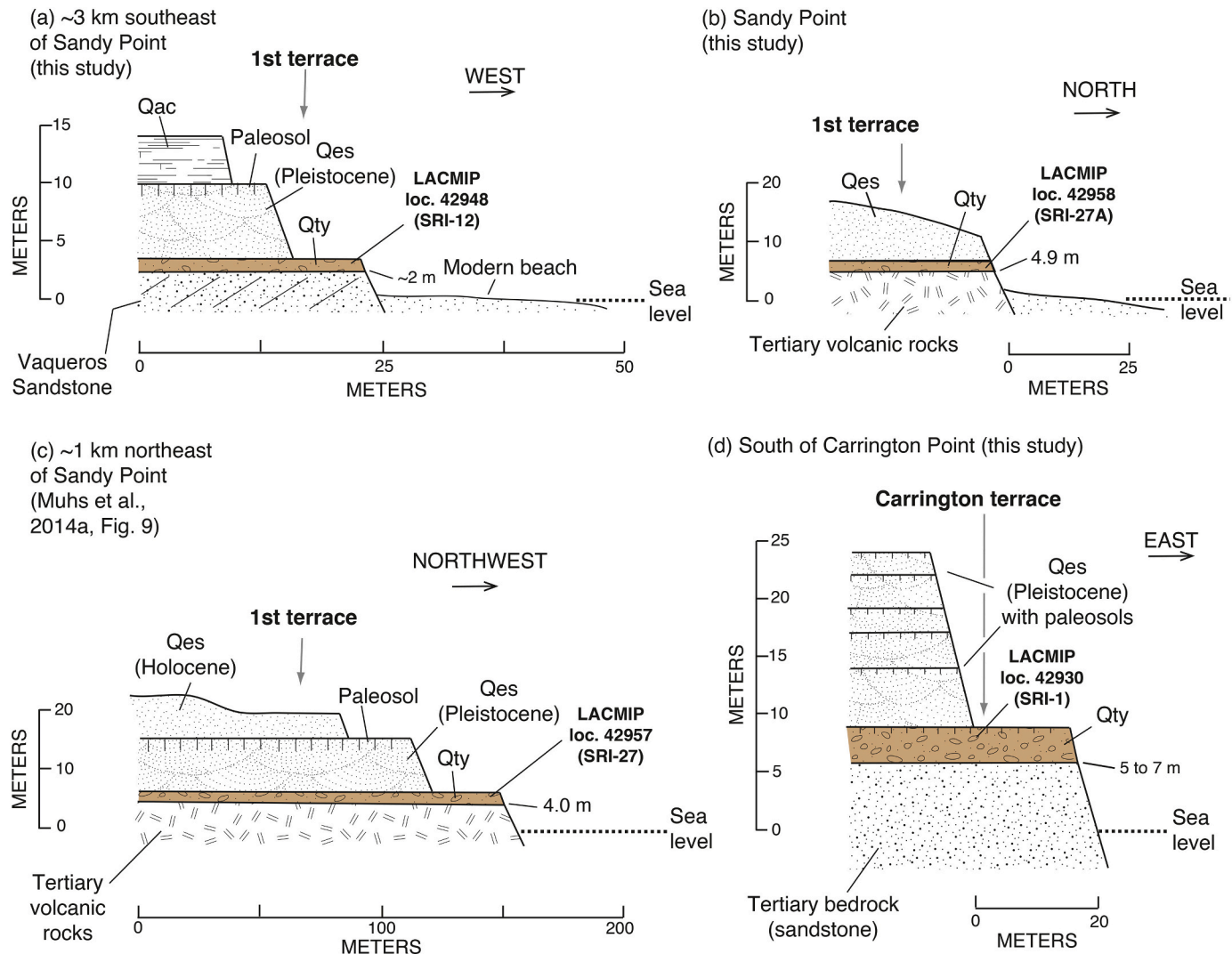


Fig. 14. Topographic profiles, geologic units, and measured elevations of the 1st marine terrace exposed in the Sandy Point area of northwestern Santa Rosa Island (Fig. 3) and the Carrington Point area (Fig. 4) of northeastern Santa Rosa Island, and LACMIP fossil localities 42948 (a), 42958 (b), 42957 (c) and 42930 (d). All elevations measured by a differential GPS instrument and are taken from Muhs et al. (2014a) and the present study. Abbreviations for geologic units as in Figs. 3, 4.

Muhs et al. (2014a) noted that Orr's (1960) faunal list included two extralimital northern species, two northward-ranging species, and five southward-ranging species. This makes the assemblage from this terrace an example of a thermally anomalous fauna. To assess this interpretation more rigorously, the new collections from the 2nd terrace studied here were examined in light of their modern zoogeography.

Both the north side and south side fossil localities of the 2nd terrace host cool-water and warm-water species of mollusks (Fig. 18). Both sides of the island have four warm-water species, but there are more species of cool-water mollusks (6 species on the south side; 8 species on the north side) on both sides of the island. Within the assemblage of warm-water forms, none are strictly extralimital, but are southward-ranging species, with their northern range limits at or close to Santa Rosa Island. Three of these taxa, the gastropods *Norrisia norrisii* (G.B. Sowerby I, 1838), *Ophiodermella inermis* (Reeve, 1843), and *Thylacodes squamigerus*, all have similar modern ranges. Both *N. norrisii* and *O. inermis* are presently found from Isla la Asunción, just south of Punta Eugenia in central Baja California, México (Fig. 1a) north to either Point Conception (*N. norrisii*) or to Santa Rosa Island itself (*O. inermis*). *Thylacodes squamigerus*, in its form as twisted masses of tubes, is found a bit farther south in central Baja California and extends northward into southern California, but is reported not to range north of the Santa Barbara-Point

Conception area (McLean, 1978), similar to *N. norrisii* and *O. inermis*. It is perhaps worth noting that the present authors have recently (May 2022) found modern specimens of *T. squamigerus* (twisted-mass form) within recent beach drift near the mouth of Villa Creek, west of Cayucos, San Luis Obispo County, California (N35.460°), well north of Santa Barbara. It is suspected that this occurrence may be the result of a very recent migration due to 21st century warming.

On the Pacific Coast of the Americas, cowries are typically found in warm, tropical waters, with seven species found in the Panamic (Baja California Sur to northern Perú) province (Keen, 1971). *Neobernaya spadicea* (Swainson, 1823) is the only species of the family Cypraeidae of the northeast Pacific that presently lives farther north than the Panamic province, within the Californian province (Groves, 2019). Modern specimens of *N. spadicea* are documented in collections in LACM from both San Miguel Island and Santa Rosa Island. Although the species has been reported in modern waters as far north as Big Sur, Monterey County, California (LACM 178911, 178924, 179044), it is rare north of Santa Barbara (McLean, 1978; Abbott and Haderlie, 1980; Bertsch and Aguilar Rosas, 2016; Groves, 2019). In LACM collections, there are no other specimens confirmed from north of San Miguel Island. Indeed, it may even be a species with a disjunct distribution in its northern range, although this hypothesis needs verification with more surveys north of

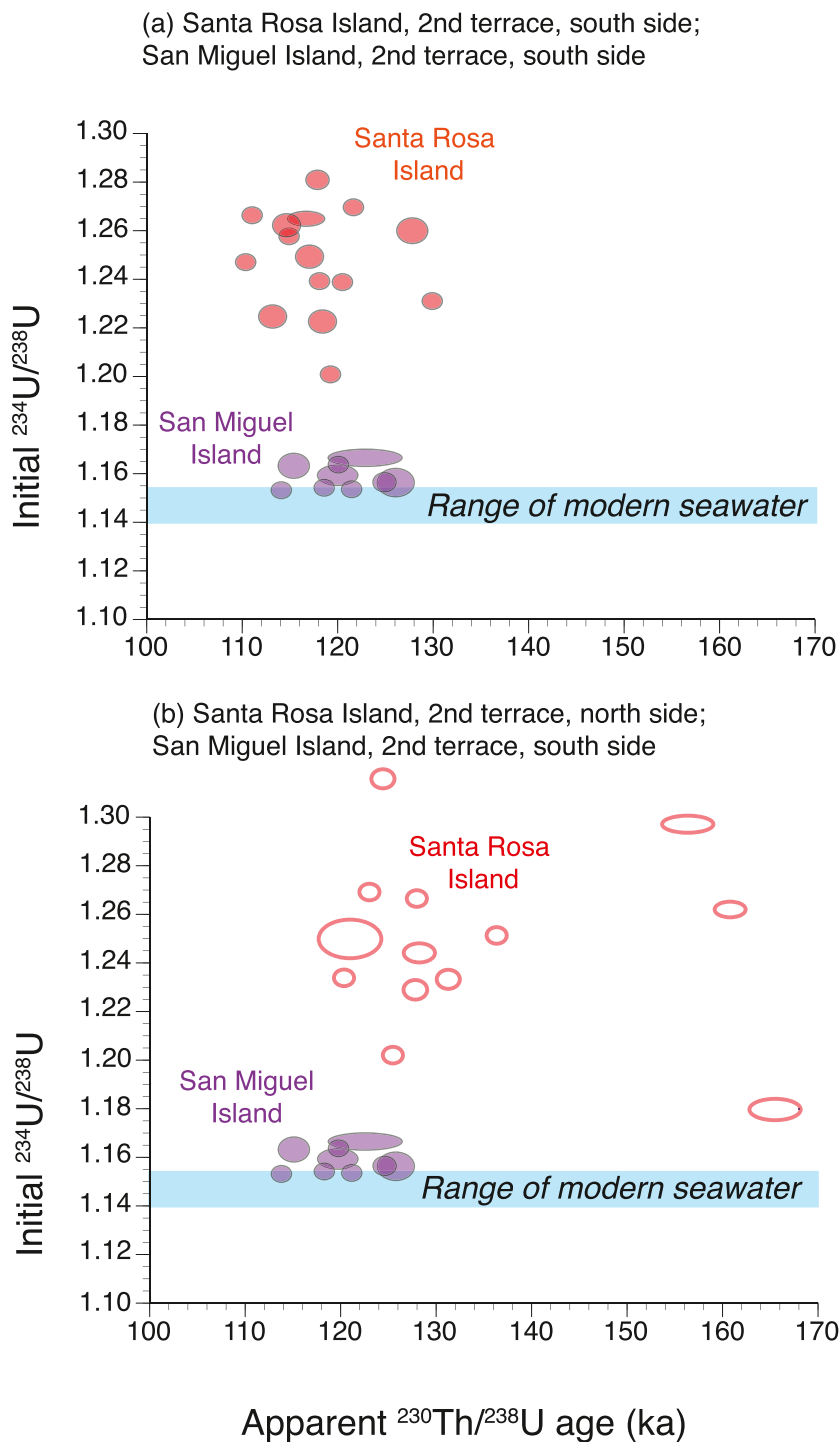


Fig. 15. Plot of apparent U-series ages vs. back-calculated initial $^{234}\text{U}/^{238}\text{U}$ values for marine terrace corals, showing contrast between corals having a closed-system history and those having an open-system history. (a) Corals from the 2nd terrace on the south side of Santa Rosa Island (open-system history; data from Table 1) and the 2nd terrace on San Miguel Island (mostly closed-system history; data from Table 1 and Muhs et al., 2014a). (b) Corals from the 2nd terrace on the north side of Santa Rosa Island (open-system history; data from Table 1) and the 2nd terrace on the south side of San Miguel Island (data from Table 1 and Muhs et al., 2014a).

Point Conception. Another interpretation is that it is a recent arrival to Monterey County, as Dall (1921) reported it living only as far north as Santa Barbara, California (although Keen, 1937 reported it living as far north as 37°N). It is presently found as far south as Isla la Asunción, ~ 110 km southeast of Punta Eugenia (Fig. 1) in central Baja California (LACM 1967–66.3). Jackson (2001) reported finding a single, dead *N. spadicea* at the “13 Fathom Spot,” off Baja California Sur, nearly 300 km farther south, although there are not intervening localities where the species has been confirmed in collections at LACM. Nevertheless, in what is now known of its distribution, *N. spadicea* is regarded here as a southward-ranging species.

An interesting southward-ranging species found in deposits of the

2nd terrace on Santa Rosa Island is the small gastropod *Siphonaria brannani* Stearns, 1872. McLean (2007) points out that members of the family Siphonariidae, such as *S. brannani*, also occur mostly in tropical waters. Indeed, of 41 species of *Siphonaria* recognized worldwide, 31 occur in the warm, tropical waters of the Indo-West Pacific faunal province (Dayrat et al., 2014). Elsewhere in North America, all species of *Siphonaria* but one (*S. thersites*) occur in warm, tropical or subtropical waters of the Caribbean, Gulf of Mexico, or western Atlantic (Abbott, 1974; Abbott and Morris, 1995). Although *S. brannani* has a living population around Santa Barbara Island today and has been reported from San Miguel Island (USNM 800515) and Santa Cruz Island (LACM 63547, LACM1969–11.38), the species has not been reported around the

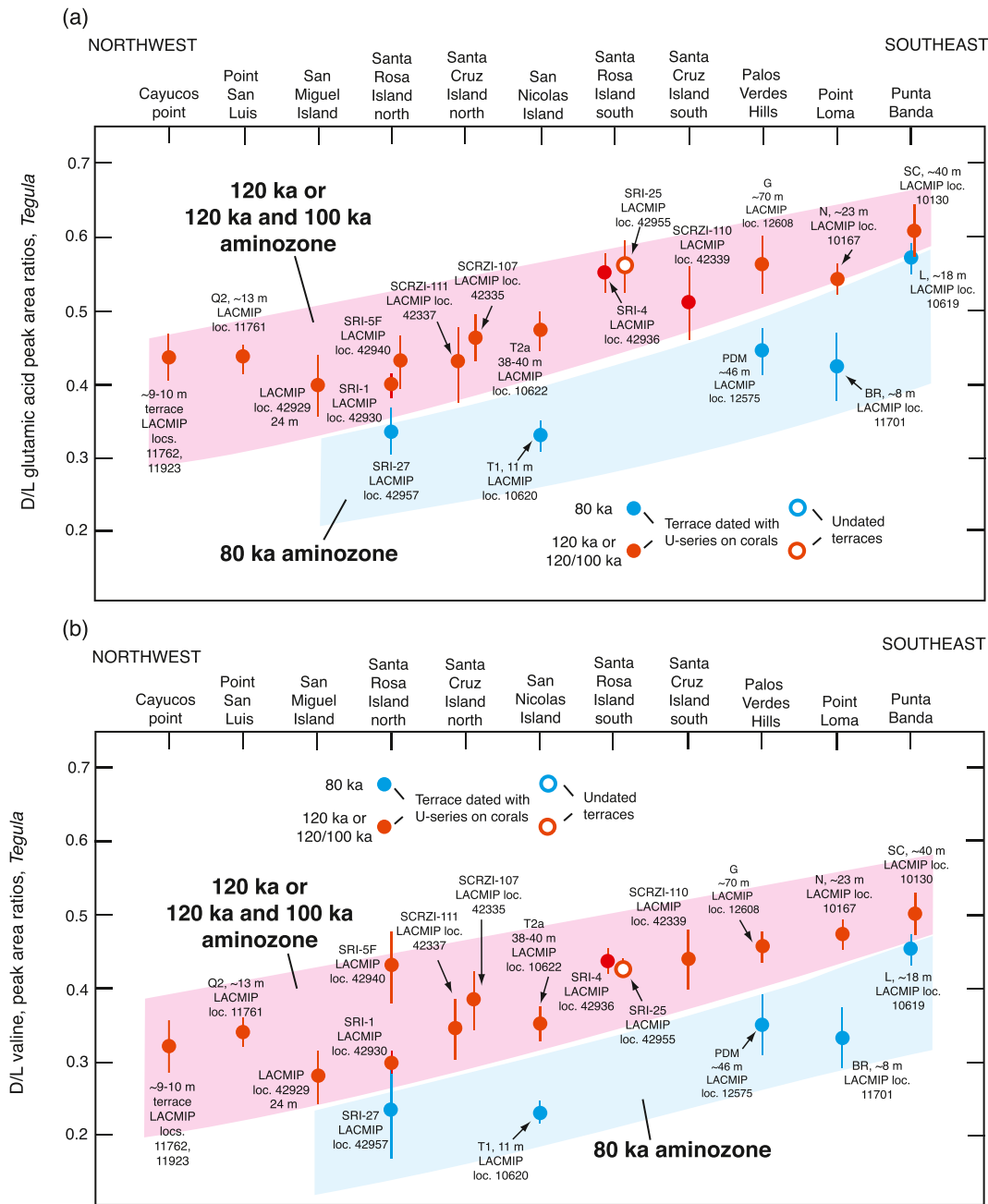


Fig. 16. Plots of mean D/L values (from peak areas) in glutamic acid (a) and valine (b) in fossil *Tegula* from U-series-dated (filled circles) and undated (open circles) marine terraces on the California and Baja California coasts, arrayed from the northwest (cooler temperatures) to the southeast (warmer temperatures). Blue (~ 80 ka or ~ 100 ka) and pink (~ 120 ka or ~ 120 ka and ~ 100 ka) shades define aminozones that allow lateral correlation from dated to undated deposits. Ages (in ka) given for each aminozone are based on U-series ages of corals that show closed-system histories, from Muhs et al. (1994, 2002, 2006, 2014a, 2015, 2021). Santa Cruz Island amino acid data are from Table 1; amino acid data for other localities are from Muhs et al. (2014a). Error bars are one-sigma; LACMIP = Natural History Museum of Los Angeles County Invertebrate Paleontology number. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

other Channel Islands or mainland localities in California (Littler, 1980). Keen (1971) reports that *S. brannani* may be living (or have lived recently) at Cabo San Lucas, Baja California Sur (possibly USNM 4024), and D.R. Lindberg (22 February 1976) reported its occurrence at Islas San Benito (N28.3°, W115.6°), Baja California (California Academy of Sciences CAS-IZ 6128.00). Thus, the species may have a disjunct distribution, but relative to Santa Rosa Island, it is considered to be a southward ranging taxon.

Orr (1960) reported two other southward-ranging species of mollusks from the 2nd terrace on Santa Rosa Island, *Lottia conus* (Test, 1945) and the chiton *Stenoplax conspiciua* (Dall, 1879), but neither taxon could

be confirmed in the fossil collections of the present study. Neither species lives north of Point Conception at the present time, so if their presence in fossil form on Santa Rosa Island is confirmed, they are both at their modern northern limits.

With one exception, the cool-water forms found in the deposits of the 2nd terrace are all northward-ranging species (Fig. 18). The dashed lines shown for these species in Fig. 18 indicate that although there are occasional finds of these cool-water taxa south of Point Conception, they are very rare. Nevertheless, there are nine such species, outnumbering the warm-water forms found in these terrace deposits. In addition, there is one strictly extralimital northern species, the gastropod *Styldium*

Table 3

Marine terrace fossil localities (LACMIP=Natural History Museum of Los Angeles County Invertebrate Paleontology), coordinates, elevation, species, aragonite content, element concentrations, $^{87}\text{Sr}/^{86}\text{Sr}$ values, and age estimates.

Sample name	LACMIP locality	Latitude (°)	Longitude (°)	Elevation (m)	Species	Aragonite (%)	Ca (%)	Mg (%)	Sr (ppm)	Ba (ppm)	Si (%)	Al (%)	Fe (%)	K (%)	Mn (ppm)	$^{87}\text{Sr}/^{86}\text{Sr}$	+/-	% error	$^{87}\text{Sr}/^{86}\text{Sr}$ age (Ma)	Lower limit (Ma)	Upper limit (Ma)	# runs
SANTA BARBARA ISLAND LIVING SPECIMENS																						
SBI - 0A - 1	na	33.467403	-119.028723	minus 12-14 m	<i>Epilucina californica</i>	100	41.8	0.01	1550	5.6	0.09	0.01	<0.01	0.16	<10	0.709174	0.000006	0.0009	modern	modern	modern	4
SBI - 0A - 2	na	33.467403	-119.028723	minus 12-14 m	<i>Epilucina californica</i>	100	43.4	0.01	1360	3	0.2	0.01	<0.01	0.16	<10	0.709173	0.000005	0.0007	modern	modern	modern	4
SBI - 0A - 3	na	33.467403	-119.028723	minus 12-14 m	<i>Epilucina californica</i>	100	41.9	0.01	1500	3.5	0.15	0.01	<0.01	0.18	<10	0.709175	0.000009	0.0013	modern	modern	modern	3
SBI - 0B - 1	na	33.487594	-119.027933	minus 7-8 m	<i>Epilucina californica</i>	100	42.4	0.01	1260	3.1	0.13	0.01	<0.01	0.14	<10	0.709170	0.000003	0.0005	modern	modern	modern	6
SAN NICOLAS ISLAND, MODERN, DEAD SPECIMENS																						
SNI - ACB - 1	na	33.265871	-119.497493	Modern beach	<i>Epilucina californica</i>	100	40.7	0.02	1600	4.6	0.24	0.04	<0.01	0.19	<10	0.709173	0.000004	0.0004	modern	modern	modern	5
SNI - ACB - 3	na	33.265871	-119.497493	Modern beach	<i>Epilucina californica</i>	100	41.1	0.01	1390	2.8	0.08	<0.01	<0.01	0.17	<10	0.709174	0.000009	0.0013	modern	modern	modern	4
SNI - ACB - 4	na	33.265871	-119.497493	Modern beach	<i>Epilucina californica</i>	100	41.7	0.01	1090	2.7	0.14	<0.01	<0.01	0.18	<10	0.709175	0.000007	0.0010	modern	modern	modern	6
SNI - ACB - 5	na	33.265871	-119.497493	Modern beach	<i>Epilucina californica</i>	100	44.3	0.02	1680	3.6	0.17	<0.01	<0.01	0.19	<10	0.709173	0.000006	0.0009	modern	modern	modern	5
SNI - ACB - 6	na	33.265871	-119.497493	Modern beach	<i>Epilucina californica</i>	100	42.2	0.02	1490	2.9	0.1	<0.01	<0.01	0.16	<10	0.709174	0.000006	0.0009	modern	modern	modern	4
SANTA ROSA ISLAND FOSSILS																						
SRI - 13A - A	42977	33.983467	-120.214033	130	<i>Epilucina californica</i>	100	42.9	0.03	1860	11.9	0.17	<0.01	<0.01	0.16	<10	0.709131	0.000006	0.00086	1.108	1.07	1.15	8
SRI - 13A - B	42977	33.983467	-120.214033	130	<i>Epilucina californica</i>	100	42.1	0.01	1560	14.5	0.06	<0.01	<0.01	0.16	<10	0.709125	0.000003	0.00038	1.196	1.15	1.25	16
SRI - 13C - a	42952	33.99376667	-120.22615	112	<i>Epilucina californica</i>	97-98	41.6	0.01	1760	19.9	0.13	0.02	<0.01	0.16	<10	0.709138	0.0000053	0.00075	0.987	0.960	1.02	14
SRI - 13C - b	42952	33.99376667	-120.22615	112	<i>Epilucina californica</i>	99	43.4	0.02	1580	11.1	0.14	0.01	<0.01	0.15	<10	0.709142	0.0000045	0.00064	0.910	0.880	0.94	9
SRI - 13C - c	42952	33.99376667	-120.22615	112	<i>Callianax biplicata</i>	99	42.2	<0.01	1710	22.7	0.18	0.01	<0.01	0.17	<10	0.709121	0.000005	0.00075	1.249	1.20	1.30	8
SRI - 13C - d	42952	33.99376667	-120.22615	112	<i>Callianax biplicata</i>	99	40.4	<0.01	1730	39.5	0.27	0.02	<0.01	0.17	<10	0.709121	0.000004	0.00052	1.249	1.20	1.30	10
SRI - 13C - e	42952	33.99376667	-120.22615	112	<i>Callianax biplicata</i>	99	41.4	<0.01	1750	31.6	0.15	0.01	0.01	0.17	<10	0.709123	0.000004	0.00049	1.222	1.17	1.27	15
SRI - 13C - f	42952	33.99376667	-120.22615	112	<i>Callianax biplicata</i>	100	43.1	<0.01	1540	21.3	0.15	0.01	<0.01	0.14	<10	0.709121	0.000006	0.0008	1.249	1.20	1.30	9
SRI - 13C - g	42952	33.99376667	-120.22615	112	<i>Callianax biplicata</i>	100	43.4	<0.01	1490	23	0.2	0.01	<0.01	0.16	<10	0.709110	0.000003	0.00045	1.397	1.34	1.45	11
SRI - 13 - A	42950	33.984407	-120.21416	127	<i>Epilucina californica</i>	99-100	39.2	0.01	1590	16.2	0.04	<0.01	<0.01	0.1	<10	0.709078	0.000003	0.0005	2.245	2.13	2.36	8
SRI - 13 - B	42950	33.984407	-120.21416	127	<i>Epilucina californica</i>	100	38.6	0.01	1530	16.5	0.06	<0.01	<0.01	0.11	<10	0.709076	0.000004	0.0006	2.305	2.19	2.42	16
SRI - 13 - C	42950	33.984407	-120.21416	127	<i>Epilucina californica</i>	100	38.2	0.01	2170	15.3	0.06	<0.01	<0.01	0.11	<10	0.709095	0.000004	0.0005	1.717	1.59	1.84	12
SRI - 13 - D	42950	33.984407	-120.21416	127	<i>Epilucina californica</i>	99	41.8	0.01	1660	17.4	0.15	<0.01	<0.01	0.17	<10	0.709096	0.000003	0.0004	1.684	1.57	1.80	26
SRI - 13 - E	42950	33.984407	-120.21416	127	<i>Epilucina californica</i>	99	40.4	0.01	2080	17.3	0.1	<0.01	<0.01	0.18	<10	0.709095	0.000003	0.0004	1.717	1.59	1.84	18

Table 4

Invertebrate marine fossils from low-elevation marine terrace deposits on Santa Rosa Island, California.

LACMIP Invertebrate Paleontology locality #	42946	42948	42957	42958	42937	42941	42930	42935	42936	42947	42940	42938	42939	42942
USGS field locality #	SRI-9	SRI-12	SRI-27	SRI-27a	SRI-5	SRI-5G	SRI-1	SRI-3	SRI-4	SRI-11	SRI-5F	SRI-5D	SRI-5E	SRI-5J
Geomorphology	1st terrace	1st terrace	1st terrace	1st terrace	1st terrace	1st terrace	Carrington terrace	2nd terrace	2nd terrace	2nd terrace	2nd terrace	2nd terrace	2nd terrace	2nd terrace
General location on Santa Rosa Island	Johnsons Lee	SE of Sandy Point	NE of Sandy Point	Sandy Point	Garañon Canyon	Garañon Canyon	Carrington Point	Johnsons Lee	Johnsons Lee	Johnsons Lee	Garañon Canyon	Garañon Canyon	Garañon Canyon	Garañon Canyon
Elevation above sea level (shoreline angle, in meters)	5.4	>5, <12	>5, <12	>5, <12	7.4	7.4	≥10	20	20	20	24	24	24	24

Gastropoda

<i>Acanthinucella punctulata</i> (G.B. Sowerby I, 1825)		X					X		X			X	X	
<i>Acmaea mitra</i> Rathke, 1833							X	X	X	X	X	X	X	X
<i>Acteocina</i> sp.							X							
<i>Aesopus</i> sp.							X							
<i>Alia carinata</i> (Hinds, 1844)			X	X	X		X	X	X					
<i>Alvania compacta</i> (Carpenter, 1864)		X												
<i>Alvinia purpurea</i> (Dall, 1871)			X					X						X
<i>Alvinia</i> sp.							X							
<i>Amphissa reticulata</i> Dall, 1916												X		
<i>Amphissa versicolor</i> Dall, 1871				X			X		X					
<i>Amphissa</i> sp.		X	X	X	X			X	X			X	X	X
<i>Amphithalamus tenuis</i> Bartsch, 1911														X
<i>Amphithalamus</i> sp.							X							
<i>Antisabia panamensis</i> (C.B. Adams, 1852)	X	X	X	X	X		X	X	X	X	X	X	X	X
<i>Atrimitra idae</i> (Melvill, 1893)		X					X			X				
<i>Barbarofusus</i> sp.					X									
<i>Barleeia haliotiphila</i> Carpenter, 1864		X	X	X			X	X	X		X			X
<i>Barleeia</i> sp.			X											
<i>Borsonella bartschi</i> (Arnold, 1903)							X							
<i>Bostrycapulus decorus</i> Collin, 2019		X												X
<i>Bittium</i> spp.			X				X	X	X					
<i>Caecum californicum</i> Dall, 1885		X						X	X					
<i>Californiconus californicus</i> (Reeve, 1844)							X	X	X					
<i>Callianax baetica</i> (Carpenter, 1864)			X											

(continued on next page)

Table 4 (continued)

LACMIP Invertebrate Paleontology locality #	42946	42948	42957	42958	42937	42941	42930	42935	42936	42947	42940	42938	42939	42942
USGS field locality #	SRI-9	SRI-12	SRI-27	SRI-27a	SRI-5	SRI-5G	SRI-1	SRI-3	SRI-4	SRI-11	SRI-5F	SRI-5D	SRI-5E	SRI-5J
Geomorphology	1st terrace	1st terrace	1st terrace	1st terrace	1st terrace	1st terrace	Carrington terrace	2nd terrace	2nd terrace	2nd terrace	2nd terrace	2nd terrace	2nd terrace	2nd terrace
General location on Santa Rosa Island	Johnsons Lee	SE of Sandy Point	NE of Sandy Point	Sandy Point	Garañon Canyon	Garañon Canyon	Carrington Point	Johnsons Lee	Johnsons Lee	Johnsons Lee	Garañon Canyon	Garañon Canyon	Garañon Canyon	Garañon Canyon
Elevation above sea level (shoreline angle, in meters)	5.4	>5, <12	>5, <12	>5, <12	7.4	7.4	≥10	20	20	20	24	24	24	24
<i>Callianax biplicata</i> (G.B. Sowerby I, 1825)	X	X			X		X	X	X	X	X	X	X	
<i>Calliostoma ligatum</i> (Gould, 1849)									X					
<i>Calliostoma</i> sp.		X					X		X					
<i>Cerithiopsis</i> sp.							X							
<i>Chrysallida</i> sp.							X							
<i>Clathurella canfieldi</i> Dall, 1871														
<i>Clathurella</i> sp.									X					
<i>Crepidatella lingulata</i> Gould, 1846				X			X							
<i>Crepidula adunca</i> G.B. Sowerby I, 1825		X	X	X			X		X	X		X		X
<i>Crepidula perforans</i> (Valenciennes, 1846)							X					X		
<i>Crepidula</i> spp.		X	X	X	X		X	X	X		X		X	X
<i>Crossata californica</i> (Hinds, 1843)								X	X					
<i>Diodora arnoldi</i> McLean, 1966												X		
<i>Diodora aspersa</i> (Rathke, 1833)								X	X			X		
<i>Discurria insessa</i> (Hinds, 1842)		X	X	X	X		X	X	X		X	X	X	X
<i>Epitonium</i> sp.				X										
<i>Epitoniid</i> sp.									X					
<i>Fissurella volcano</i> Reeve, 1849		X	X	X	X	X	X	X	X	X		X		X
<i>Fissurellid</i> spp.			X											
<i>Fissurellidea bimaculata</i> Dall, 1871				X					X	X				
Gastropoda indet.			X				X		X					
<i>Glossaulax</i> sp.							X							
<i>Haliotis cracherodii</i> Leach, 1814							X	X	X	X		X	X	X
<i>Haliotis rufescens</i> Swainson, 1822					X		X		X	X		X	X	
<i>Haliotis</i> cf. <i>H. rufescens</i> Swainson, 1822		X												
<i>Haliotis</i> spp.			X				X	X				X		X

(continued on next page)

Table 4 (continued)

LACMIP Invertebrate Paleontology locality #	42946	42948	42957	42958	42937	42941	42930	42935	42936	42947	42940	42938	42939	42942
USGS field locality #	SRI-9	SRI-12	SRI-27	SRI-27a	SRI-5	SRI-5G	SRI-1	SRI-3	SRI-4	SRI-11	SRI-5F	SRI-5D	SRI-5E	SRI-5J
Geomorphology	1st terrace	1st terrace	1st terrace	1st terrace	1st terrace	1st terrace	Carrington terrace	2nd terrace	2nd terrace	2nd terrace	2nd terrace	2nd terrace	2nd terrace	2nd terrace
General location on Santa Rosa Island	Johnsons Lee	SE of Sandy Point	NE of Sandy Point	Sandy Point	Garañon Canyon	Garañon Canyon	Carrington Point	Johnsons Lee	Johnsons Lee	Johnsons Lee	Garañon Canyon	Garañon Canyon	Garañon Canyon	Garañon Canyon
Elevation above sea level (shoreline angle, in meters)	5.4	>5, <12	>5, <12	>5, <12	7.4	7.4	≥10	20	20	20	24	24	24	24
<i>Harfordia harfordii</i> (Stearns, 1871)		X					X							
<i>Harfordia</i> sp.					X						X		X	
<i>Helminthoglypta ayresiana</i> (Newcomb, 1861), Recent?		X					X							X
<i>Hima mendica</i> (Gould, 1849)							X		X	X				
<i>Hipponix tumens</i> Carpenter, 1864		X	X	X	X		X	X	X	X		X		X
Hipponicid spp.			X											
<i>Homalopoma luridum</i> (Dall, 1885)			X	X	X		X	X	X		X	X	X	
<i>Homalopoma</i> sp.		X	X					X						X
<i>Lacuna unifasciata</i> Carpenter, 1857									X					
<i>Lacuna</i> sp.				X				X						
<i>Lirobittium</i> sp.		X		X										X
<i>Lirularia</i> sp.			X											
<i>Littorina keenae</i> Rosewater, 1978							X							
<i>Littorina scutulata</i> Gould, 1849			X			X		X	X					
<i>Littorina</i> sp.		X	X	X	X		X	X	X		X	X		
<i>Lottia scabra</i> (Gould, 1846)		X	X	X	X	X	X	X	X	X		X	X	X
<i>Lottia</i> spp.		X			X		X	X	X	X	X	X	X	X
<i>Lucapinella callomarginata</i> (Dall, 1871)				X										
<i>Melanella thersites</i> (Carpenter, 1864)				X										
<i>Mitrella aurantiaca</i> (Dall, 1871)				X										
<i>Mitrella tuberosa</i> (Carpenter, 1864)		X	X	X	X			X	X					
<i>Mitrella</i> sp.														X
<i>Mitromorpha carpenteri</i> Glibert, 1954			X	X										
Nassariidae sp.					X		X							
<i>Neobernaya spadicea</i> (Swainson, 1823)									X	X				
<i>Norrissia norrisii</i> (G.B. Sowerby I, 1838)									X					X

(continued on next page)

Table 4 (continued)

LACMIP Invertebrate Paleontology locality #	42946	42948	42957	42958	42937	42941	42930	42935	42936	42947	42940	42938	42939	42942
USGS field locality #	SRI-9	SRI-12	SRI-27	SRI-27a	SRI-5	SRI-5G	SRI-1	SRI-3	SRI-4	SRI-11	SRI-5F	SRI-5D	SRI-5E	SRI-5J
Geomorphology	1st terrace	1st terrace	1st terrace	1st terrace	1st terrace	1st terrace	Carrington terrace	2nd terrace	2nd terrace	2nd terrace	2nd terrace	2nd terrace	2nd terrace	2nd terrace
General location on Santa Rosa Island	Johnsons Lee	SE of Sandy Point	NE of Sandy Point	Sandy Point	Garañon Canyon	Garañon Canyon	Carrington Point	Johnsons Lee	Johnsons Lee	Johnsons Lee	Garañon Canyon	Garañon Canyon	Garañon Canyon	Garañon Canyon
Elevation above sea level (shoreline angle, in meters)	5.4	>5, <12	>5, <12	>5, <12	7.4	7.4	≥10	20	20	20	24	24	24	24

Nucella emarginata
(Deshayes, 1839)

Onoba sp.

Opalia sp.

Ophiidermella inermis
(Reeve, 1843)

Paciocinebrina circumtexta
(Stearns, 1871)

Paciocinebrina lurida
(Middendorff, 1848)

Paciocinebrina spp.

Perimangelia interfossa
(Carpenter, 1864)

Perimangelia nitens
(Carpenter, 1864)

Petalococonchus

montereyensis Dall, 1919

Plesiocysticus jewettii
(Carpenter, 1857)

Pomaulax gibberosa
(Dillwyn, 1817)

Pseudomelotoma torosa
(Carpenter, 1864)

Pseudomelotoma sp.

Pusula californiana (Gray, 1827)

Seila montereyensis Bartsch, 1907

Siphonaria brannani
Stearns, 1872

Siphonaria sp.

Stylidium eschrichtii
(Middendorff, 1849)

Tectura paleacea (Gould, 1853)

Tegula brunnea (Philippi, 1849)

Tegula funebris (A. Adams, 1855)

Tegula gallina (Forbes, 1852)

Tegula montereyi (Kiener, 1850)

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Table 4 (continued)

LACMIP Invertebrate Paleontology locality #	42946	42948	42957	42958	42937	42941	42930	42935	42936	42947	42940	42938	42939	42942
USGS field locality #	SRI-9	SRI-12	SRI-27	SRI-27a	SRI-5	SRI-5G	SRI-1	SRI-3	SRI-4	SRI-11	SRI-5F	SRI-5D	SRI-5E	SRI-5J
Geomorphology	1st terrace	1st terrace	1st terrace	1st terrace	1st terrace	1st terrace	Carrington terrace	2nd terrace	2nd terrace	2nd terrace	2nd terrace	2nd terrace	2nd terrace	2nd terrace
General location on Santa Rosa Island	Johnsons Lee	SE of Sandy Point	NE of Sandy Point	Sandy Point	Garañon Canyon	Garañon Canyon	Carrington Point	Johnsons Lee	Johnsons Lee	Johnsons Lee	Garañon Canyon	Garañon Canyon	Garañon Canyon	Garañon Canyon
Elevation above sea level (shoreline angle, in meters)	5.4	>5, <12	>5, <12	>5, <12	7.4	7.4	≥10	20	20	20	24	24	24	24
<i>Tegula pulligo</i> (Gmelin, 1791)														X
<i>Tegula</i> sp.		X	X	X				X	X		X	X		
<i>Thylacodes squamigerus</i> (Carpenter, 1857)		X	X				X	X	X		X			X
<i>Trimusculus reticulatus</i> (G. B. Sowerby I, 1835)														X
<i>Triphora pedroanus</i> Bartsch, 1907									X					
<i>Turbonilla</i> sp.									X					X
Turrid sp.								X						
<i>Turritella cooperi</i> Carpenter, 1864								X	X					
<i>Vitreolina</i> sp.									X					
Bivalvia														
Bivalvia indet.	X		X				X		X					
<i>Bernardina bakeri</i> Dall, 1910									X					
<i>Chlamys</i> sp.							X							
<i>Cumingia californica</i> Conrad, 1837		X		X			X	X	X			X		X
<i>Cyclocardia ventricosa</i> (Gould, 1850)				X										
<i>Epilucina californica</i> (Conrad, 1837)	X	X	X	X	X		X	X	X	X	X	X	X	X
<i>Glans carpenteri</i> (Lamy, 1922)		X	X	X	X		X	X	X		X	X	X	X
<i>Glycymeris septentrionalis</i> (Middendorff, 1849)				X										
<i>Irusella lamellifera</i> (Conrad, 1837)							X	X	X		X	X		
<i>Kellia suborbicularis</i> (Montagu, 1803)												X		
<i>Lasaea adansoni</i> (Gmelin, 1791)			X					X	X					X
<i>Leukoma staminea</i> (Conrad, 1837)		X			X		X	X		X		X		
<i>Leukoma</i> sp.	X		X						X			X		
<i>Mytilus californianus</i> Conrad, 1837		X	X				X	X	X					

(continued on next page)

Table 4 (continued)

LACMIP Invertebrate Paleontology locality #	42946	42948	42957	42958	42937	42941	42930	42935	42936	42947	42940	42938	42939	42942
USGS field locality #	SRI-9	SRI-12	SRI-27	SRI-27a	SRI-5	SRI-5G	SRI-1	SRI-3	SRI-4	SRI-11	SRI-5F	SRI-5D	SRI-5E	SRI-5J
Geomorphology	1st terrace	1st terrace	1st terrace	1st terrace	1st terrace	1st terrace	Carrington terrace	2nd terrace	2nd terrace	2nd terrace	2nd terrace	2nd terrace	2nd terrace	2nd terrace
General location on Santa Rosa Island	Johnsons Lee	SE of Sandy Point	NE of Sandy Point	Sandy Point	Garañon Canyon	Garañon Canyon	Carrington Point	Johnsons Lee	Johnsons Lee	Johnsons Lee	Garañon Canyon	Garañon Canyon	Garañon Canyon	Garañon Canyon
Elevation above sea level (shoreline angle, in meters)	5.4	>5, <12	>5, <12	>5, <12	7.4	7.4	≥10	20	20	20	24	24	24	24
<i>Mytilus</i> sp.													X	
<i>Nutricula tantilla</i> (Gould, 1853)			X	X			X	X	X					X
Pectinid sp.									X				X	
<i>Penitella penita</i> (Conrad, 1837)							X							
<i>Penitella</i> sp.												X		
<i>Petricola carditoides</i> (Conrad, 1837)									X	X		X		
<i>Septifer bifurcatus</i> (Conrad, 1837)							X		X					X
<i>Sphenia laticola</i> (Valenciennes, 1846)							X							
Polyplacophora														
<i>Cryptochiton stelleri</i> Middendorff, 1847		X					X		X			X		
Mixed chiton plates		X	X	X	X		X	X		X	X	X	X	X
ARTHROPODA														
Barnacle fragments		X	X	X	X		X	X	X	X		X		X
Barnacle operculum									X					
Crab claws		X	X				X	X						
<i>Pagurus</i> sp. (on gastropods)							X		X					
ECHINODERMATA														
Echinoid spines		X	X	X			X	X	X	X		X		X
Echinoid plates		X	X	X			X	X	X	X		X		X
CNIDARIA														
<i>Balanophyllia elegans</i> Verrill, 1864		X	X				X		X			X		

(continued on next page)

Table 4 (continued)

LACMIP Invertebrate Paleontology locality #	42946	42948	42957	42958	42937	42941	42930	42935	42936	42947	42940	42938	42939	42942
USGS field locality #	SRI-9	SRI-12	SRI-27	SRI-27a	SRI-5	SRI-5G	SRI-1	SRI-3	SRI-4	SRI-11	SRI-5F	SRI-5D	SRI-5E	SRI-5J
Geomorphology	1st terrace	1st terrace	1st terrace	1st terrace	1st terrace	1st terrace	Carrington terrace	2nd terrace	2nd terrace	2nd terrace	2nd terrace	2nd terrace	2nd terrace	2nd terrace
General location on Santa Rosa Island	Johnsons Lee	SE of Sandy Point	NE of Sandy Point	Sandy Point	Garañon Canyon	Garañon Canyon	Carrington Point	Johnsons Lee	Johnsons Lee	Johnsons Lee	Garañon Canyon	Garañon Canyon	Garañon Canyon	Garañon Canyon
Elevation above sea level (shoreline angle, in meters)	5.4	>5, <12	>5, <12	>5, <12	7.4	7.4	≥10	20	20	20	24	24	24	24
BRYOZOA														
<i>Cellaria</i> sp. Encrusting bryozoa								X	X					
Branching bryozoa		X						X						
ANNELIDA														
Polychaete tubes?								X						
PROTOZOA (forams)														
<i>Cibicides?</i> sp.			X					X						
<i>Quinqueloculina?</i> sp.			X											
<i>Triloculina?</i> sp.			X											
VERTEBRATA														
Fish vertebrae								X						
Fish tooth?								X						
Marine mammal bone fragments?								X				X		
Mammoth remains						X								

(a) *Callianax biplicata*, LACMIP loc. 42936(b) *Epilucina californica*, LACMIP loc. 42936

Fig. 17. Examples of broken shells and better-preserved growth-series shells from LACMIP loc. 42936 (=SRI-4), 2nd terrace, Johnsons Lee area, south side of Santa Rosa Island, for *Callianax biplicata* (a) and *Epilucina californica* (b). Photographs by L.T. Groves.

eschrichtii (Middendorff, 1849), also reported by Orr (1960). This species lives as far north as the Kenai Peninsula of Alaska, but only as far south as Shell Beach, San Luis Obispo County, in central California. Its presence on Santa Rosa Island, therefore, is ~135 km south of its modern southern limit.

The composition of the extralimital and northward- and southward-ranging taxa of the Carrington terrace has some similarities to that of the 2nd terrace, consistent with the overall similarity in faunas of the two terraces (Fig. 18). One difference is that only three warm-water forms are present, *Borsonella bartschi* (Arnold, 1903), *Tegula gallina*, and *Thylacodes squamigerus*; of these, only *T. squamigerus* is present in deposits of the 2nd terrace. Based on LACM records, *B. bartschi* has a very limited distribution, from San Miguel Island south only to San Diego. Both *T. gallina* and *T. squamigerus* (in its form as twisted masses) do not range north of Point Conception (although see earlier note on the latter), and are found as far south as Baja California Sur (McLean, 1978). However, the Carrington terrace hosts eight cool-water forms (*Crepidula adunca*, *Haliotis rufescens*, *Harfordia harfordii* (Stearns, 1871), *Paciocinebrina lurida*, *Stylidium eschrichtii*, *Tegula brunnea*, *Tegula montereyi*, and *Cryptochiton stelleri*), all of which are also hosted by deposits of the 2nd

terrace, with one exception, as *Harfordia harfordii* is an extralimital northern species. Based on LACM collections, this taxon lives only from Hope Island, British Columbia, south to Monterey County, California (LACM 1959–13.43).

3.6.2. Paleozoogeography of mollusks from the 1st marine terrace on Santa Rosa Island

Corals that show closed-system U-series histories indicate that the 1st terrace dates to the ~80 ka high-sea stand, or MIS 5a. Previous studies of marine terraces with U-series ages dating to this high stand have consistently yielded fossil faunas with a number of cool-water species and no warm-water species (Addicott, 1966; Zullo, 1969; Kern, 1977; Rockwell et al., 1989; Kennedy et al., 1992; Muhs et al., 2006). Some of those findings are mirrored in the composition of the fauna of the ~80 ka terrace on Santa Rosa Island. Two strictly extralimital northern forms were found, along with five northward-ranging species (Fig. 19a; Table 4). One of the extralimital species is the aforementioned *Stylidium eschrichtii*, whose southern range endpoint is at Shell Beach. The other extralimital northern species is *Harfordia harfordii* which, as noted above, lives only from Hope Island, British Columbia, south to Monterey

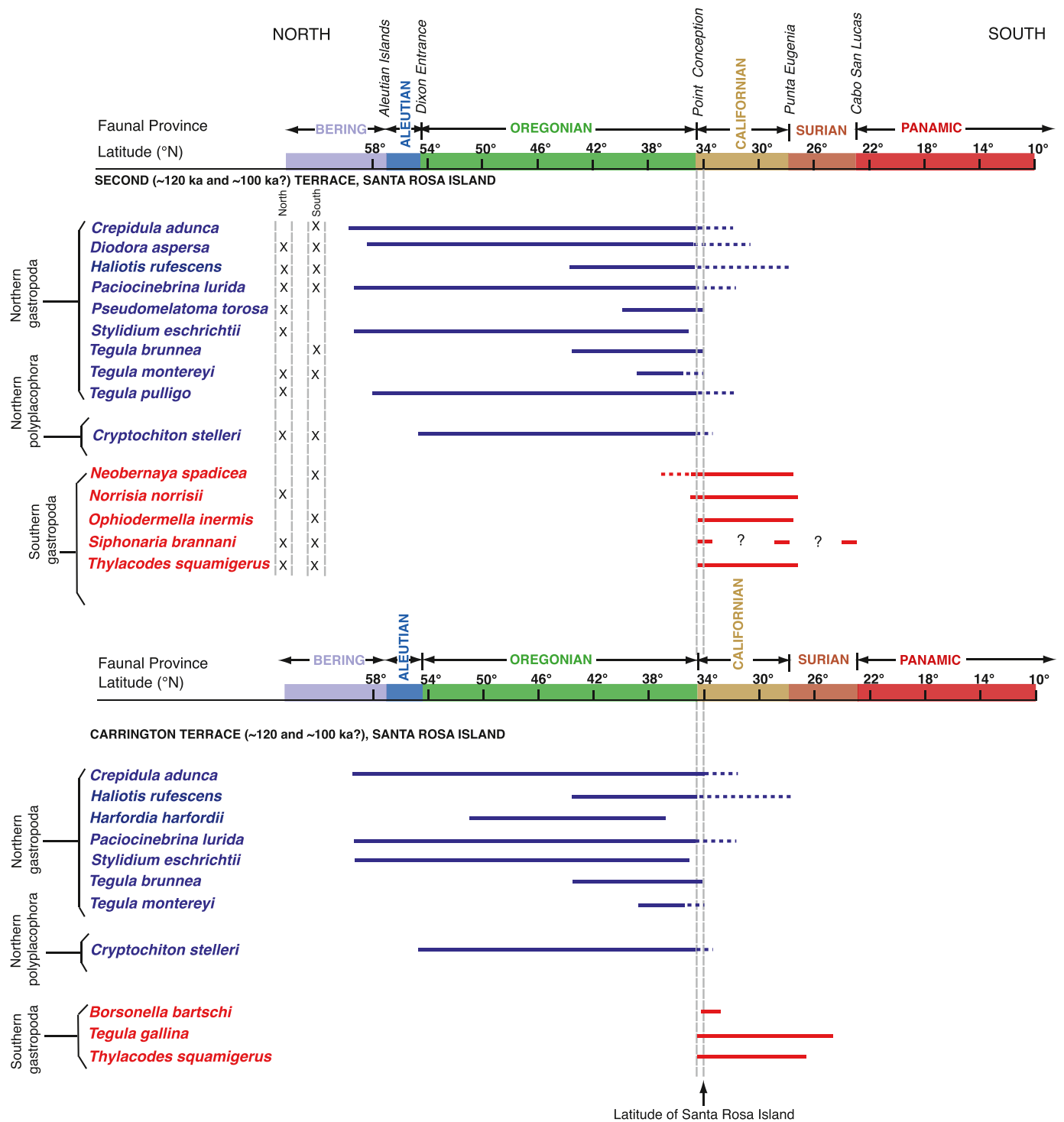


Fig. 18. North-south latitudinal plots, with latitudes in degrees north and marine invertebrate faunal zones (Valentine, 1966; see Fig. 1a) on horizontal axis at top. Below are modern latitudinal ranges of extralimital marine invertebrate taxa found in deposits of the 2nd marine terrace (upper plot) and Carrington terrace (lower plot) on Santa Rosa Island, as well as species that have modern ranges whose endpoints lie close to Santa Rosa Island (shown by vertical line; additional vertical line marks Point Conception, a major faunal boundary). Faunal data are from Table 4; latitudinal ranges plotted by the authors from references given in the text.

County, California. Thus, the fossil occurrence of this taxon on Santa Rosa Island is at least ~300 km southeast of its southernmost range limit. As is the case with the 2nd terrace discussed above, the five northward-ranging forms found in the 1st marine terrace all have modern ranges including or at least close to Santa Rosa Island, but all five are rarely found south of Point Conception. Orr (1960) also reported a number of cool-water forms that could not be confirmed in the collections reported here. He found two additional extralimital northern

species (*Amphissa columbiana* Dall, 1916 and *Lottia persona* (Rathke, 1833) [reported as *Acmaea persona*]) and four northward-ranging forms (*Paciocinebrina lurida* (Middendorff, 1848), *Lottia scutum* (Rathke, 1833) [reported as *Acmaea patina*], *Tegula brunnea* (Philippi, 1849) and *Tegula pulligo* (Gmelin, 1791)).

An unexpected observation made here is the presence of several southward-ranging forms in the ~80 ka terrace of Santa Rosa Island. Four warm-water gastropods were found, including *Mitromorpha*

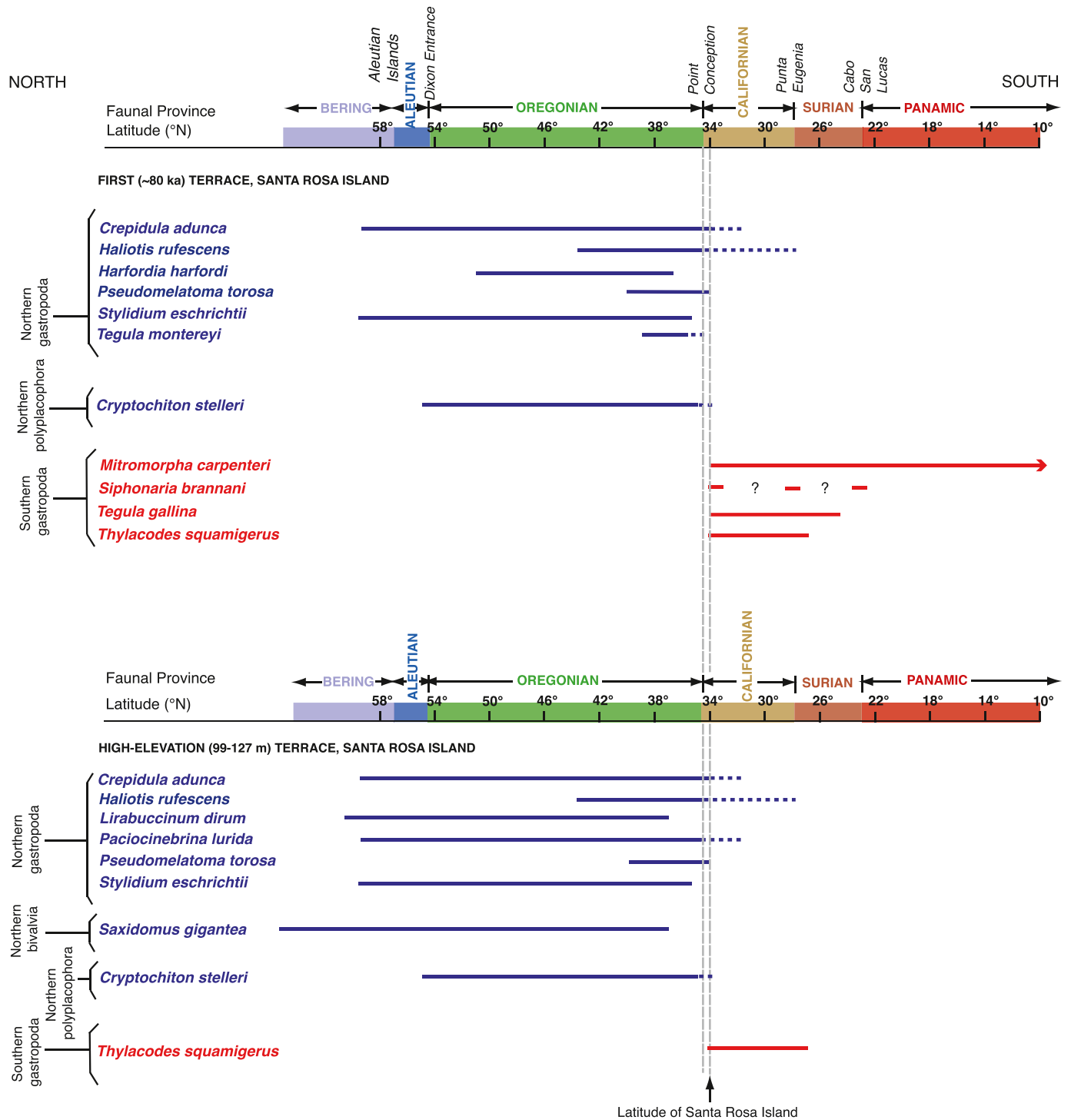


Fig. 19. North-south latitudinal plots, with latitudes in degrees north and marine invertebrate faunal zones (Valentine, 1966; see Fig. 1a) on horizontal axis at top. Below are modern latitudinal ranges of extralimital marine invertebrate taxa found in deposits of the 1st marine terrace (upper plot) and the high-elevation terrace (lower plot) on Santa Rosa Island, as well as species that have modern ranges whose endpoints lie close to Santa Rosa Island (shown by vertical line; additional vertical line marks Point Conception, a major faunal boundary). Faunal data are from Tables 4 and 5; latitudinal ranges plotted by the authors from references given in the text.

carpenteri Glibert, 1954, *Siphonaria brannani* (discussed earlier), *Tegula gallina*, and *Thylacodes squamigerus*. McLean (1978) incorrectly listed *M. carpenteri* ranging as far north as Monterey, California, but later stated (in manuscript) that the northern limit is actually Santa Rosa Island (LACM 73–9), with a distribution south to Panama and Islas Galápagos. As noted earlier, both *T. gallina* and *T. squamigerus* (in its form as twisted masses) do not range north of Point Conception (again,

see earlier note on the latter species) but are found as far south as Baja California Sur (McLean, 1978).

3.6.3. Paleontology and paleozoogeography of higher-elevation marine terrace deposits

A distinctive taxon found only in higher-elevation terrace deposits of Santa Rosa Island (as well as in other, pre-last interglacial deposits in

California) is the gastropod *Pusio fortis*, formerly known as *Calicantharus fortis*. On western Santa Rosa Island, this taxon was observed in most of the high-terrace localities (Fig. 8). With the exception of one probable reworked specimen on San Nicolas Island, this species is not known to occur in marine terrace deposits of peak LIG age (MIS 5e, ~120 ka) or younger (Muhs et al., 2012). It is found in pre-MIS 5e marine terrace deposits on San Miguel Island (Johnson, 1972), Anacapa Island (Valentine and Lipps, 1963), Santa Barbara Island (Lipps et al., 1968; Muhs and Groves, 2018), San Nicolas Island (Vedder and Norris, 1963), and San Clemente Island (Cockerell, 1939a), as well as in the Lomita Marl of San Pedro, California (Woodring et al., 1946). The Sr isotope ages given earlier (no younger than ~0.91 Ma and possibly as old as ~2.3 Ma) are consistent with the presence of *Pusio fortis* in these deposits on Santa Rosa Island.

The high terrace fossil site with the greatest species diversity is LACMIP loc. 42950 (field number SRI-13), at an elevation of ~127 m (Figs. 6, 8; Table 5). This locality contains at least 25 species of gastropods and 9 species of bivalves. Gastropods include *Californiconus californicus* (Reeve, 1844), *Callianax biplicata*, *Crepidula adunca*, the aforementioned *Pusio fortis*, and the bivalves *Crassadoma gigantea* (Gray, 1825), *Saxidomus gigantea* (Deshayes, 1839), *Epilucina californica*, *Macoma secta* (Conrad, 1837), and *Mytilus californianus*. Thus, among the bivalves, the deposit contains taxa that are typical of a high-energy, rocky shore environment (*E. californica* and *M. californianus*) and those that are characteristic of a protected, quiet-water bay or lagoonal setting (*S. gigantea* and *M. secta*). From this locality, marine terrace deposits can be traced southeast along the sea cliff discontinuously for ~100 m to LACMIP loc. 42977 (field number SRI-13A), one of the three localities for which Sr isotope ages are available. The assemblage at LACMIP loc. 42977 is less diverse than that at LACMIP loc. 42950, but also contains, among the gastropods, abundant specimens of *Callianax biplicata*, and among the bivalves, *Crassadoma gigantea*, *Saxidomus* sp., *Epilucina californica*, and *Mytilus californianus*. Landward of both these sites is LACMIP loc. 42951, a locality in an arroyo exposure (Figs. 3, 6). The fossil assemblage here is similar to that of LACMIP loc. 42977, with *Callianax biplicata* within the gastropod assemblage, and *Crassadoma gigantea*, *Saxidomus* sp., *Epilucina californica*, and *Mytilus californianus* among the bivalves. *Pusio fortis*, abundant at LACMIP loc. 42950, is absent at LACMIP locs. 42977 and 42951. The third locality for which Sr isotope ages are available is LACMIP loc. 42952 (the “Scott’s Shack” site; Figs. 3, 6). This locality has the second most diverse assemblage, with *Californiconus californicus*, *Callianax biplicata*, and *Crepidula* sp. among the gastropods, as well as the extinct *Pusio fortis*. Bivalves are less diverse here, but *Epilucina californica* and *Mytilus californianus* are both present, as well as *Petricola carditoides*. These, along with the gastropods, indicate a predominantly rocky-shore environment.

It is interesting to note that the high terrace localities studied here do not contain any extralimital southern species and only a single southward-ranging species (*Thylacodes squamigerus*). These deposits do, however, include eight cool-water forms. These include the northward-ranging gastropods *Crepidula adunca*, *Haliotis rufescens*, *Paciocinebrina lurida*, and *Pseudomelatomia torosa* (Carpenter, 1865), all of which are, at present, rare south of Point Conception. Two other localities host the northward-ranging species, *Cryptochiton stelleri*, found at LACMIP loc. 43113 and LACMIP loc. 43116 (Figs. 6, 8). In addition, there are three strictly extralimital northern species in these early Pleistocene deposits, none of which range south of central California at present, including the gastropods *Lirabuccinum dirum* (Reeve, 1846) and *Stylidium eschrichtii*, and the bivalve *Saxidomus gigantea* (Table 5).

4. Discussion

4.1. Ages of marine terraces of the last interglacial period

In assessing the integrity of U-series ages of corals, several criteria are considered, established during the early years of U-series

geochronology by Thurber et al. (1965) and still valid today. These include: (1) absence of recrystallization of primary aragonite to calcite, based on both examination of samples under magnification and X-ray diffraction analyses; (2) confirmation that bulk U concentrations are within the range of modern samples of the same species, indicating no gain or loss of U since deposition; (3) verification that ^{230}Th measured is due to in situ radioactive decay of parent ^{234}U and not reflective of detrital silicate contaminants, confirmed by high values of $^{230}\text{Th}/^{232}\text{Th}$; and (4) measured $^{234}\text{U}/^{238}\text{U}$ values that, when combined with apparent $^{230}\text{Th}/^{234}\text{U}$ ages, yield back-calculated initial $^{234}\text{U}/^{238}\text{U}$ values that fall within the range of modern seawater.

Here, the apparent ages of the corals collected from the 1st, 2nd, and Carrington terraces on Santa Rosa Island are evaluated in light of these criteria for reliability. All but nine specimens are 100% aragonite and of those nine corals, all but two are 99% aragonite, so there is no measurable evidence of substantial recrystallization (Table 1). Muhs et al. (2002) showed that living specimens of *Balanophyllia elegans* from San Nicolas Island and San Clemente Island, California contain ~3.0 to ~3.7 ppm U, and modern, dead specimens contain ~3.3 to ~4.7 ppm U. All modern specimens, however, whether living or dead, have $^{234}\text{U}/^{238}\text{U}$ values within the range of modern seawater. Muhs et al. (2002) interpreted these data to mean that after death, but while still in the marine environment, *Balanophyllia elegans* takes up additional U from seawater. The corals analyzed here have U contents within or close to the range of modern live-collected or dead-collected *Balanophyllia elegans* (Table 1). A few corals have U contents slightly over 5 ppm, but these somewhat higher values have been reported for fossil *Balanophyllia elegans* elsewhere in California (Ku and Kern, 1974; Muhs et al., 2002, 2006). Hence, there is no evidence of substantial post-mortem gain or loss of U in the corals from Santa Rosa Island.

A third consideration in interpreting U-series ages of corals is contamination by detrital, U-and-Th-bearing minerals, typically fine-grained silicate minerals derived from the host marine terrace sediments. In the early years of U-series geochronology, a $^{230}\text{Th}/^{232}\text{Th}$ activity value of ~20 was an informally established lower limit for accepting corals that were considered to have no substantial detrital mineral contamination (Thurber et al., 1965). By that early criterion, all of the corals from Santa Rosa Island easily meet the requirement of little or no detrital mineral contamination (Table 1). Nevertheless, with the greater precision of modern instrumentation, higher standards for what constitutes an acceptable degree of contamination have emerged. Dutton et al. (2015) considered a $^{230}\text{Th}/^{232}\text{Th}$ activity value of ~500 to be an acceptable lower limit for negligible influence from detrital Th-bearing minerals. Even with these higher standards for consideration of contamination, all corals analyzed here have $^{230}\text{Th}/^{232}\text{Th}$ activity values greater than ~300, all but two have values >500, and 26 have values >1000. Thus, contamination by U and Th-bearing silicate minerals in these corals is not substantial.

The U-series dating method has internal isotopic checks on whether fossil corals have behaved as closed systems with respect to U and Th isotopes during their history since coral growth. The most commonly used method for assessing closed-system history is that back-calculated initial $^{234}\text{U}/^{238}\text{U}$ values (based on apparent $^{230}\text{Th}/^{238}\text{U}$ ages and measured $^{234}\text{U}/^{238}\text{U}$ values) should fall within the range of modern seawater and modern, living corals. As noted earlier, modern seawater has $^{234}\text{U}/^{238}\text{U}$ activity ratios of 1.140 to 1.155, similar to $^{234}\text{U}/^{238}\text{U}$ activity ratios in live-collected and modern-dead-collected specimens of *Balanophyllia elegans* (1.142 to 1.151; see Muhs et al., 2002, 2006). Based on this criterion, as well as the others cited above, the most reliable ages come from the 1st terrace, at LACMIP loc. 42957 (SRI-27), located ~1.1 km northeast of Sandy Point (Fig. 3). Three of the corals from this locality have back-calculated $^{234}\text{U}/^{238}\text{U}$ values ranging from 1.143 to 1.1478, well within the range of modern seawater. These three samples plot within a theoretical, closed-system isotopic evolution pathway on a $^{230}\text{Th}/^{238}\text{U}$ vs. $^{234}\text{U}/^{238}\text{U}$ evolution diagram (Fig. 20a) and the ages of ~79 ka to ~83 ka (Table 1) can be considered to be reliable with a high

Table 5

Invertebrate marine fossils from high-elevation marine terrace deposits on Santa Rosa Island, California.

LACMIP Invertebrate Paleontology locality #	42977	42950	42951	42952	43113
USGS field locality #	SRI-13A	SRI-13	SRI-13B	SRI-13C	SRI-13D
Geomorphology	High terrace	High terrace	High terrace	High terrace	High terrace
General location on Santa Rosa Island	Pocket Field	Pocket Field	Pocket Field	Pocket Field	Pocket Field
Latitude (degrees north)	33.983467	33.98441667	33.98555	33.99376667	34.0015016
Longitude (degrees west)	120.214033	120.2141667	120.2129333	120.22615	120.238776
Elevation above sea level (meters)	127	127	122	112	99

Gastropoda:

<i>Acmaea mitra</i> Rathke, 1833				X	
<i>Alvinia purpurea</i> (Dall, 1871)		X	X		
<i>Antisabia panamensis</i> (C.B. Adams, 1852)	X	X	X	X	X
<i>Atrimitra idae</i> (Melvill, 1893)				X	
<i>Barleeia haliotiphila</i> Carpenter, 1864		X		X	
<i>Caecum californicum</i> Dall, 1885			X		
<i>Caesia perpinguis</i> (Hinds, 1844)		X			
<i>Californiconus californicus</i> (Reeve, 1844)		X		X	
<i>Callianax biplicata</i> (G.B. Sowerby I, 1825)	X	X	X	X	
<i>Crepidula adunca</i> G.B. Sowerby I, 1825		X	X		
<i>Crepidula</i> sp.		X	X	X	
<i>Discurria insessa</i> (Hinds, 1842)		X			
<i>Epitonium tinctum</i> (Carpenter, 1864)		X			
<i>Eulithidium</i> sp.		X			
<i>Granulina margaritula</i> (Carpenter, 1857)		X			
<i>Haliotis rufescens</i> Swainson, 1822				X	X
<i>Haliotis</i> sp.			X	X	
<i>Hipponix tumens</i> Carpenter, 1864	X			X	
<i>Lacuna unifasciata</i> Carpenter, 1857				X	
<i>Lirabuccinum dirum</i> (Reeve, 1846)		X			
<i>Lirobittium</i> sp.		X	X	X	
<i>Littorina</i> sp.		X		X	
<i>Lottia scabra</i> (Gould, 1846)	X			X	
<i>Lottia</i> sp.					X
<i>Naticid</i> sp.				X	
<i>Neptunea tabulata</i> (Baird, 1863)		X			
<i>Paciocinebrina barbarensis</i> (Gabb, 1865)		X			
<i>Paciocinebrina foveolata</i> (Hinds, 1844)		X			
<i>Paciocinebrina lurida</i> (Middendorff, 1848)		X			
<i>Paciocinebrina</i> sp. or spp.		X		X	
<i>Perimangelia interfossa</i> (Carpenter, 1864)		X			
<i>Perimangelia nitens</i> (Carpenter, 1864)		X			
<i>Plesiocysticus jewetti</i> (Carpenter, 1857)		X			
<i>Pseudomelatoma torosa</i> (Carpenter, 1864)	X	X			
<i>Pusio fortis</i> (Carpenter, 1866)		X		X	X
<i>Stylidium eschrichtii</i> (Middendorff, 1849)	X	X			
<i>Tegula</i> sp.		X			
<i>Thylacodes squamigerus</i> (Carpenter, 1857)				X	X
<i>Turbonilla</i> sp.		X			

Bivalvia:

<i>Crassadoma gigantea</i> (Gray, 1825)	X	X	X		
<i>Cumingia californica</i> Conrad, 1837	X	X	X		
<i>Cyclocardia ventricosa</i> (Gould, 1850)		X			
<i>Epilucina californica</i> (Conrad, 1837)	X	X	X	X	X
<i>Glycymeris septentrionalis</i> (Middendorff, 1849)	X				
<i>Lasaea adansoni</i> (Gmelin, 1791)				X	
<i>Macoma secta</i> (Conrad, 1837)		X			
<i>Mytilus californianus</i> Conrad, 1837	X	X	X	X	
<i>Mytilus</i> sp.					X
<i>Nutricula tantilla</i> (Gould, 1853)			X	X	
<i>Nutricula</i> sp.	X	X			
<i>Pectinid</i> sp.			X		
<i>Petricola carditoides</i> (Conrad, 1837)	X	X			
<i>Saxidomus gigantea</i> (Deshayes, 1839)		X			
<i>Saxidomus</i> sp.	X		X		

Polyplacophora:

(continued on next page)

Table 5 (continued)

LACMIP Invertebrate Paleontology locality #	42977	42950	42951	42952	43113
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Longitude (degrees west)	120.214033	120.2141667	120.2129333	120.22615	120.238776
Elevation above sea level (meters)	127	127	122	112	99
<i>Cryptochiton stelleri</i> Middendorff, 1847					X
Chiton plate		X		X	
Echinodermata:					
Echinoid spines and/or plates	X	X	X	X	X
Arthropoda:					
Barnacle fragments	X	X		X	X
Crab claw	X	X		X	
Bryozoa:					
Branching bryozoan fragment				X	
Foraminifera:					
<i>Elphidium crispum</i> (Linnaeus, 1758)		X	X		
Vertebrata:					
Bone (?) fragment	X			X	

degree of confidence. Three other corals from this locality have back-calculated $^{234}\text{U}/^{238}\text{U}$ values ranging from 1.154 to 1.158, overlapping or plotting only slightly above the closed-system evolution zone shown in Fig. 20a. These the corals yield apparent ages of ~79 ka to ~84 ka, similar to the ages of the three closed-system corals.

The 1st terrace can be traced laterally from LACMIP loc. 42957 around Sandy Point to LACMIP loc. 42948 (Fig. 3), so it was expected that the corals from both localities should give similar ages. However, the corals collected from LACMIP loc. 42948 have back-calculated initial $^{234}\text{U}/^{238}\text{U}$ values ranging from 1.210 to 1.259, substantially greater than those from LACMIP loc. 42957 (Table 1). Nevertheless, the apparent ages of these corals range from ~77 ka to ~84 ka, similar to the age range of all corals from LACMIP loc. 42957.

Higher-than-expected $^{234}\text{U}/^{238}\text{U}$ values in fossil corals can, in principle, be the result of U-bearing terrestrial waters passing through the host sediment column. Although Th is very insoluble, under favorable circumstances, U is soluble in terrestrial waters. Thus, as dissolved ^{234}U and ^{238}U atoms decay during passage of water through a sediment column (or ^{234}U and ^{238}U atoms in the sediment column itself decay), recoiling daughter products, ^{230}Th and ^{234}U , respectively, can be emplaced on solid particles, such as corals. The result for a fossil coral is no change in bulk ^{238}U content, but higher $^{234}\text{U}/^{238}\text{U}$ values and higher $^{230}\text{Th}/^{238}\text{U}$ values, with higher apparent ages. This process is, in part, the basis of the experimental uranium-trend dating method of dating bulk soils or sediments themselves (Muhs et al., 1989).

Gallup et al. (1994), studying fossil corals on Barbados, observed the same kind of open-system behavior noted here (i.e., higher-than-expected initial $^{234}\text{U}/^{238}\text{U}$ values) with many of their samples. These investigators pointed out that Barbados corals affected in this way formed a roughly linear array on an isotope evolution diagram such as that shown in Fig. 20b, with those corals plotting above the closed-system pathway biased to older apparent ages. They proposed a

method for correcting such ages, when apparent, back-calculated $^{234}\text{U}/^{238}\text{U}$ values exceed those of modern seawater. Age correction for the process of such an open-system history was more formally proposed in a quantitative approach by Thompson et al. (2003), if certain very strict requirements are met.

If the rigid requirements for age corrections of Thompson et al. (2003) are not met, it is still possible to obtain approximate ages if a suite of fossil corals shows at least a roughly linear array of isotopic compositions on a $^{230}\text{Th}/^{238}\text{U}$ vs. $^{234}\text{U}/^{238}\text{U}$ evolution diagram, similar to that described by Gallup et al. (1994). Where such a linear array intersects the closed-system pathway, it can be inferred that the intersection point with an isochron is the age of the entire suite of corals. Such an approach also has been taken for linear arrays of last-interglacial-aged ooids from Florida and the Bahamas that have experienced open-system histories (Muhs et al., 2020). Thus, in the suite of corals from Barbados shown in Fig. 20b, although only a few samples fall within the closed-system zone, the array of all corals forms an open-system trend zone that intersects the ~120 ka isochron within the range of seawater values. Such a trend is referred to here as *continuing* post-emergence recoil additions of ^{230}Th and ^{234}U , with steady increases in apparent age as the process proceeds over the history of the corals.

In contrast, what appears to be the dominant process with the corals on the 1st terrace on Santa Rosa Island is what is referred to here as *early* post-emergence recoil additions of ^{230}Th and ^{234}U (Fig. 20b). It is hypothesized that in a situation where this process is dominant, recoil additions of ^{230}Th and ^{234}U were emplaced shortly after terrace emergence. The result is no change in ^{238}U concentrations, higher-than-expected $^{234}\text{U}/^{238}\text{U}$ values, and all ages similar to those in corals that have experienced closed-system histories. In Fig. 20b, an example of this is shown with a suite of corals from western San Nicolas Island, California, originally reported by Muhs et al. (2006). Here, corals with elevated $^{234}\text{U}/^{238}\text{U}$ values yield ages similar to those with $^{234}\text{U}/^{238}\text{U}$

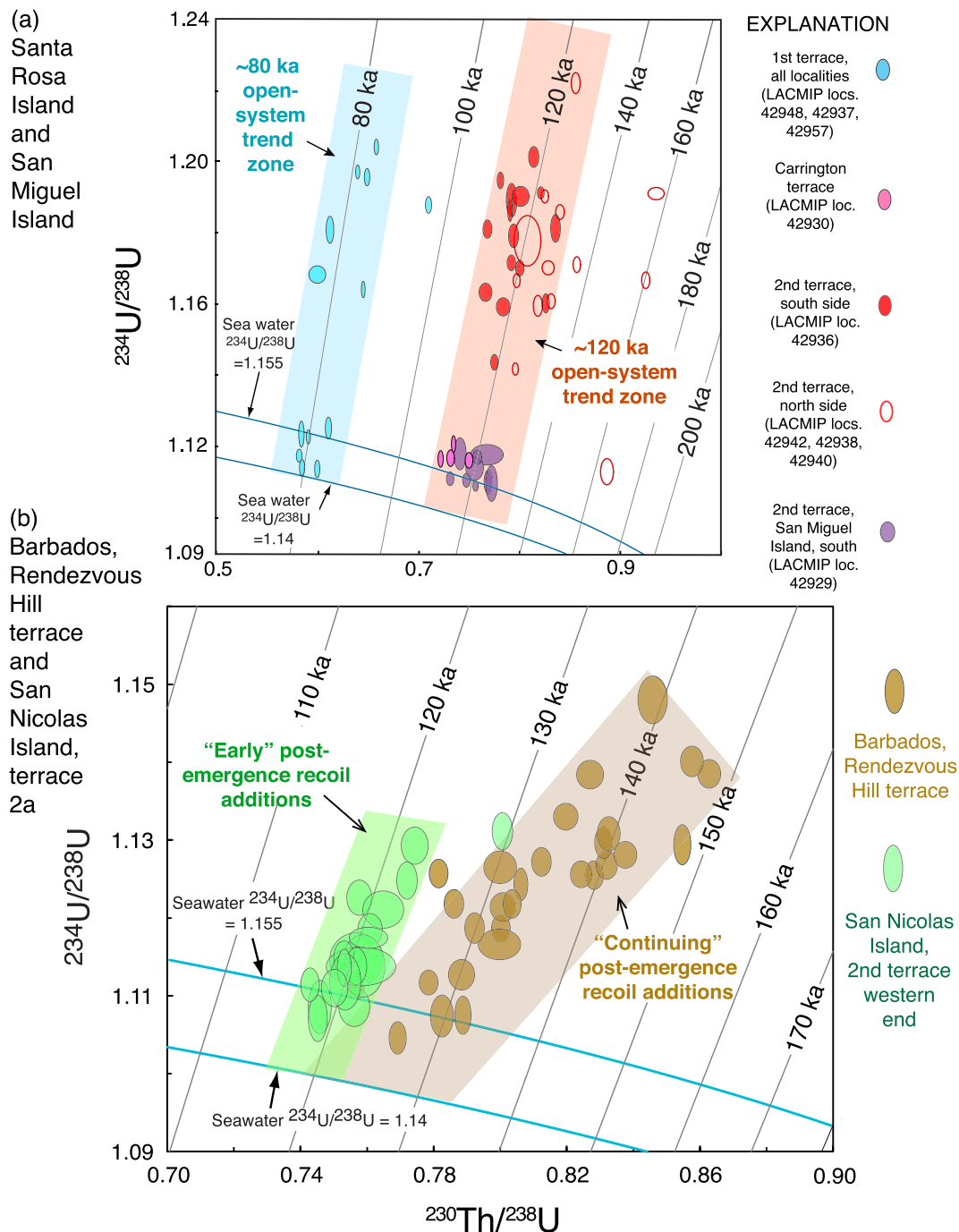


Fig. 20. (a) Isotopic evolution curves (solid blue lines) showing sympathetic variation in $^{230}\text{Th}/^{238}\text{U}$ and $^{234}\text{U}/^{238}\text{U}$ activity values over time in materials with no initial ^{230}Th and with initial $^{234}\text{U}/^{238}\text{U}$ activity ratios of 1.14 and 1.155, spanning the range of modern seawater values. Age in thousands of years (ka) is shown by isochrons (thin diagonal lines). Superimposed on the theoretical plots are measured values (blue, red, pink and purple ellipses) of fossils of the solitary coral *Balanophyllia elegans* from the 1st (blue), 2nd (red, open and filled), and Carrington (pink) terraces on Santa Rosa Island, and the 2nd terrace (purple) on San Miguel Island. Data are mostly from the present study (Table 1), but also included are data from Santa Rosa Island and San Miguel Island in Muhs et al. (2014a, 2015). Ellipses define the measured values and 2-sigma uncertainties, as calculated using Isoplot/Ex software (Ludwig, 2001). (b) Isotopic evolution curves, as in (a), but plotted ellipses in light green are corals from terrace 2a on the western tip of San Nicolas Island, California, showing specimens thought to have “early only” post-emergence recoil additions of ^{230}Th and ^{234}U (data from Muhs et al., 2006); plotted ellipses in brown are from corals from the Rendezvous Hill terrace on Barbados, showing specimens thought to have “continuing” post-emergence recoil additions of ^{230}Th and ^{234}U (data from Muhs and Simmons, 2017). Shaded areas in plots of both (a) and (b) indicate open-system trend zones. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

values falling within the pathway defining a closed-system history. A similar situation with fossil corals, of both Holocene and LIG age, from the Gulf of Aqaba in the northern Red Sea, was observed by Scholz et al. (2004). These investigators proposed that the intersection of a

regression line fitted to corals with elevated $^{234}\text{U}/^{238}\text{U}$ values with a closed-system evolution line (as in Fig. 20b) corresponds to the true age of the coral suite.

Corals from the 2nd terrace on Santa Rosa Island show the same kind

of open-system history as those from the 1st terrace (Fig. 20a) and those reported by Scholz et al. (2004). On the south side of the island, corals from the 2nd terrace at Johnsons Lee (LACMIP loc. 42936, SRI-4 series; Table 1) have apparent ages ranging from ~130 ka to ~110 ka, with back-calculated initial $^{234}\text{U}/^{238}\text{U}$ values ranging from 1.201 to 1.281, and no discernible trend of apparent ages increasing with higher $^{234}\text{U}/^{238}\text{U}$ values. All the corals from this locality are 100% aragonite and have no evidence of substantial additions or loss of bulk U when compared to fossil corals elsewhere in California. On the north side of the island, three corals from the Cañada Garañon area at LACMIP locs. 42942 and 42938 (SRI-5D-1, SRI-5D-5, and SRI-5J-4) all have apparent ages in excess of ~150 ka and are very likely biased old. However, the remaining corals from localities on this terrace on the north side of the island have apparent ages ranging from ~136 ka to ~120 ka. All have back-calculated initial $^{234}\text{U}/^{238}\text{U}$ values that fall into the range of 1.202 to 1.316, but, as with the corals from the south side of the island on this terrace, have no evidence of substantial gain or loss of bulk U. Also, as with the corals on the 2nd terrace on the south side of the island, there is no discernible trend of older apparent ages with higher initial $^{234}\text{U}/^{238}\text{U}$ values. All these corals have experienced open-system histories, as evidenced by their positions above a closed-system pathway on an isotopic evolution diagram (Fig. 20a). Nevertheless, if the model presented above regarding “early post-emergence” recoil-derived ^{234}U and ^{230}Th nuclide additions has validity, most of the corals from the 2nd terrace on Santa Rosa Island have a broad trend towards an age range of ~125 ka to ~115 ka (Fig. 20a). This interpretation is reinforced by this modeled trend zone including the nine corals from the 2nd terrace on San Miguel Island, all of which show little or no bias from open-system histories and have ages ranging from ~126 ka to ~114 ka. The four corals analyzed from the Carrington terrace also show minimal evidence of open-system history, and fall within this trend zone as well, with apparent ages ranging from ~118 ka to ~110 ka.

Amino acid data support the interpretations of U-series ages of the terraces on Santa Rosa Island. D/L values in fossil *Tegula* from the 2nd terrace and Carrington terrace on Santa Rosa Island both fall within the ~120 ka aminozone for both glutamic acid and valine (Fig. 16). Furthermore, the D/L values for these terraces fall above those for the 1st terrace on Santa Rosa Island, which has values that fall clearly within the ~80 ka aminozone. From the observations of both U-series data and amino acid data, it is concluded that the 1st terrace on Santa Rosa Island is ~83 ka to ~79 ka and can be correlated with MIS 5a. The 2nd terrace and the Carrington terrace on Santa Rosa Island both can be correlated with MIS 5e and, by comparison with minimally biased U-series ages from San Miguel Island, likely have an age range of ~126 ka to ~114 ka.

4.2. Ages of early Pleistocene marine terrace deposits

In principle, on a steadily uplifting coast, with terraces forming primarily during interglacial high-sea stands, ages of fossils should always increase with increasing terrace elevation. On the western end of Santa Rosa Island, Sr isotope ages of mollusks from higher-elevation terrace deposits do not follow this simple model (Fig. 8). It is true that at the lowest elevation (~112 m) site, LACMIP loc. 42952, *Epilucina* shells have ages of 0.91 Ma to 0.99 Ma, and *Callianax* shells have ages of 1.2 Ma to 1.4 Ma. The next highest locality, LACMIP loc. 42950 at ~127 m, also has two clusters of ages, all from *Epilucina* valves, of ~1.7 Ma and ~2.2 to ~2.3 Ma, which are again analytically distinguishable. However, LACMIP loc. 42977, also at ~127 m elevation but landward of LACMIP loc. 42950, has shells with ages of ~1.1 Ma and ~1.2 Ma. Because all shells at all three localities show no evidence of substantial conversion of primary aragonite to calcite or any geochemical evidence of substantial alterations in original composition (Table 3), there is no a priori reason to suppose that diagenetic effects have caused these age differences.

A simple interpretation is that the entire length of high-elevation marine deposits, from ~99 m elevation above Sandy Point to ~4.5 km

inland at ~127 m represents a single terrace. In this interpretation, the abrupt change in platform elevation from ~122 m to ~127 m is due to a component of vertical, to up-to-the-south movement along the Santa Rosa Island fault (Fig. 8), consistent with interpretations presented earlier by Dibblee et al. (1998) and Minor et al. (2012). In this scenario, the terrace might date to the youngest ages of fossils, ~0.91 Ma to ~0.99 Ma, and all older fossils, certainly those dating to ~1.7 Ma and ~2.3 Ma, are reworked from earlier high-sea stands. In such an interpretation, the terrace could have been occupied a number of times during interglacial periods as far back as MIS 89 or 87 and as recently as MIS 21, and potentially including intermediate-aged interglacials of MIS 61, 59, 39, 37, 31, and 25 (Fig. 21).

In any interpretation of the Sr isotope ages, an inescapable conclusion is that some amount of terrace reoccupation and reworking of fossils has taken place. At least two factors could have played roles in bringing about the fossil ages and landscape we see today. One of these is that in the early Pleistocene, before ~1.2 Ma, glacial-interglacial cycles were shorter, linked to the ~41 ka obliquity cycle of orbital controls on climate (Fig. 21). In the latter part of the Pleistocene, from ~0.78 Ma on, glacial-interglacial cycles were longer, linked, for reasons still not clearly understood, to the ~100 ka eccentricity cycle of orbital control. Between these two time periods is what has been called the “Mid-Pleistocene transition.” Some of the glacial-interglacial cycles in this time interval were relatively short, perhaps on the order of ~50 ka. For example, in the ~400 ka interval between ~0.9 Ma and ~1.3 Ma (a period that includes many of the Sr isotope ages presented here), as many as eight to nine interglacial periods are recorded, represented by MIS 23, 25, 27, 29, 31, 33, 35, 37, and 39. With such rapid shifts to interglacial periods compared to the latter part of the Pleistocene, the potential for terrace reoccupation is high.

This leads to the second factor that is likely an important part of the explanation for what is seen on Santa Rosa Island, which is a relatively low, long-term rate of uplift. The best marker for determining this is of course the shoreline angle, but definitive evidence of shoreline angles of high terraces in northwestern Santa Rosa Island could not be found, owing to an extensive cover of eolian sand. The next best estimate is to use the bench elevation from the highest (~127 m) and most landward terrace locality (LACMIP loc. 42977 and near it). Knowledge of the magnitude of early Pleistocene paleo-sea level is also necessary for calculating an uplift rate, but as pointed out by Murray-Wallace and Woodroffe (2014), there are few independent records of paleo-sea levels during this time period. Assuming the ~127-m-high bench at LACMIP loc. 42977 and locations near it formed during a sea level close to present, the ages of 1.1 Ma to 1.2 Ma yield uplift rates of 0.11 m/ka to 0.12 m/ka. Alternatively, assuming that sea level was as much as 20 m lower than present (a possibility: see Murray-Wallace and Woodroffe, 2014, p. 265 for discussion), the uplift rates increase only to 0.12 m/ka to 0.13 m/ka. Using the ~112 m elevation of the terrace at LACMIP loc. 42952 and its youngest age (~0.91 Ma) yields an uplift rate of 0.12 m/ka (assuming a paleo-sea level near present) or 0.14 m/ka (assuming a paleo-sea level 20 m below present). Assumptions of paleo-sea levels higher than present would of course decrease estimates of uplift rate from those just described. Similarly, if the older Sr isotope ages (those ranging from 1.11 Ma to 2.30 Ma) are used, uplift rates of 0.11 m/ka to 0.06 m/ka are calculated. Thus, in any possible model, long-term uplift rates have likely been relatively low on Santa Rosa Island during the Pleistocene, although caution must be taken with an assumption that the long-term uplift rates calculated for the higher terrace have been constant over time.

4.3. Comparison of early Quaternary and late Quaternary uplift rates

Uplift rates of the older (middle-to-early Quaternary) marine deposits on the western side of the island can be compared to calculations of late Quaternary uplift rates. The greatest uncertainty in late Quaternary uplift rate calculations lies in estimates of paleo-sea level at the

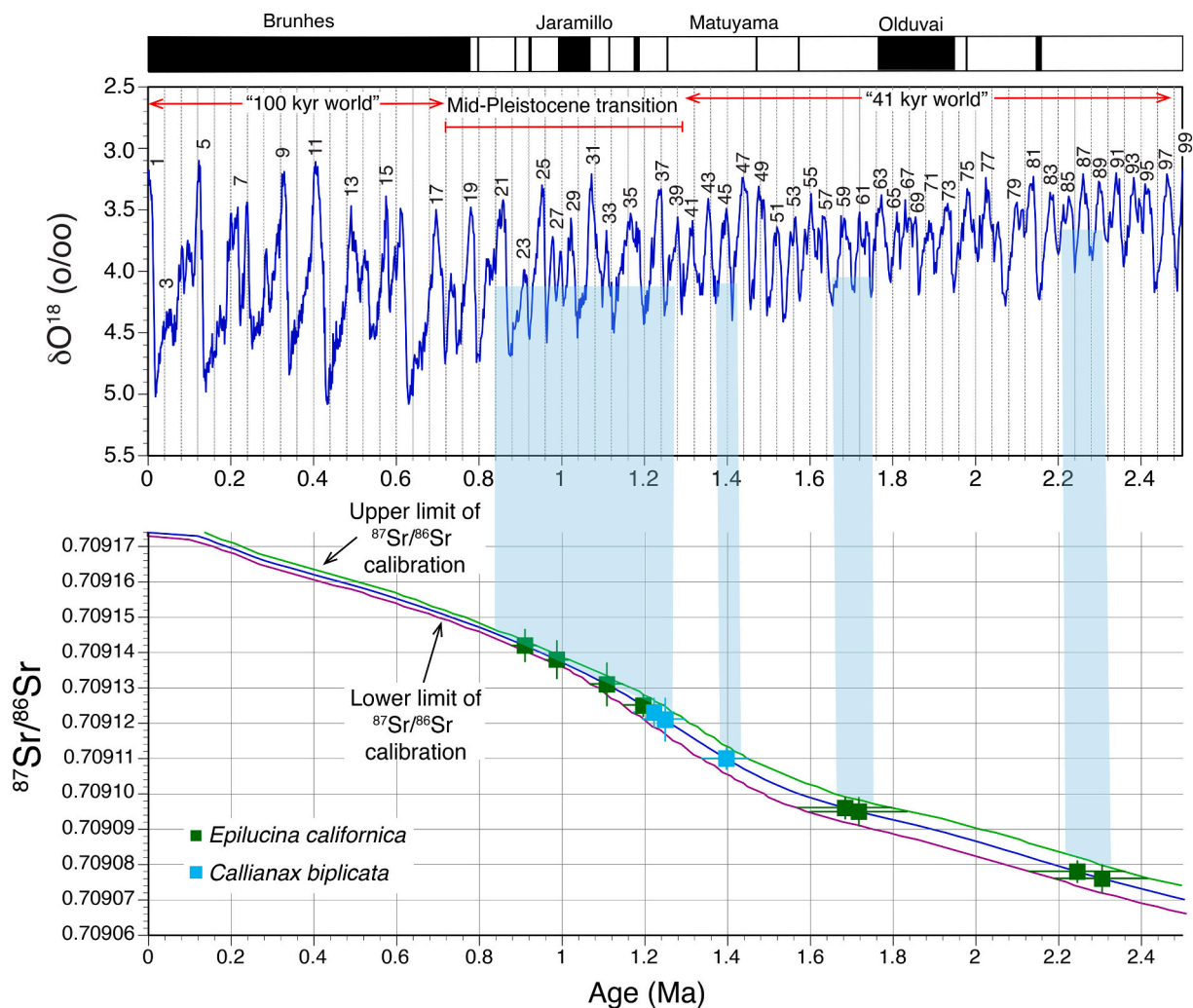


Fig. 21. Upper: Stacked global marine oxygen isotope record of the past 2.5 Ma, from Lisiecki and Raymo (2005), with age scale calibration in part from the magnetic record, shown at top (from Roberts and Turner, 2013): black bands indicate normal polarity, white bands indicate reversed polarity. Odd numbers indicate interglacial marine isotope stages (MIS). Time period marked for the Mid-Pleistocene Transition is from ages given in Clark et al. (2006). Lower: plot of the Sr isotopic composition of seawater over the past 2.5 Ma, with mean, upper, and lower age limits, from McArthur et al. (2020), from LOWESS version 6. Also shown are Sr isotopic compositions of *Epilucina californica* and *Callianax biplicata* fossil shells from the high-elevation marine terrace deposits on Santa Rosa Island (Table 3). Vertical bars are analytical errors; horizontal bars show age uncertainties based on calibration curves. Light blue shades show possible correlations with oxygen isotope stages. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

time of terrace formation. A worldwide average of +6 m is commonly quoted for MIS 5e (see discussion in Murray-Wallace and Woodroffe, 2014), but consideration of GIA effects makes this assumption uncertain on many of the world's coastlines (Creveling et al., 2015). North America, including California, is particularly subject to this uncertainty, because both the Laurentide and Cordilleran ice sheets had dramatic effects on GIA processes for the coasts of this continent. In a recent modeling effort, Simms et al. (2016) estimated that local (relative) MIS 5e paleo-sea level could have been as much +13 m, relative to present, in northern and central California, as well as on San Miguel and Santa Rosa Islands. Elsewhere in southern California and northern Baja California, these investigators modeled an MIS 5e paleo-sea level of +12 m to +12.5 m, relative to present. Muhs et al. (2021) challenged some of these modeling efforts, pointing out that there were many localities in California and Baja California where terraces dating to ~120 ka either lie at these elevations (implying no uplift) or below them (implying subsidence), despite independent evidence that long-term uplift has been in progress at many of these sites. Thus, for the present calculations, the paleo-sea level for MIS 5e on tectonically stable Isla de Guadalupe, Baja California (Fig. 22a) was chosen. The island is appropriate

for such considerations 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). Lindberg et al. (1980) reported that emergent marine deposits on Isla de Guadalupe have elevations of 1–8 m above sea level, with most localities described as 1–6 m above sea level. Muhs et al. (2002) dated corals from these deposits to ~120 ka, or MIS 5e. Thus, for uplift rate calculations, a paleo-sea level of +6 m at ~120 ka is assumed for this part of offshore North America.

Results indicate that late Quaternary uplift rates around Santa Rosa Island are variable. Using the shoreline angle elevations of the 2nd terrace (~20–21 m) at Johnsons Lee gives rates of ~0.12–0.13 m/ka. In the southern part of Bechers Bay, but north of the Santa Rosa Island fault (at Water Canyon and Torrey Pines; see Muhs et al., 2014a) shoreline angle elevations are ~20 m, which yields a rate similar to those of Johnsons Lee. However, farther north, the shoreline angle of the Carington terrace is only ~16 m, giving an uplift rate of 0.08 m/ka. Continuing west from there to Cañada Garañon, where the shoreline angle elevation is ~24 m, a higher uplift rate of 0.15 m/ka is implied for

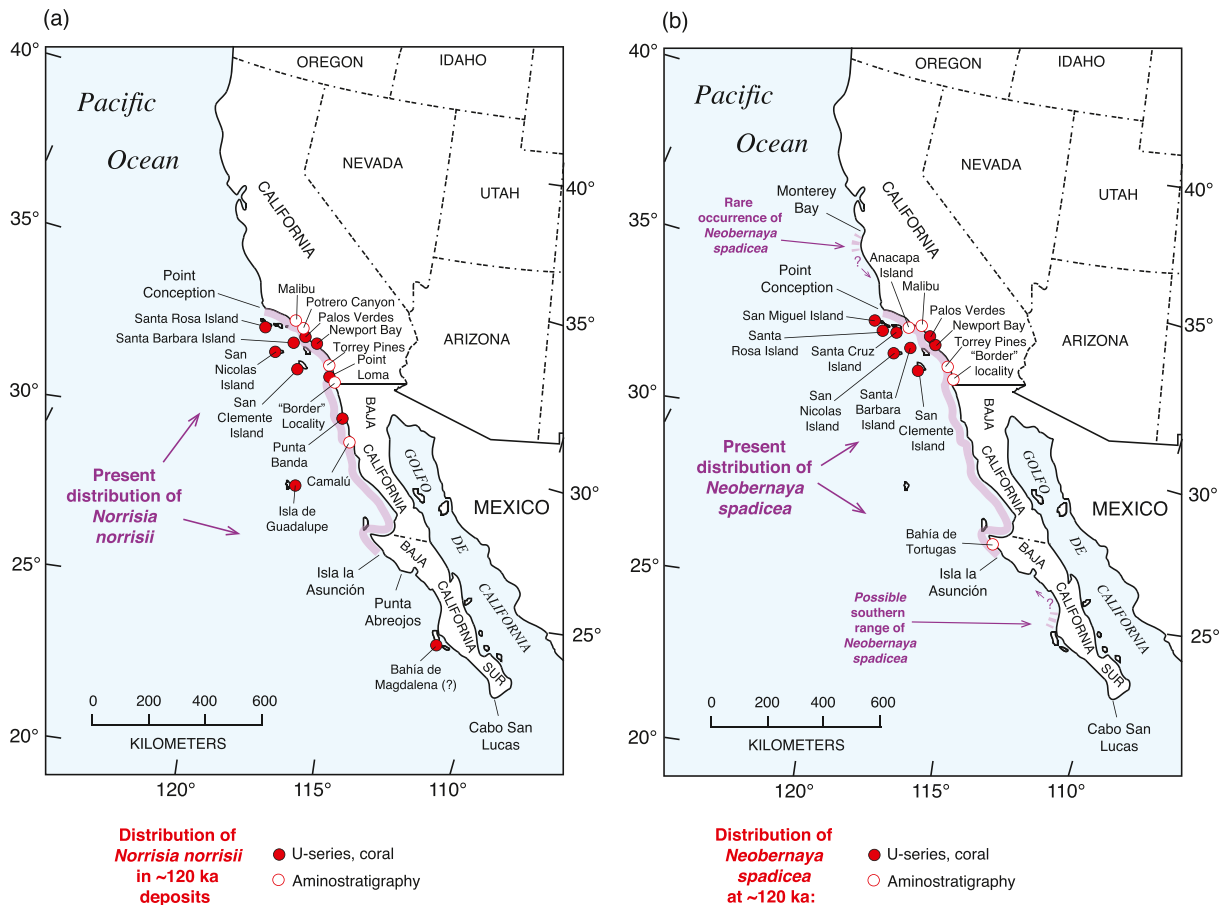


Fig. 22. Maps of California and Baja California showing the modern northern limits of two warm-water taxa, *Norrisia norrisii* (a) and *Neobernaya spadicea* (b), found in deposits of the 2nd terrace on Santa Rosa Island and other localities dated to the ~120 ka high-sea stand. Modern distributions of these taxa are from McLean (1978) and LACM collections. Terrace faunas of last-interglacial age that contain these taxa are from sources as follows: (1) San Miguel Island: faunal and age data from Muhs et al. (2014a) and the present study; (2) Santa Rosa Island: faunal and age data from this study; (3) Anacapa Island: faunal and age data from Muhs and Groves (2018); (4) Santa Cruz Island: faunal and age data from Muhs et al. (2018) and Muhs and Groves (2018), age data from Muhs et al. (2021); (5) Santa Barbara Island: faunal data from Lipps et al. (1968) and Muhs and Groves (2018), age data from Muhs et al. (2021); (6) Malibu, faunal data from Addicott (1964), age data from Kennedy et al. (1982); (7) Potrero Canyon: faunal data from Valentine (1956; from collection at LACMIP locality 23,225), age data from Kennedy et al. (1982); (8) Palos Verdes Hills: faunal data from Muhs et al. (2006) and Woodring et al. (1946, p. 72), age data from Muhs et al. (2006); (9) Newport Bay: faunal data from Kanakoff and Emerson (1959), age data from Grant et al. (1999); (10) San Nicolas Island, age and faunal data from Muhs et al. (2012); (11) San Clemente Island: faunal data from Muhs et al. (2014b), age data from Muhs et al. (2002); (12) Point Loma: faunal data from Valentine and Meade (1961), age data from Muhs et al. (2002); (13) Torrey Pines: faunal data from Valentine (1960), age data from Kennedy et al. (1982); (14) Border locality, faunal data from Emerson and Addicott (1953), age data from Kennedy et al. (1982); (15) Punta Banda: faunal data from LACMIP collections (LACMIP localities 8222 and 8220) of Rockwell et al. (1989), age data from Muhs et al. (2002); (16) Camalu: faunal data from Valentine (1980), age data from Keenan et al. (1987); (17) Isla de Guadalupe: faunal data from Lindberg et al. (1980), age data from Muhs et al. (2002); (18) Bahía de Tortugas: faunal data from Emerson (1980), age data from Emerson et al. (1981); (19) Bahía de Magdalena: faunal data from Jordan (1936), age data from Omura et al. (1979).

the north side of the island. Some of the apparent slight differences in uplift rates could be real, but also could be due simply to small variations in the shoreline angle elevations that available exposures permit. In any case, however, both the long-term (early Quaternary) and shorter-term (late Quaternary) uplift rates are consistent with one another and indicate a relatively low rate of uplift compared to other localities on the Pacific Coast of North America (see compilation in Muhs et al., 2014a).

4.4. Paleozoogeography of marine terrace fossils dating to the last interglacial complex

4.4.1. Santa Rosa Island during MIS 5e (~120 ka) and/or MIS 5c (~100 ka)

If the interpretation of the U-series and amino acid data given above are correct, the 2nd terrace and the Carrington terrace on Santa Rosa Island date to the peak of the LIG period, ~120 ka, equivalent to MIS 5e, and the 1st terrace dates to ~80 ka, or MIS 5a. Early generalizations

about these time periods on the Pacific Coast implied that marine terraces dating to MIS 5e typically had a warm-water fauna, characterized by a number of extralimital southern and southward-ranging species (e.g., Kennedy et al., 1982, 1992). In contrast, marine terraces dating to MIS 5a were reported to have substantial numbers of extralimital northern and northward-ranging species, reflective of cooler waters. When deep-sea core records extending into MIS 5e became available, both planktonic foraminiferal records (e.g., Kennett and Venz, 1995) and alkenone records (e.g., Herbert et al., 2001) supported the interpretation that during MIS 5e, ocean waters off the Pacific Coast were warmer than present.

Some of the paleontological data reported here support the view that SST around Santa Rosa Island was warmer during MIS 5e. From localities on the 2nd terrace at Johnsons Lee and Cañada Garañon, as well as at Coati Point on the Carrington terrace, at least seven gastropods (*Borsonella bartschi*, *Neobernaya spadicea*, *Norrisia norrisii*, *Ophiodemella inermis*, *Siphonaria brannani*, *Tegula gallina*, and *Thylacodes squamigerus*)

are all species with warm-water affinities. Five of these taxa, *Neobornaya spadicea*, *Norrisia norrisii*, *Ophiodermella inermis*, *Tegula gallina*, and *Thylacodes squamigerus*, also have been reported from a number of other localities in southern California and México that are dated to ~120 ka (Fig. 22). In addition, *Neobornaya spadicea* and *Ophiodermella inermis* have not been reported in known or suspected MIS 5e marine terrace fossil assemblages north of Point Conception. Thus, their occurrences on Santa Rosa Island and San Miguel Island (Muhs et al., 2014a) are the northernmost localities for these taxa in late Quaternary fossil assemblages of which the authors are aware. Finally, it is worth noting that *Neobornaya spadicea*, *Norrisia norrisii*, and *Ophiodermella inermis* have not been reported from any confidently dated ~80 ka marine terrace deposits in California or northern Baja California. The favored interpretation presented here is that the southward-ranging taxa found in

deposits of the 2nd terrace likely date to the ~120 ka high-sea stand, consistent with warmer-than-present waters implied by the planktonic foraminiferal (Kennett and Venz, 1995) and alkenone (Herbert et al., 2001) records in ODP core 893, in the Santa Barbara Channel just north of Santa Rosa Island (Fig. 1).

On the other hand, deposits of the 2nd terrace on Santa Rosa Island also contain cool-water species, and the number of these taxa actually exceeds the number of warm-water forms (Fig. 18). One of these, *Styliidium eschrichtii*, an extralimital northern species, has a modern southernmost range endpoint that is ~135 km north of Santa Rosa Island. It has been reported from ~120 ka deposits at Cayucos, California, near its modern southern range endpoint (Fig. 23a). However, the presence of this species on Santa Rosa Island, at both Cañada Garañon and in deposits of the Carrington terrace, is mirrored by reports of its presence in

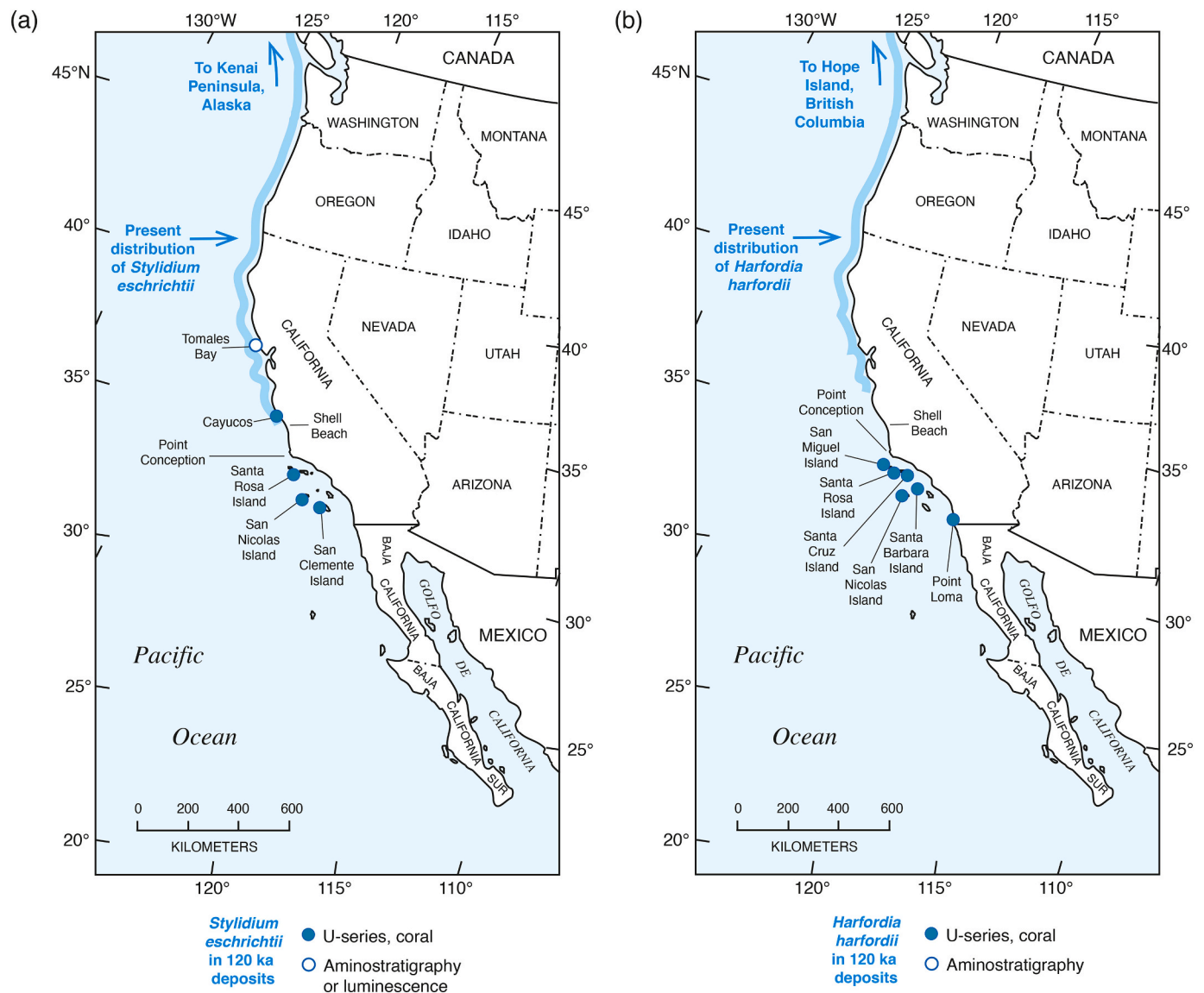


Fig. 23. Maps of the Pacific Coast of North America, showing the modern distribution of (a) *Styliidium eschrichtii* and (b) *Harfordia harfordii* (blue lines on both maps) and their occurrence in fossil form in deposits dating to the ~120 ka high-sea stand. Sources of faunal and age data for *S. eschrichtii*: (1) Tomales Bay: faunal data from Johnson (1962), age data from Muhs and Groves (2018); (2) Cayucos, faunal data from Valentine (1958), age data from Muhs et al. (2002); (3) Santa Rosa Island: faunal and age data from the present study; (4) San Nicolas Island: age and faunal data from Muhs et al. (2012); (5) San Clemente Island: faunal data from Lipps (1966) and Muhs et al. (2014b), age data from Muhs et al. (2002). Sources of faunal and age data for *H. harfordii*: (1) San Miguel Island: faunal and age data from Muhs et al. (2014a) and the present study; (2) Santa Rosa Island: faunal and age data from the present study; (3) Santa Cruz Island: faunal and age data from Muhs et al. (2021); (4) Santa Barbara Island: faunal data from Muhs and Groves (2018), age data from Muhs et al. (2021); (5) San Nicolas Island: faunal and age data from Muhs et al. (2012); (6) Point Loma: faunal data from Valentine and Meade (1961), age data from Muhs et al. (2002). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

marine terraces dated to ~120 ka on San Nicolas Island (Muhs et al., 2012) and San Clemente Island (Lipps, 1966; Muhs et al., 2014b), even farther south (Fig. 23a). A similar situation exists with regard to the extralimital species *Harfordia harfordii*, whose modern southern range endpoint is even farther north, in Monterey County (Fig. 23b). However, as with *Stylidium eschrichtii*, other southern California marine terrace deposits dated to MIS 5e host fossil *H. harfordii*, including San Miguel Island, Santa Cruz Island, Santa Barbara Island, and Point Loma. In addition, other cool-water taxa are found in deposits of the 2nd terrace and Carrington terrace, including the northward-ranging *Crepidula adunca*, *Haliotis rufescens*, *Paciocinebrina lurida*, *Tegula brunnea*, *Tegula montereyi*, and *Cryptochiton stelleri* (Fig. 18).

The mix of warm-water and cool-water species found in deposits of the 2nd terrace and Carrington terrace, described above, is a classic example of a thermally anomalous fauna. As outlined in the introduction, there are a number of possible explanations, many of them not mutually exclusive. Here, three combinations of these explanations are offered to explain the thermally anomalous fauna on Santa Rosa Island.

The first explanation is a combination of hypothesis (1), latitudinal changes in water temperatures over the Pleistocene, and hypothesis (2), reworking of older fossils into deposits with younger fossils. In recent years, there has been an increasing appreciation of the importance of GIA processes on many coastlines, including California. Modeling results by Muhs et al. (2012), Simms et al. (2016), and Creveling et al. (2017) indicate that relative sea level in southern California during MIS 5c (~100 ka) could have been close to present or even above present sea level. This scenario contrasts to that of far-field (with respect to GIA processes) localities such as Barbados and New Guinea, where relative sea level during MIS 5c was likely as much as 15 m to 20 m below present (Bender et al., 1979; Chappell et al., 1996).

If the modeling of a higher-than-present MIS 5c sea level on the California coast is correct, it has important implications for the history of emergent marine terraces. With such a sea level history on a coastline with a low uplift rate, too little emergence would have occurred in the ~10,000–20,000 yr between the peak of the MIS 5e sea level and the peak of the MIS 5c sea level. For example, with an uplift rate of ~0.12 m/ka, only ~2–3 m of uplift would have occurred between ~120 ka and ~100 ka. With such slow uplift, a higher-than-present sea level at ~100 ka (MIS 5c) could easily have overtaken at least the outer parts of an emergent ~120 ka (MIS 5e) terrace, mixing shells of ~100 ka age with those of ~120 ka before sea level dropped again during MIS 5b. In support of this model, marine terrace deposits containing corals dating to both ~100 ka and ~120 ka, and hosting both cool-water and warm-water faunas, have been documented at Cayucos, Point Loma, and San Nicolas Island, California (Muhs et al., 2002, 2012).

This explanation has several points in its favor for explaining the 2nd and Carrington terrace faunas on Santa Rosa Island, with their mixes of cool-water and warm-water species. Although he based his analysis on a broad global model, Melnick (2016) estimated that coastlines with uplift rates lower than 0.2 m/ka likely have experienced terrace reoccupation in the Quaternary. Assuming that the shoreline angles of the 2nd terrace and Carrington terrace reported here represent the high-sea stand at ~120 ka, low rates of uplift are implied, as described above, ranging from ~0.15 m/ka at Cañada Garañon, to ~0.12 m/ka at Johnsons Lee, and ~0.08 m/ka around Carrington Point, which fits Melnick's (2016) proposition. Although these rates of uplift are higher than those for the Cayucos area noted above, they are comparable to the rate at Point Loma, and are lower than the rates computed for San Nicolas Island, where mixes of ~100 ka and ~120 ka corals are confirmed.

The faunal record itself, beyond its mix of cool-water and warm-water forms, is also indicative of possible mixing of fossils with different ages. Earlier, it was noted that at Johnsons Lee, the 2nd terrace has, for both the modal gastropod species (*Callianax buplicata*) and the modal bivalve species (*Epilucina californica*) suites of both (a) broken and abraded shells and (b) well-preserved shells that display a growth series (Fig. 17). Boucot (1953), referring to fossil faunas in a given deposit,

proposed the terms “life assemblage” and “death assemblage” to distinguish between fossil assemblages that originate from different processes. A “life assemblage,” in his view, consists of fossils that originally constituted a community of organisms that lived together. A “death assemblage,” on the other hand, consists of fossils that, when living, never constituted a community, but were brought together by physical processes after death. Craig and Hallam (1963), modifying Boucot's (1953) scheme, considered that life assemblages would consist of those fossil faunas that are in situ, whereas death assemblages are faunas that have been transported. That modification, in turn, led them to propose three classes of death assemblages: (a) *indigenous*, meaning they have been transported (“derived” in their terminology), but in essentially the same environment as the original living community; (b) *exotic*, meaning fossils derived from different environments, but were contemporaneous; and (c) *remanié* (in English, “reworked”), meaning fossils derived from older deposits.

Unlike emergent Quaternary coral reef terraces in the tropics (see Muhs and Simmons, 2017 for examples), fossil faunas that would qualify as life assemblages are very rare in California marine terrace deposits. One example is rock-boring mollusks, such as *Penitella penita*, still in an articulated state and still found in the holes they bored in a marine platform (see Muhs, 2022, Fig. 6d). In most places, fossils have been transported at least some distance. Thus, in the terminology of Craig and Hallam (1963), most California marine terrace deposit fossils are part of death assemblages. Squires (1981) suggested three criteria that can be used in ascertaining whether a fossil death assemblage fauna is indigenous (as compared to exotic or reworked): (1) articulated valves (in the case of the bivalves), (2) preservation of delicate morphologic features, and (3) a nearly complete growth series (juveniles to adults). Both exotic death assemblages and reworked death assemblages would be less likely to have any of these characteristics. On Santa Rosa Island, fossil assemblages of the 2nd and Carrington terraces do not host taxa that are found in sandy, quiet-water environments; all localities studied here are characterized by fossil species that are typical of high-energy, rocky shores. Thus, an “exotic” death assemblage is ruled out for these faunas. However, as shown for the dominant species of the 2nd terrace at Johnsons Lee (LACMIP loc. 42936), there is both a growth series with well-preserved shells and suites of broken and/or abraded shells (Fig. 17). From this, it could be inferred that the growth series shells might represent an indigenous assemblage (perhaps ~100 ka, MIS 5c) and the broken/abraded shells represent a reworked assemblage (perhaps ~120 ka, MIS 5e). Although these are persuasive lines of evidence for terrace reoccupation, arguing against this interpretation is the lack of U-series ages of corals that could represent MIS 5c, and a lack of mollusks with amino acid ratios that could represent MIS 5c. A more definitive test could be made by U-series analyses of a larger number of corals and amino acid analyses of a larger number of mollusks to see if two ages of populations emerge.

Another interpretation of the thermally anomalous faunas on Santa Rosa Island is that they all represent fossils of the same MIS 5e age, but that there was SST variability over the time period when this high stand took place. On the Canary Islands of Spain, Muhs et al. (2014c) showed that marine deposits dated to MIS 5e contained both extralimital southern (tropical, Senegalese) species and extralimital northern (Mediterranean) species. These islands are tectonically stable and, based on GIA modeling, do not appear to have had substantial departures from a purely eustatic sea level history during MIS 5e (Creveling et al., 2015). Thus, Muhs et al. (2014c) interpreted the mix of contrasting extralimital species to be the result of an early, insolation-forced warming during MIS 5e, with northward migration of the intertropical convergence zone (ITCZ), weakened trade winds and diminished upwelling, followed by a later, cooler period with reduced insolation, southward migration of the ITCZ, reestablished trade winds and enhanced upwelling, all still broadly within MIS 5e. A similar scenario may also explain a contrasting mix of southern and northern extralimital fossil species for MIS 11 deposits on the Canary Islands. Alkenone SST data, taken from a marine

core raised near the Canary Islands that includes both the MIS 5e and MIS 11 interglacial periods, are consistent with such an interpretation. Here, the same kind of interpretation for Santa Rosa Island is explored. June insolation at 30°N was at a maximum at ~127 ka and the benthic foraminiferal oxygen isotope record from Santa Barbara Basin (Kennett, 1995) shows compositions shifted rapidly from high values of MIS 6 to interglacial (lower) values between ~127 ka and ~126 ka. These values remained low until ~118 ka, when heavier oxygen isotope compositions are apparent in the core, reaching their highest values at ~115 ka, interpreted to be a part of MIS 5d by Kennett (1995) and Kennett and Venz (1995). Between ~118 ka and ~115 ka is also the time period when Kennett and Venz (1995) report the biggest drop in the abundance of the warm-water planktonic foraminiferal species *Neogloboquadrina incompta* (Cifelli, 1961), as well as four other warm-water foraminiferal species, coinciding closely with the oxygen isotope record. Assuming that the age estimates for this core are correct, then the youngest, and least-biased ages for the 2nd terrace on San Miguel Island and the Carington terrace on Santa Rosa Island, ranging from ~118 ka to ~110 ka, could conceivably have been deposited during the very last part of MIS 5e or even the beginning of MIS 5d. If so, then the cool-water, northern forms could represent not the peak of the MIS 5e interglacial, but its

waning stages, analogous to the record from the Canary Islands.

A third possibility for explaining the thermally anomalous faunas on Santa Rosa Island is SST variability within the LIG period, essentially hypothesis (8) in the introduction section, proposed by Zinsmeister (1974). An early observation made by Cockerell (1939b, 1940) was that the northern Channel Islands, including both Santa Rosa Island and San Miguel Island, are very close to what is now recognized as the major faunal boundary between the Oregonian and Californian provinces, Point Conception (Fig. 1a). North of Point Conception, the coast is dominated by the cold California Current (and its associated upwelling) and south of it, the coast is dominated by the warm Inshore Counter-current (Fig. 1b). Cockerell (1939b, 1940) drew parallels between the Channel Islands and Islas Galápagos, which are in a similar position with respect to contrasting ocean currents, namely the cold, northward-flowing Peru (Humboldt) Current against the warm, southward-flowing Panama Current and warm, eastward-flowing Cromwell Current. Cockerell (1940) pointed out that because of exposure to both currents, the marine invertebrate communities of the Channel Islands should have a greater diversity than would be expected in regions well to the north or well to the south. Muhs (2018) tested this hypothesis by plotting the latitudinal range of all modern species of mollusks found on

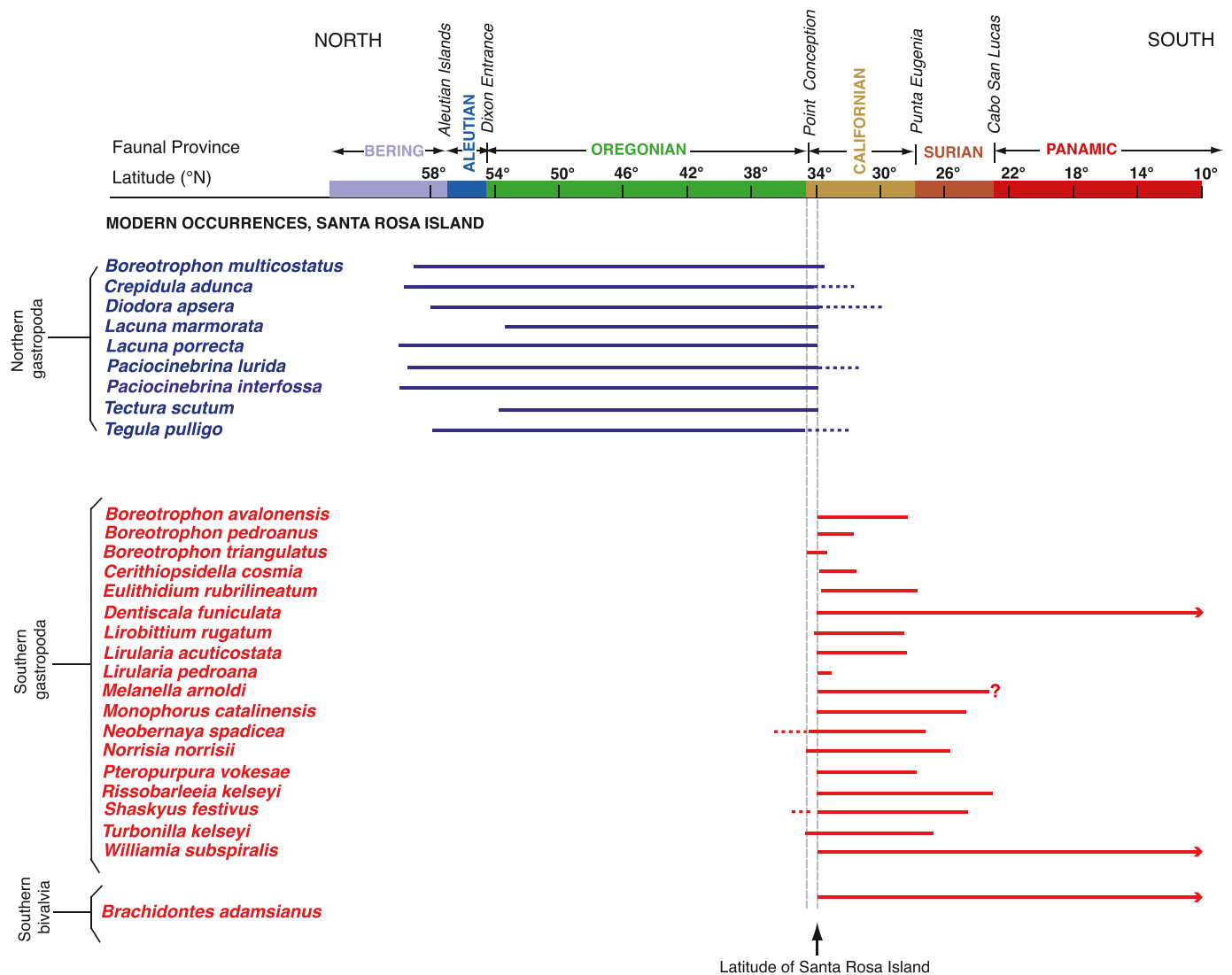


Fig. 24. North-south latitudinal plot, with latitudes in degrees north and marine invertebrate faunal zones (Valentine, 1966; see Fig. 1a) on horizontal axis at top. Below are modern latitudinal ranges of marine invertebrate species living around Santa Rosa Island at present, whose modern range endpoints lie close to Santa Rosa Island (shown by vertical line; additional vertical line marks Point Conception, a major faunal boundary). Faunal data are from Seapy and Littler (1993) and collections in the Department of Malacology, Natural History Museum of Los Angeles County; latitudinal ranges plotted by the authors from references given in the text.

San Nicolas Island that have range endpoints near that island. Results indicate that the modern marine molluscan community of San Nicolas Island hosts 16 northward-ranging species and 18 species of southward-ranging species, approximately equal numbers of cool-water and warm-water forms, supporting Cockerell's hypothesis.

For Santa Rosa Island, it is possible to conduct a test of the Cockerell hypothesis using the same biogeographic approach. For this effort, all modern Santa Rosa Island molluscan species reported by Seapy and Littler (1993) and all verified species housed in the Department of Malacology, Natural History Museum of Los Angeles County were inventoried. Results indicate that, as is the case with San Nicolas Island, Santa Rosa Island does indeed host a substantial number of both northward-ranging and southward-ranging taxa (Fig. 24). There are at least 9 northward-ranging species of mollusks and at least 19 southward-ranging species. This simple exercise demonstrates that both Santa Rosa Island and San Nicolas Island (and presumably San Miguel Island) are situated in a sensitive position with regard to both the cold California Current, with its attendant upwelling, and the warm Inshore Counter-current. The modern marine invertebrate fauna of Santa Rosa Island includes both taxa that range mostly within the Oregonian Province and others that range mostly within the Californian Province. A clear implication of this, therefore, is that the apparently "thermally anomalous" mix of cool-water and warm-water fossil species found in the 2nd terrace and the Carrington terrace of Santa Rosa Island could simply reflect conditions during MIS 5e that are little different from those of today, with cold waters dominant at some times and warmer waters dominant at other times. In support of this interpretation, it is worth noting that of the species from these terraces plotted in Figs. 18, all but the two extralimital taxa (*Harfordia harfordii* and *Stylidium eschrichtii*) have north or south range endpoints that are located at or very near to Santa Rosa Island.

During the present interglacial period, there is substantial year-to-year variability in SST in Santa Barbara Basin and, by geographic proximity, this is also likely for the waters around Santa Rosa Island. Based on the historic (1955–2012 CE) records for the eastern Pacific Ocean from NOAA (Seidov et al., 2017), the mean annual SST around the northern Channel Islands, including Santa Rosa Island, is $\sim 15^\circ\text{C}$ (Fig. 1a). North of Point Conception, in the Oregonian Province, SSTs for the same time period range from $\sim 14^\circ\text{C}$ at the southern end of the province to $\sim 9.5^\circ\text{C}$ at the northern end, near Dixon Entrance (Fig. 1a). From Point Conception south, in the Californian Province, SSTs range from $\sim 15^\circ\text{C}$ at the northern end to $\sim 18.5^\circ\text{C}$ at the southern end, at Punta Eugenia. Historic records and those constructed from alkenones in Santa Barbara Basin, reported by Kennedy and Brassell (1992), show that over the 20th century, there is considerable variability in SST, ranging over $\sim 2.5^\circ\text{C}$. Warmer SSTs correspond to El Niño years, whereas cooler SSTs presumably correspond to times when the California Current was dominant, with its associated upwelling. A longer SST record for Santa Barbara Basin was constructed by Zhao et al. (2000), who used alkenones over the period from 1440 CE to 1940. Their reconstruction shows that the coldest period (1899–1908 CE) had an average SST of $\sim 14.7^\circ\text{C}$, whereas the warmest period (1651–1660 CE) had an average SST of $\sim 16.3^\circ\text{C}$. From alkenone records in sediments raised from ODP hole 1017 (Fig. 1), off Point Conception, Seki et al. (2002) have documented Holocene SSTs ranging from $\sim 13.7^\circ\text{C}$ to $\sim 15.7^\circ\text{C}$. Thus, with SSTs oscillating between those characteristic of the southernmost Oregonian Province and those characteristic of the northernmost Californian Province, it is not surprising that the modern molluscan faunas of the northern Channel Islands and San Nicolas Island host a number of northward-ranging and southward-ranging species, and could have done so in the past as well.

4.4.2. Santa Rosa Island during MIS 5a ($\sim 80\text{ ka}$)

Previous studies of $\sim 80\text{ ka}$ marine terrace deposits elsewhere on the Pacific Coast, from southern Oregon to northern Baja California (Rockwell et al., 1989; Kennedy et al., 1982, 1992; Muhs et al., 2006)

show evidence of cooler-than-present ocean waters, with numerous extralimital northern or northward-ranging marine invertebrate species. In deposits dating to $\sim 80\text{ ka}$ on Santa Rosa Island, there are two extralimital northern species, the aforementioned *Stylidium eschrichtii* and *Harfordia harfordii*. *Stylidium eschrichtii* has been reported in a number of marine terraces either dated to, or correlated with the $\sim 80\text{ ka}$ high-sea stand, including localities within its modern range (Addicott, 1966; Muhs et al., 2006), and some localities well south of its modern southern limit (Kennedy et al., 1992; Muhs et al., 2012). *Harfordia harfordii* has a southernmost modern range endpoint that is $\sim 330\text{ km}$ north of where it is found in fossil form on Santa Rosa Island. The 1st terrace on this island also contains, based on the study reported here, five northward-ranging species (*Crepidula adunca*, *Haliotis rufescens*, *Pseudomelasma torosa*, *Tegula montereyi*, and *Cryptochiton stelleri*), all of which range largely to the north of Santa Rosa Island today (Fig. 19). Orr (1960), in his early studies of the 1st terrace on Santa Rosa Island, reported other cool-water taxa, including the extralimital northern species *Amphissa columbiana* and *Lottia persona*, as well as the northward-ranging *Paciocinebrina lurida*, *Lottia scutum*, *Tegula brunnea*, and *Tegula pulligo*. Although these taxa could not be confirmed in collections made in the present study, these findings, if correct, are consistent with the other cool-water forms reported here. From both collections, the presence of 13 extralimital northern and northward-ranging species would imply cooler-than-present waters off Santa Rosa Island, consistent with the planktonic foraminiferal (Kennett and Venz, 1995) record from ODP site 893 in the Santa Barbara Channel, immediately to the north of Santa Rosa Island (Fig. 1).

What is more difficult to explain in deposits of the 1st terrace on Santa Rosa Island is the presence of four species typically found in warm waters (Fig. 19). These taxa (*Mitromorpha carpenteri*, *Siphonaria brannani*, *Tegula gallina*, and *Thylacodes squamigerus*) are not strictly extralimital, as all live around or near Santa Rosa Island today. However, all are southward-ranging species, so their association with the cool-water taxa described above is puzzling. What is particularly curious is that the 1st terrace on Santa Rosa Island hosts both *Tegula gallina*, at its modern northern limit, and *T. montereyi* (found in the present study) and *T. brunnea* (reported by Orr, 1960), both of which are at their modern southern limits. Unlike the $\sim 100\text{ ka}$ high-sea stand, which is modeled to be above present sea level on the California coast due to GIA processes, the $\sim 80\text{ ka}$ high-sea stand has been modeled consistently to have been below modern sea level by a few meters (Muhs et al., 2012; Simms et al., 2016; Creveling et al., 2017). Thus, reoccupation of a higher terrace with warm-water taxa does not seem likely.

Simple sea cliff retreat of the $\sim 120\text{ ka}$ 2nd terrace, during the $\sim 80\text{ ka}$ MIS 5a high-sea stand, is certainly a possible explanation for the warm-water fauna found in deposits of the 1st terrace on Santa Rosa Island. It is worth noting that on the north side of Santa Rosa Island at Cañada Garañon, fossil-bearing deposits (LACMIP locs. 42938 and 42939) are exposed at the outermost edge of the 2nd terrace (Fig. 13a). Immediately below this, the shoreline angle of the 1st terrace is also exposed. If the 2nd terrace once had a greater seaward extent than is the case at present, sea cliff retreat during MIS 5a could have undercut the outer edge of the 2nd terrace, resulting in colluvial transport of $\sim 120\text{ ka}$ fossils into deposits of the 1st terrace as it was forming.

It is also possible that the geographic position of Santa Rosa Island, close to both a northern cold current and a southern warm current, as discussed above, can also explain the presence of some warm-water forms with a fauna that would otherwise be considered to indicate cool SSTs. It is not known whether MIS 5a ($\sim 80\text{ ka}$) was a time period when the Santa Barbara Channel area might have experienced El Niño-like conditions. Although, as noted above, the Santa Barbara Basin record of planktonic foraminifera indicates SSTs cooler than present during MIS 5a, other paleoclimatic data do not. It is true that alkenone data reported by Herbert et al. (2001) indicate cooler-than-modern temperatures off northern California (ODP Hole 1020) during MIS 5a, and Seki et al. (2002) and Yamamoto et al. (2007) report the same for

alkenones derived from ODP Holes 1017 and 1016, respectively, off Point Conception (Fig. 1b). However, Herbert et al. (2001) report alkenone data for Santa Barbara Basin (ODP 893; Fig. 1) and EW03 (~72 km southwest of San Diego) that imply SSTs during MIS 5a were about the same as the Holocene. Further, alkenone data from Cortes Basin (ODP 1012; Fig. 1b) and Tanner Basin (ODP 1014) imply SSTs that are actually warmer than the Holocene during MIS 5a (Herbert et al., 2001; Yamamoto et al., 2007).

The observations made above seem to indicate that from Point Conception north, SSTs during MIS 5a were cooler than modern from both the alkenone record (Herbert et al., 2001) and the marine terrace molluscan record (Muhs et al., 2006). South of Point Conception, the alkenone record, from four cores, seems to indicate SSTs during MIS 5a that are about as warm as present (or slightly warmer), but the molluscan record from Santa Rosa Island indicates a mix of cool-water (mostly) forms with some southward-ranging forms. A question that arises from these observations is whether the Santa Rosa Island molluscan record is explained by the same, variable SST record during the MIS 5a high-sea stand as that discussed for the MIS 5e record above, due to the Santa Rosa Island's geographic position with respect to both cold and warm currents.

One way of approaching this problem is to determine if the Santa Rosa Island record is unique or if there are other MIS 5a marine terrace records from nearby that have similar mixes of warm and cool fossil mollusks. Earlier, the modern molluscan fauna of San Nicolas Island was discussed, with the observation that it contains about equal numbers of northward-ranging and southward-ranging species. Because San Nicolas

Island, like Santa Rosa Island, is bathed by both the cold California Current and the warm Inshore Countercurrent (Fig. 1b), an MIS 5a record determined for San Nicolas Island might be expected to shed some light on this issue. Apart from zoogeographically "neutral" species, Muhs et al. (2006) described only extralimital northern or northward-ranging species from a single fossil locality dated to ~80 ka from San Nicolas Island. In a later study, fossils from additional localities on the ~80 ka terrace of this island were studied and reported by Muhs et al. (2012). Here, that more extensive fauna is plotted by latitude, with updated species names and better information about distribution limits. Results indicate that while there are a number of extralimital northern or northward-ranging species (13 total), there are also 10 southward-ranging species (Fig. 25). Thus, Santa Rosa Island's MIS 5a faunal record of a mix of cool and warm fossils is not unique and this record, plus that for San Nicolas Island, may be explained by highly variable SSTs, due to the positions of these islands near currents with opposing thermal properties.

4.5. Paleozoogeography of early Pleistocene marine terrace fossils

The low rate of late Quaternary uplift for Santa Rosa Island, combined with influence from GIA processes, offers one explanation for the possibility of reworking and mixing of fossils of MIS 5e and MIS 5c age in deposits of the 2nd terrace, despite the lack of direct geochronological evidence for both ~120 ka and ~100 ka fossil ages. However, fossil reworking is highly probable for the early Pleistocene terrace on the western part of the island, based on the widely varying Sr isotope ages.

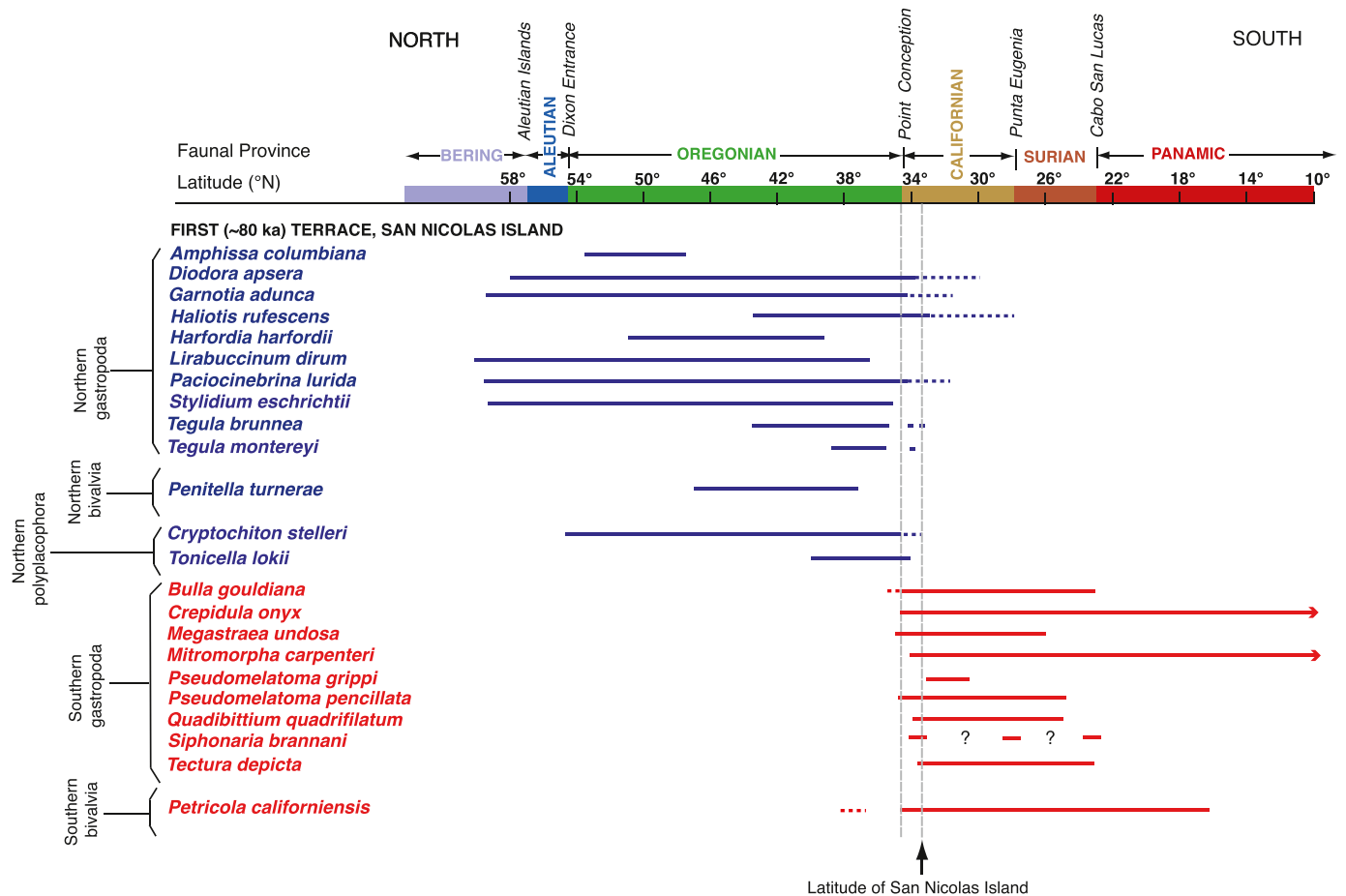


Fig. 25. North-south latitudinal plot, with latitudes in degrees north and marine invertebrate faunal zones (Valentine, 1966; see Fig. 1a) on horizontal axis at top. Below are modern latitudinal ranges of extralimital and north- and south-ranging marine invertebrate taxa found in deposits of the 1st marine terrace (~80 ka) on San Nicolas Island (shown by vertical line; additional vertical line marks Point Conception, a major faunal boundary). Faunal data are from Vedder and Norris (1963), Clark (1999) and Muhs et al. (2006, 2012); latitudinal ranges plotted by the authors from references given in the text.

Here too, it is likely that a low, early Pleistocene uplift rate played an important role in bringing about terrace reoccupation and fossil reworking. Fossil reworking from terrace reoccupation in the early Pleistocene may also explain the mixing of both quiet-water forms (e.g., *Saxidomus* and *Macoma*) with high-energy, rocky shore forms (e.g., *Mytilus* and *Epilucina*). Put into the terms of [Craig and Hallam \(1963\)](#), this is an example of an *exotic death assemblage*. At present, northwestern Santa Rosa Island has a high-energy, rocky shore environment. In the early Pleistocene, a similar environment must have existed, based on the presence of genera such as *Mytilus* and *Epilucina*. At other times, however, a quiet-water environment must have been present in order to explain the presence of *Saxidomus* and *Macoma*. Additional Sr isotope analyses of these latter two taxa might help elucidate the timing of when these very different environments were dominant during the early Pleistocene, but in any case, mixing of fossils of different ages is implied.

In addition to a low long-term uplift rate, an additional factor favoring reworking on the early Pleistocene marine terrace of Santa Rosa Island is the timing of glacial-interglacial cycles prior to the late-middle Pleistocene. From ~2.58 Ma to ~1.3 Ma, glacial-interglacial cycles were

modulated by the 41 ka obliquity cycle. Six shells from the high terrace have ages of ~2.3 Ma to ~1.4 Ma, falling within this “41 kyr world” ([Fig. 21](#)). The remaining shells have ages that fall within the mid-Pleistocene transition period, but even here, glacial-interglacial cycles are estimated to have an ~50 ka duration, much shorter than the ~100 ka cycles that followed. Thus, although the potential for fossil reworking on Santa Rosa Island probably decreased over time, with a low uplift rate, reworking was still likely at least until the end of the mid-Pleistocene transition period.

Even with fossil reworking explained by a low uplift rate and shorter glacial-interglacial cycles, there is an additional problem with the faunal composition of the early Pleistocene marine terrace deposits on Santa Rosa Island. As noted earlier, the faunas documented here ([Table 5](#)) include three extralimital northern species (*Lirabuccinum dirum*, *Styliidium eschrichtii*, and *Saxidomus gigantea*) and an additional five northward-ranging species (*Crepidula adunca*, *Cryptochiton stelleri*, *Haliothis rufescens*, *Paciocinebrina lurida*, and *Pseudomelatoma torosa*). Within these early Pleistocene deposits, there are no extralimital southern species and only a single southward-ranging species (*Thylacodes*

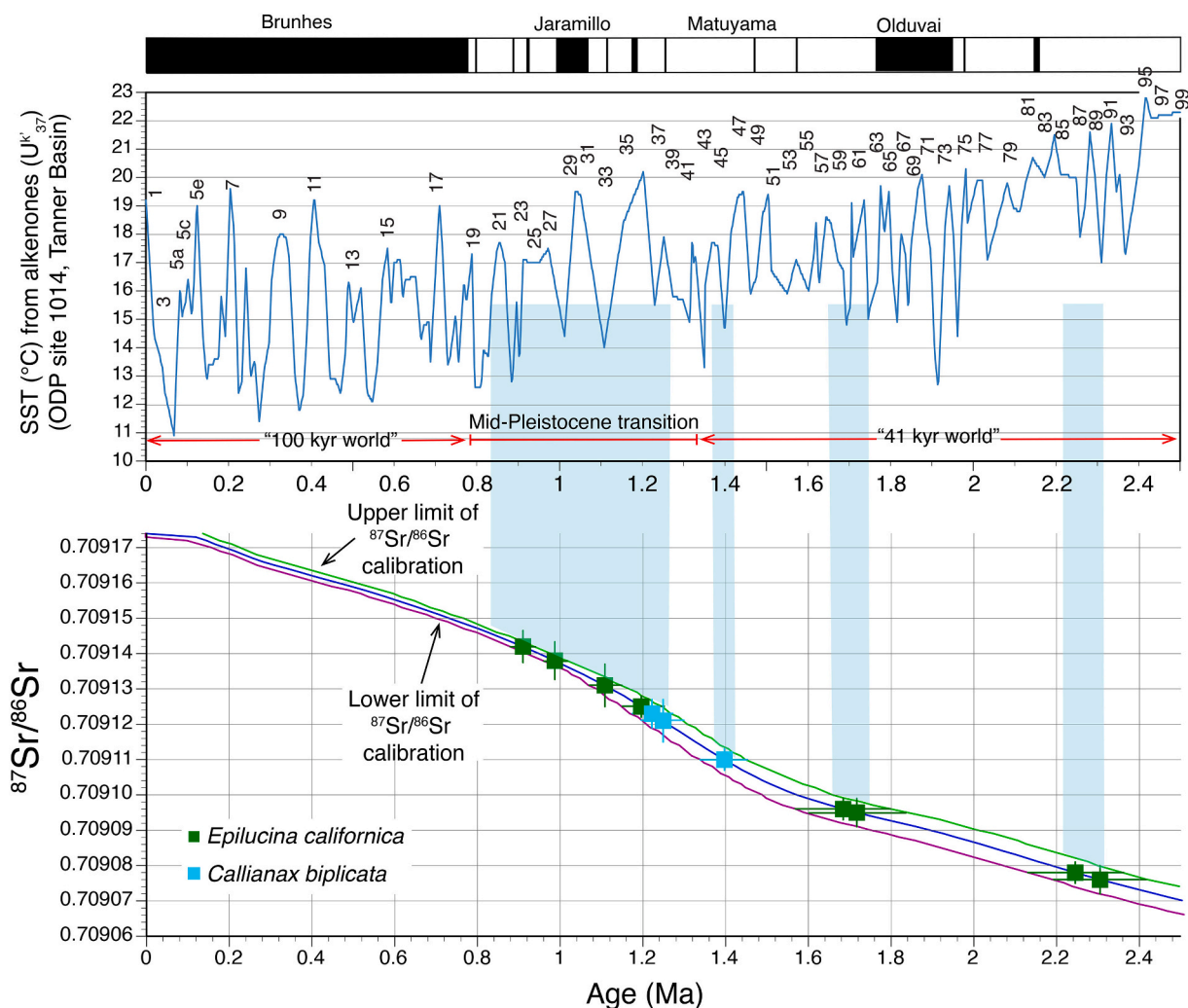


Fig. 26. Upper: sea surface temperature (SST) record derived from alkenone unsaturation index in Ocean Drilling Program (ODP) site 1014, Tanner Basin (see [Fig. 1](#) for location). Alkenone data are from [Dekens et al. \(2007\)](#), [Brierley et al. \(2009\)](#), and [Federov et al. \(2013\)](#). Odd numbers above blue line for SST plot indicate interglacial marine isotope stages (MIS). Magnetic record, shown at very top, is from [Roberts and Turner \(2013\)](#): black bands indicate normal polarity, white bands indicate reversed polarity. Time period marked for the Mid-Pleistocene Transition is from ages given in [Clark et al. \(2006\)](#). Lower: plot of the Sr isotopic composition of seawater over the past 2.5 Ma, with mean, upper, and lower age limits, from [McArthur et al. \(2020\)](#), from LOWESS version 6. Also shown are Sr isotopic compositions of *Epilucina californica* and *Callianax biplicata* fossil shells from the high-elevation marine terrace deposits on Santa Rosa Island ([Table 3](#)). Vertical bars are analytical errors; horizontal bars show range of possible ages based on uncertainties in the Sr isotope calibration curve. Light blue bands show possible correlations with oxygen isotope stages. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

squamigerus) (Fig. 19). Alkenone records that extend into the early Pleistocene are now available for two ODP sites off southern California, site 1012 in East Cortes Basin and site 1014 in Tanner Basin (Fig. 1b). The alkenone record at site 1012 goes back to just over ~4 Ma, while that in 1014 goes back to ~4.8 Ma (Dekens et al., 2007; Brierley et al., 2009; Federov et al., 2013). Although the focus of these studies was on the difference between the warmer Pliocene world and the present, cores from both basins also have excellent records of glacial-interglacial SSTs of the entire Pleistocene.

Here, the alkenone SST record from Tanner Basin is examined for the time period for the high terrace deposits on Santa Rosa Island, from ~2.4 Ma to ~0.9 Ma. Interestingly, based on the alkenone estimates, many early Pleistocene interglacial SSTs in this time interval, including those of MIS 85, 83, 81, 77, 75, 73, 63, 47, and 35, were as warm or warmer than the warmest interglacials of the later part of the Pleistocene, such as MIS 5e, 7, 9, and 11 (Fig. 26). If Pacific Ocean waters off southern California during interglacial periods of the early Pleistocene were so warm (based on the alkenone record), it raises the question of why extralimital southern species are not more abundant (and cool-water forms *are* present) in early Pleistocene marine terrace deposits of Santa Rosa Island. Understanding the causes for the very different early Pleistocene alkenone and marine terrace faunal records of Pacific Ocean SSTs is a subject worthy of further investigation.

5. Conclusions

Studies of marine terraces and their fossils on Santa Rosa Island show that the paleontological and paleogeographic records of both the late and early Pleistocene are complex. Terraces dating to both the early Pleistocene and the last interglacial complex are present around the island, but geochronological investigations do not show a simple history. Two prominent low-elevation terraces rim much of the coast of Santa Rosa Island. Corals in the lower of these two terraces give U-series ages of ~80 ka (MIS 5a), but those with evidence of closed-system history and others with evidence of open-system history give similar ages, indicating that open-system conditions may have existed for only a short, early time period after terrace emergence. Similar results are apparent for almost all the corals of the 2nd terrace, which, if they experienced a similar history, likely date to ~120 ka (MIS 5e), but the open-system histories of these corals leave open the possibility that some of them could date to ~100 ka (MIS 5c).

An interpretation of terrace reoccupation and mixing of ~120 ka and ~100 ka fossils is supported by the molluscan assemblages, which allow paleogeographic interpretations. The 2nd terrace hosts about equal numbers of northern and southern species. One interpretation of these observations is that the ~100 ka high-sea stand reoccupied the terrace that formed during the ~120 ka high-sea stand, resulting in mixing of cool-water (~100 ka) and warm-water (~120 ka) forms. Such interpretations have been made elsewhere in central and southern California. Terrace reoccupation has been ascribed to glacial isostatic adjustment (GIA) processes, under which North American coastlines experienced higher-than-expected paleo-sea levels during MIS 5c (~100 ka). Such terrace reoccupation and fossil mixing, even with GIA effects, would only be possible, however, if late Quaternary uplift rates are relatively low. Elevation measurements of the youngest terraces on Santa Rosa Island demonstrate, along with the geochronology, that the island has been experiencing slow uplift in the late Pleistocene, which supports this explanation.

Alternatively, Santa Rosa Island is situated near a major faunal boundary at Point Conception. To the north, the composition of the marine invertebrate community, within the Oregonian province, is controlled by the cold California Current, with its frequent periods of upwelling. To the south of Santa Rosa Island, within the Californian faunal province, Pacific Ocean waters are much warmer, as they are inboard of the California Current and marine invertebrate communities are controlled to a great degree by the warm Inshore Countercurrent.

Santa Rosa Island, and the nearby Santa Barbara Basin, are today variably influenced by both of these contrasting ocean currents. As a result, the modern marine invertebrate fauna of Santa Rosa Island includes species that are found mainly to the north of the island as well as species that are found mainly to the south. Thus, during both MIS 5e and MIS 5a, the thermally anomalous faunas of Santa Rosa Island might be explained, at least in part, by this sensitive geographic position.

Study of the higher-elevation terraces on Santa Rosa Island gives a longer-term perspective on the issue of terrace reoccupation and fossil mixing in areas of low uplift rate. Strontium isotope geochronology of early Pleistocene marine terrace mollusks on Santa Rosa Island shows mixes of fossil ages, spanning almost 500 kyr at one locality and possibly as much as 600 kyr at another locality. Using a variety of possible elevations and ages yields long-term uplift rates that are relatively low and consistent with the late Pleistocene uplift rates, again demonstrating the importance of uplift rates in enhancing the potential for terrace reoccupation. In addition, however, early Pleistocene glacial-interglacial cycles, linked to the ~41 ka obliquity cycle of orbital forcing, were of much shorter duration than those in the later part of the Pleistocene, a factor that would also enhance terrace reoccupation in regions of low uplift rate. An unexplained problem from examination of the fossil record of the early Pleistocene terrace deposits, however, is the dominance of cool-water (northern extralimital and northward-ranging) species, and a near-total absence of warm-water species. Records of SSTs from alkenones in deep-sea basins off southern California indicate relatively warm waters of the Pacific Ocean in most of the interglacial periods of the early Pleistocene. Understanding why these two records differ so dramatically is a subject worthy of much more investigation, with study of early Pleistocene marine terrace records elsewhere in California.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data are available at the following U.S. Geological Survey database: <https://doi.org/10.5066/P9KDKAB9>.

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