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Tectonic influences on the preservation of marine terraces: Old and new evidence from Santa Catalina Island, California

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ABSTRACT

The California Channel Islands contain some of the best geologic records of past climate and sea-level changes, recorded in uplifted, fossil-bearing marine terrace deposits. Among the eight California Channel Islands and the nearby Palos Verdes Hills, only Santa Catalina Island does not exhibit prominent emergent marine terraces, though the same terrace-forming processes that acted on the other Channel Islands must also have occurred on Santa Catalina. We re-evaluated previous researchers' field evidence and examined new topographic, bathymetric, and stream-profile data in order to find possible explanations for the lack of obvious marine terrace landforms or deposits on the island today. The most likely explanation is associated with the island's unresolved tectonic history, with evidence for both recent uplift and subsidence being offered by different researchers. Bathymetric and seismic reflection data indicate the presence of submerged terrace-like landforms from a few meters below present sea level to depths far exceeding that of the lowest glacial lowstand, suggesting that the Catalina Island block may have subsided, submerging marine terraces that would have formed in the late Quaternary. Similar submerged marine terrace landforms exist offshore of all of the other California Channel Islands, including some at anomalously great depths, but late Quaternary uplift is well documented on those islands. Therefore, such submarine features must be more thoroughly investigated and adequately explained before they can be accepted as definitive evidence of subsidence. Nevertheless, the striking similarity of the terrace-like features around Santa Catalina Island to those surrounding the other, uplifting, Channel Islands prompted us to investigate other lines of evidence of tectonic activity, such as stream profile data. Recent uplift is suggested by disequilibrium stream profiles on the western side of the island, including nickpoints and profile convexities. Rapid uplift is also indicated by the island's highly dissected, steep topography and abundant landslides. A likely cause of uplift is a restraining bend in the offshore Catalina strike-slip fault. Our analysis suggests that Santa Catalina Island has recently experienced, and may still be experiencing, relatively rapid uplift, causing intense landscape rejuvenation that removed nearly all traces of marine terraces by erosion. A similar research approach, incorporating submarine as well as subaerial geomorphic data, could be applied to many tectonically active coastlines in which a marine terrace record appears to be missing.

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1. Introduction

Generation of a eustatic sea-level curve that tracks glacial–interglacial cycles has long been a goal of Quaternary stratigraphers and paleoclimatologists. Emergent marine terraces have typically been studied as a means of reconstructing sea-level history, whether they are erosional, shore platforms on high energy coasts, or constructional, coral reef tracts on tropical coasts. Study of emergent coral reefs on tectonically stable coasts gives information only on sea levels that were higher than present. However, actively uplifting coasts can yield past sea level estimates for times when sea-level highstands were lower than present.

One unresolved issue is the magnitude of sea-level rise during relatively high sea stands that post-date the peak of the Last Interglacial complex at ~120 ka (Marine Isotope Stage, or MIS, 5.5). The first studies on the uplifting coast of Barbados (Broecker et al., 1968; Matthews, 1973) showed that the ~80 ka sea stand (MIS 5.1) was −13 to −18 m below present and the ~100 ka sea stand (MIS 5.3) was −10 to −18 m below present. Elevations and ages of uplifted reefs on other tropical islands generally support the early Barbados studies (Veeh and Chappell, 1970; Bloom et al., 1974; Chappell, 1974; Chappell and Veeh, 1978; Dodge et al., 1983). Later studies on Barbados (Potter et al., 2004; Schellmann et al., 2004; Thompson and Goldstein, 2005) indicate that sea level could have been as

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much as −18 to −20 m during the ~80 ka sea stand and perhaps −13 to −25 m during the ~100 ka sea stand. Some of these later studies also suggest that there were multiple highstands during MIS 5.1 and MIS 5.3.

Studies on other coastlines have yielded paleo-sea level estimates that differ significantly from those on Barbados. For example, Harmon et al. (1983) report coral-bearing marine deposits above modern sea level that date to ~100 ka and ~80 ka on tectonically stable Bermuda. Subsequent, higher-precision dating of these deposits by Muhs et al. (2002a) confirms the presence of marine deposits above present sea level at ~80 ka on Bermuda. On the Japanese islands of Hateruma-shima and Kikai-jima, Ota and Omura (1992) report ages and elevations of marine terraces that indicate sea levels near present at ~80 ka and ~100 ka on Hateruma-shima or well above present at these times on Kikai-jima, although reworking of corals on Hateruma-shima make paleo-sea level estimates from this island uncertain (Radtke et al., 1996). On the tectonically stable Atlantic Coastal Plain of the eastern United States, Wehmiller et al. (2004) report marine deposits dating to ~80 ka a few meters above present sea level along more than 700 km of coastline from Virginia to Georgia. Australia, although tectonically stable like the U.S. Atlantic Coastal Plain and Bermuda, exhibits good evidence of the ~120 ka high sea stand, but no evidence of sea levels above present at ~80 ka or ~100 ka along the Australian coastline (Murray-Wallace and Belperio, 1991; Stirling et al., 1995, 1998; Murray-Wallace, 2002).

On the Pacific Coast of North America, marine terraces form step-like flights that resemble the uplifted reef terraces of Barbados and New Guinea. In contrast to those islands, however, the terraces are not constructional reefs, but wave-cut erosional landforms, formed as a result of sea level fluctuations superimposed on steady tectonic uplift (Alexander, 1953; Bradley and Griggs, 1976; Lajoie et al., 1991; Muhs et al., 1994, 2004). Although Pacific Coast marine terraces are erosional landforms that develop in the high-energy surf zone, when uplifted they commonly retain a veneer of marine sand and gravel, often including fossil marine invertebrates such as mollusks and solitary corals. Solitary corals contain uranium derived from seawater, like their hermatypic colonial counterparts, and therefore can be used to date erosional marine terraces (Muhs et al., 2002b). Elevations of the terraces, when corrected for movement by vertical tectonism and glacio-isostasy, record sea-level highstands of previous interglacial periods. Conversely, when paleo-sea levels are known, the elevations of dated marine terraces can be used to determine local rates of tectonic movement, which vary widely along the west coast of North America (Lajoie, 1986).

Santa Catalina Island, located approximately 35 km southwest of Long Beach, California, is one of the eight Channel Islands off the coast of southern California (Figs. 1, 2). Among the California Channel Islands, only Santa Catalina Island does not exhibit prominent marine terraces on its landscape. Lawson (1893) noted that Santa Catalina exhibits "no trace of an elevated wave-cut terrace, sea-cliff, or strand line of any kind observable on the island". Subsequent studies have been contradictory, with some researchers offering evidence of marine terraces on Catalina (Smith, 1897, 1933; Bailey, 1941; Clements, 1948; Emery, 1960; Loop, 1973; Samaras and Gellura, 1979), while others have proposed alternative interpretations of the terrace-like landforms (Shepard et al., 1939; Davis, 1984, 2004). Submerged terraces have been identified offshore of Santa Catalina and all of the other Channel Islands (Emery, 1958, 1960; Chaytor et al., 2008).

To understand why Santa Catalina is different with regard to its marine terrace history, it is necessary to examine the geology and tectonic history of the island and attempt to identify factors that could account for its lack of marine terraces. Possible explanations include: (1) marine terraces were formed on Santa Catalina, but because the underlying lithology is easily erodible, they have since either eroded away or been obliterated by landslides; (2) the rocks underlying Santa Catalina Island are too resistant to erosion to permit cutting of

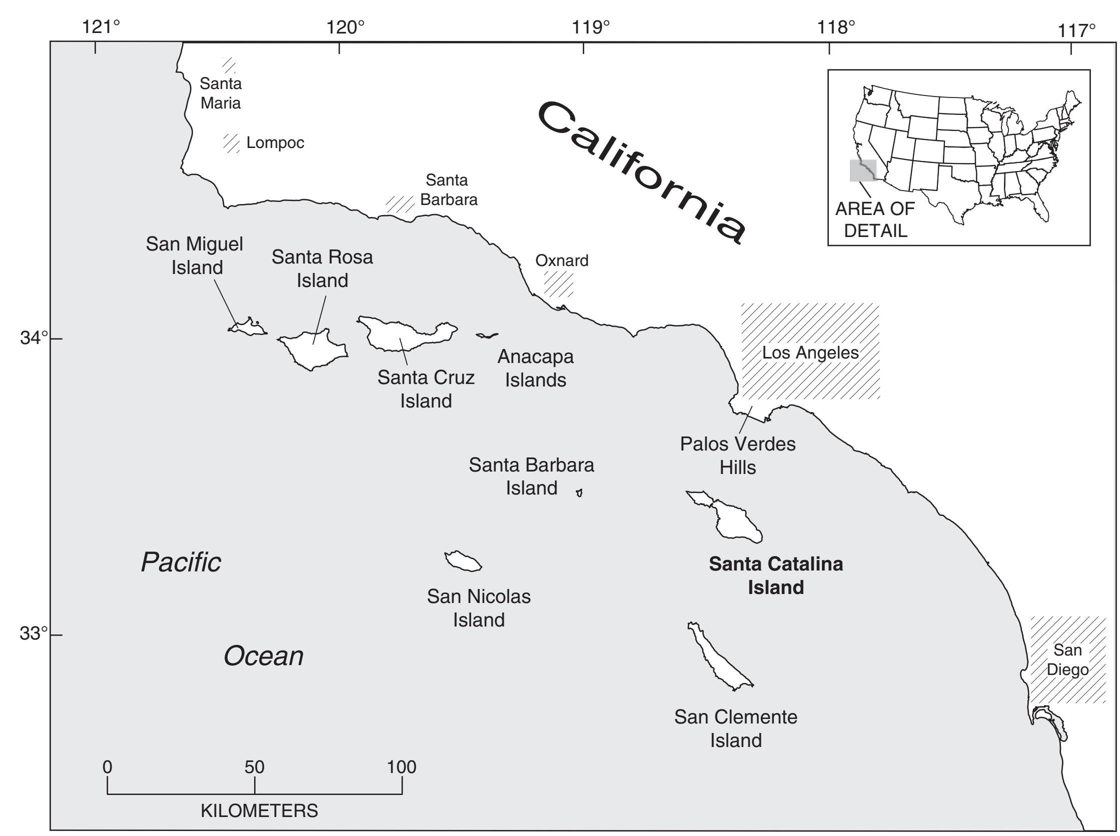

Fig. 1. Location of Santa Catalina Island relative to the southern California mainland and the other California Channel Islands.

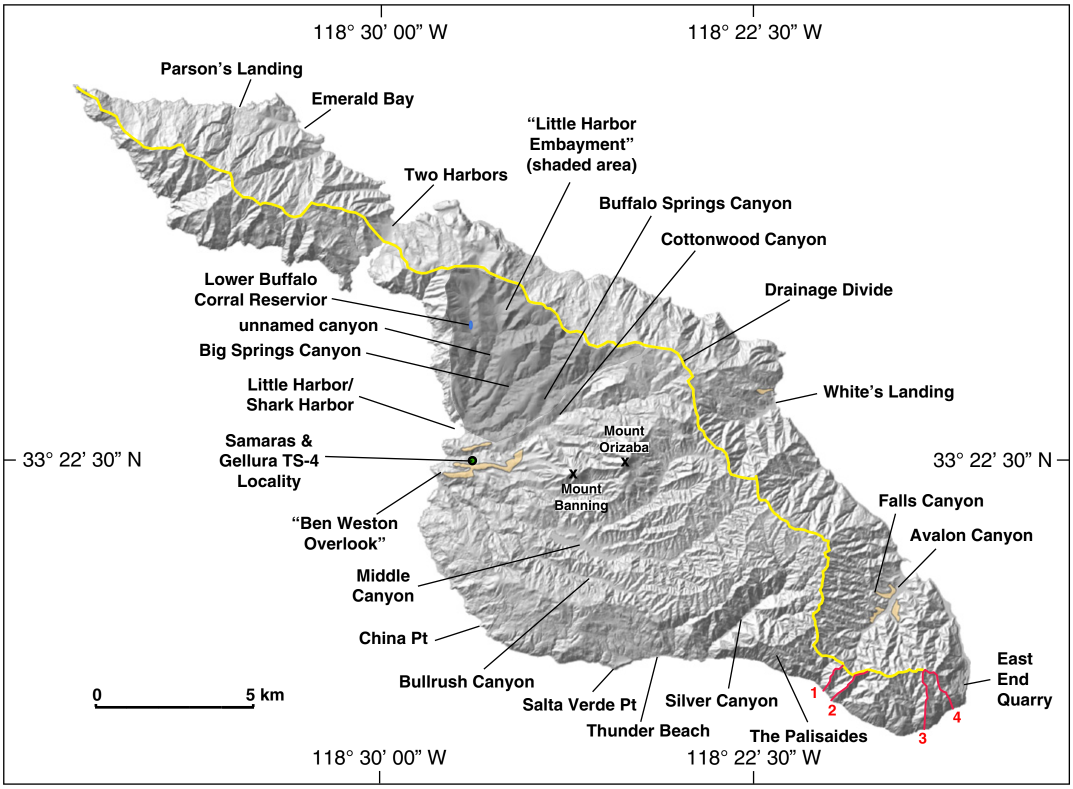

Fig. 2. Map of Santa Catalina Island showing features and locations described in the text. Shaded-relief base map derived from LiDAR digital elevation data acquired from LAR-IAC. Shaded area approximately delineates the "Little Harbor embayment" as described by Smith (1933). Tan-shaded areas were mapped as marine terrace deposits by Bailey (1941). Red lines denote locations of ridge-crest topographic profiles shown in Fig. 6. Yellow line approximately follows the main drainage divide of the island.

marine terraces; (3) Santa Catalina has undergone such rapid uplift during the Quaternary that marine terraces were not preserved, owing to erosion; or (4) Santa Catalina Island has subsided during the Quaternary and the marine terraces are now below present sea level. In this paper, we reevaluate previous researchers' field evidence and examine new topographic, bathymetric, and stream-profile data to determine which of these possible explanations for the lack of marine terrace landforms or deposits are most likely.

2. Geologic setting

The islands and submarine area offshore of southern California, called the California Continental Borderland (Shepard and Emery, 1941), consists of northwest-trending ridges and basins bounded primarily by right-lateral strike-slip faults, creating physiography resembling the Basin and Range Province (Legg, 1991; Bohannon and Geist, 1998). During the late Mesozoic to early Cenozoic, the western margin of North America was an active subduction zone (Hamilton, 1969; Platt, 1975, 1976). As the east Pacific spreading ridge approached the western edge of North America about 30 million years ago, the northern part of the intervening, partially-subducted Farallon plate began to fragment into microplates that were captured by the Pacific plate. Subduction ceased about 17–20 million years ago as the Pacific plate came into contact with the North American plate, and the Pacific plate, now coupled with fragments of the Farallon plate, began to move laterally northwestward along the plate boundary (Nicholson et al., 1994; Bohannon and Parsons, 1995). The dominant tectonic processes changed at this time from subduction to crustal extension and dextral transform faulting (Nicholson et al., 1994; Bohannon and Geist, 1998), but transpression gradually became the main tectonic mode in the Borderland region during the Quaternary (Bohannon et al., 2004). What is now the western Transverse Ranges crustal block, including the northern Channel Islands, was unable to translate northwestward because it was buttressed at one end against the North American plate, so instead it rotated clockwise about this pivot point, with crustal extension occurring in its wake (Crouch and Suppe, 1993; Nicholson et al., 1994; Bohannon and Geist, 1998). The resulting combination of crustal extension and oblique-slip (dominantly dextral strike-slip) faulting produced the northwest-trending ridges and basins of the Borderlands area (Yeats, 1976; Bohannon and Parsons, 1995; Bohannon et al., 2004). Santa Catalina Island is the emergent crest of one of these ridges formed from an uplifted block of seafloor.

The oldest rock on Santa Catalina Island is the Catalina Schist, a Cretaceous basement complex consisting of three metamorphic facies — blueschist, greenschist, and amphibolite — that underlies most of the western half of the island (Fig. 3). The lowest unit is blueschist, overlain by greenschist, with amphibolite-facies rocks forming the uppermost unit. These rocks represent oceanic trench sediments and basalts metamorphosed in mid-Cretaceous time at relatively high pressures and low to moderate temperatures during initial subduction along the plate margin (Platt, 1976). The Catalina Schist forms the basement rock of the inner part of the California Continental Borderland region (Vedder et al., 1974; Platt, 1975; Crouch and Suppe, 1993).

A small exposure of pre-middle Miocene sedimentary rocks occurs at the East End Quarry (Figs. 2, 3). This sequence consists of interbedded marine sedimentary rocks overlain by nonmarine sedimentary rocks that may correlate with the Eocene to lower Miocene Sespe Formation of the Los Angeles Basin (Vedder et al., 1979). The uppermost sedimentary unit in this location is the Miocene San Onofre Breccia. Miocene marine sedimentary rocks, volcaniclastic rocks, and the San Onofre Breccia are also exposed in the vicinity of Fisherman's Cove, near Two Harbors (Fig. 3). Notable exposures of middle Miocene fossiliferous marine sedimentary rocks are present

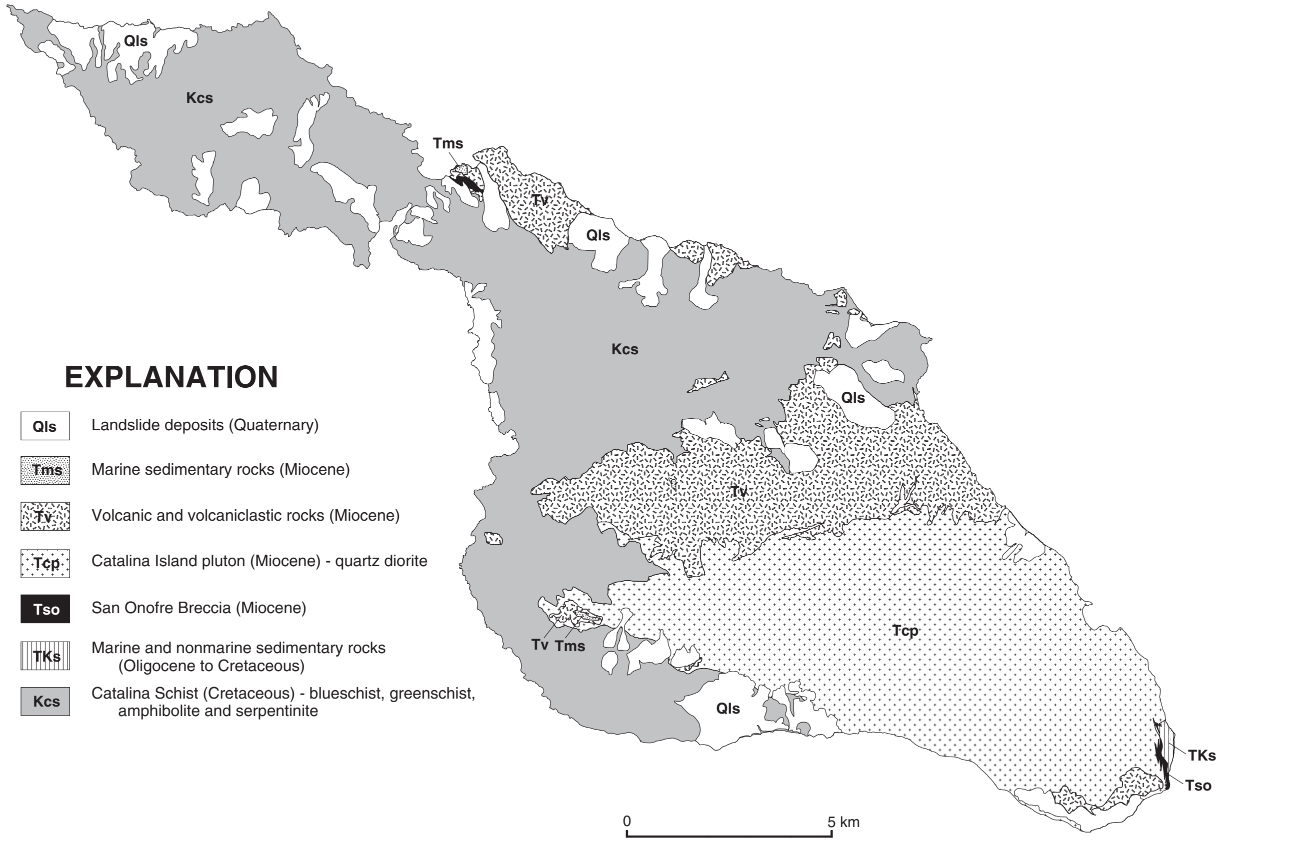

Fig. 3. Generalized geologic map of Santa Catalina Island.
Modified from Bailey (1941), Rowland (1984), and unpublished mapping by the U.S. Geological Survey (R.G. Bohannon, pers. comm., 2011).

on the slopes of Mount Banning and in Cottonwood and Middle canyons (Vedder et al., 1979).

Much of southeastern Santa Catalina Island is underlain by the Catalina Island pluton, a hornblende quartz diorite porphyry of early Miocene age that mainly intruded the Catalina Schist (Bailey, 1941; Forman, 1970). The central part of the island is underlain by volcanic rocks, primarily andesite and dacite, of middle Miocene age (Vedder et al., 1979). These rocks, remnants of a small volcanic archipelago, are also exposed along the north coast of the island between Fisherman's Cove and Empire Landing (unit Tv in Fig. 3). Quaternary deposits include alluvium in some stream valleys and colluvium on slopes (not shown in Fig. 3). Numerous landslides have formed on all types of bedrock on Santa Catalina (only the largest are shown in Fig. 3). The abundance and distribution of landslides appear to be related primarily to the prevalence of steep topography on the island, which is in turn caused by deep fluvial dissection.

3. Revisiting the evidence for marine terraces

3.1. Climatic, geologic, and physiographic considerations

With regard to the effect of climate on erosion rates, we can reasonably assume that the Quaternary climate history of Santa Catalina Island is not significantly different from that of the other Channel Islands. All of the Channel Islands currently have a Mediterranean climate. The mean annual rainfall on Santa Catalina Island is ~300 mm yr^{-1}, similar to the northern Channel Islands and the Palos Verdes Hills. The bedrock geology of Santa Catalina Island consists largely of Cretaceous through Miocene metamorphic (Catalina Schist), plutonic (quartz diorite), and volcanic (andesite, rhyolite, dacite) rocks (Smith, 1897; Bailey, 1941; Platt, 1975; Vedder et al., 1979). The Palos Verdes Hills are primarily underlain by Miocene marine sedimentary rocks, with smaller exposures of Jurassic and Cretaceous rocks of the Franciscan Complex (partly equivalent to Catalina Schist) and Miocene basalt (Woodring et al., 1946). San Clemente Island's bedrock geology is dominated by Miocene volcanic rocks, primarily andesite, dacite, and rhyolite, overlain locally by Miocene marine sedimentary rocks (Olmstead, 1958). With regard to susceptibility to erosion due to rock strength, the two islands and the Palos Verdes Hills have similar geology, but the Palos Verdes Hills and San Clemente Island have multiple, extensive, fossil-bearing marine terrace deposits and landforms (Woodring et al., 1946; Muhs et al., 2002b, 2006). Although it has a much lower uplift rate, coastal San Luis Obispo County near the town of Cayucos is underlain almost entirely by Franciscan Complex rocks, but has a well-expressed marine terrace (Muhs et al., 2002b). Santa Catalina Island is much more deeply dissected than San Clemente Island or the Palos Verdes Hills. Therefore, we conclude that erodibility of the underlying rocks is not different enough from that on nearby islands or the mainland to explain the lack of marine terrace remnants on Santa Catalina Island.

Although landslides are common and widespread on Santa Catalina, they are not so ubiquitous as to have obliterated all evidence of marine terraces, so this explanation is also inadequate to address the observed absence of marine terraces. It should be noted, however, that Santa Catalina Island exhibits considerably more, and generally, larger, landslides than any of the other Channel Islands. It is also much more deeply dissected than any of the other Channel Islands or the Palos Verdes Hills. In general, valley slopes are steeper than on the other Channel Islands, and most of the island's coastline is dominated by steep sea cliffs. Beaches are relatively few on Santa Catalina Island, primarily confined to sheltered coves, and they are notably less common on the west side of the island.

3.2. Little Harbor embayment

Smith (1897) originally identified what he considered to be two terraced areas on Santa Catalina. Describing the area east of Little Harbor (Fig. 2), he regarded the "nearly level character of the various ridges in their lower parts, their gentle seaward slope", and "the change in grade at the rear at an altitude of 600 or 700 ft" (c. 180–215 m) as topographic evidence of marine terraces. He thought that these terraces were pre-Pleistocene. More than three decades later, Smith (1933) pointed out that the amphitheater-like topography of the area resembled a drowned and later uplifted valley, which he called the "Little Harbor embayment". The ridges radiating to the north, northeast, and east from Little Harbor rise gently to an elevation of about 200 m, then rise more steeply. Whether examined in map view (Fig. 2) or perspective view (Figs. 4A, B), the topography of the area strongly resembles the dissected floor of an uplifted basin. Topographic profiles of ridge crests within the "embayment", generated from a LiDAR-based digital elevation model (DEM) obtained from the Los Angeles Region Imagery Acquisition Consortium (LAR-IAC), confirm the concordance and seaward slopes of the ridge crests (Fig. 4C). Smith (1933) reported rounded cobbles and boulders on the surfaces of the ridge crests within the "embayment". We also observed rounded pebbles and cobbles on several of the ridge surfaces, but did not find marine fossils or definitive in situ marine terrace deposits in this area. Based solely on its physiography, we conclude that this area was probably inundated by the sea in the past, prior to the late Pleistocene but during or after the Pliocene, based on the presence of Miocene and possibly Pliocene deep-water marine deposits, as discussed in the next section.

3.3. Cottonwood and Middle canyons

Smith (1933) described several exposures of marine sandstone and conglomerate deposits, particularly in the area between Cottonwood and Middle canyons (Fig. 2). Some of these deposits contain "a few indeterminate shell impressions" (Smith, 1933). Bailey (1941) also mapped inferred Quaternary marine terrace deposits along the north and south slopes of Cottonwood Canyon. We identified fossil-bearing marine deposits along the north and south slopes of Cottonwood Canyon and the north slope of Middle Canyon in outcrops along the lower 1–2 km of each canyon. On "Ben Weston Beach Overlook" ridge, which forms the north slope of Middle Canyon near its outlet (Fig. 2), a roadcut has a 10–15 m lateral exposure of calcium-carbonate-cemented, sand-matrix-supported gravel containing rounded and angular pebbles and cobbles of mixed lithologies, and marine fossils including pectens, oysters, and echinoid spines (Fig. 5A). The conglomerate, the base of which is at an elevation of approximately 143 m, is underlain by 1–2 m of calcrete and overlain by a colluvial cover of a few meters to

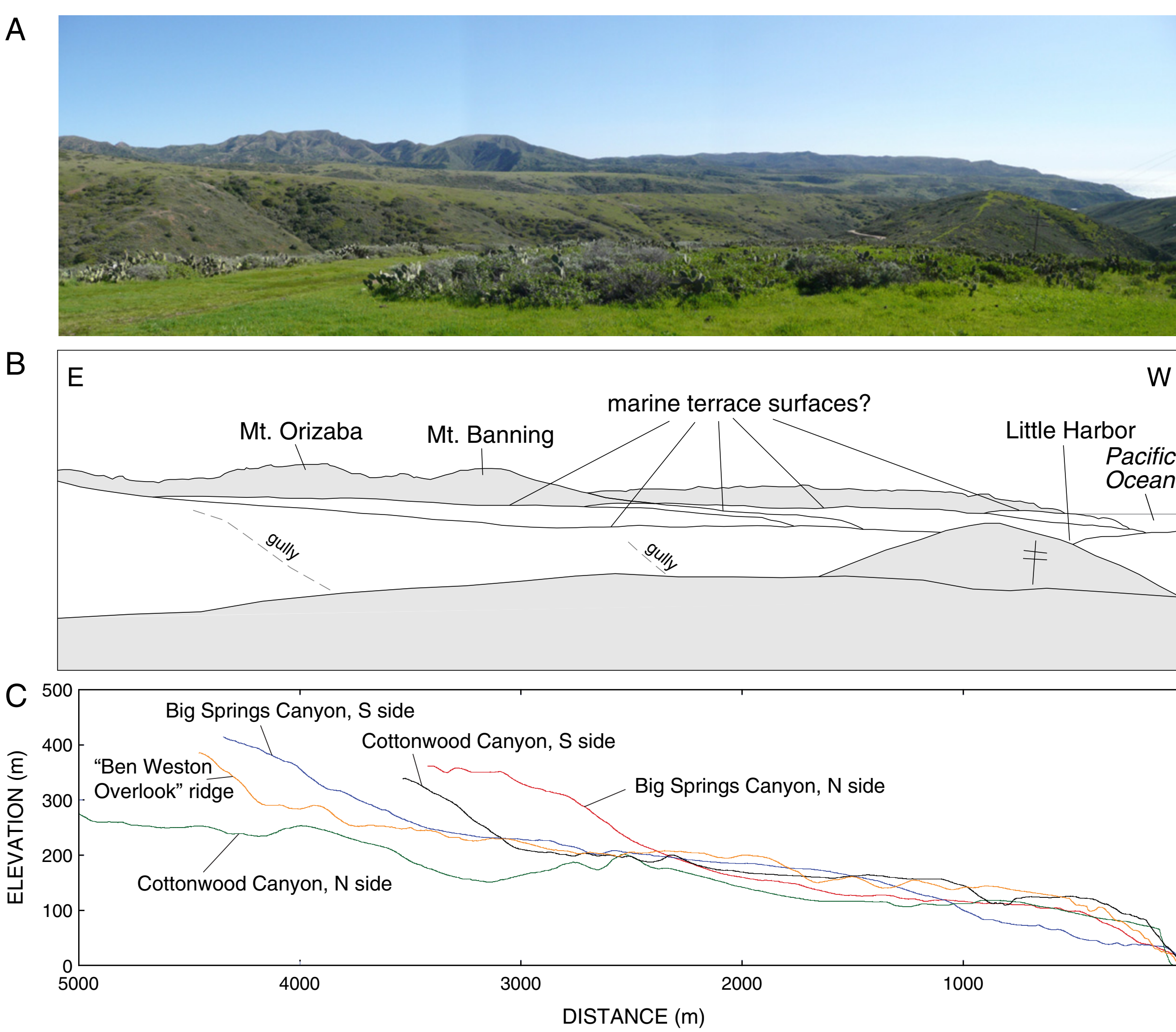

Fig. 4. (A) Panorama looking southward across the Little Harbor embayment from just below Lower Buffalo Corral Reservoir (see Fig. 2 for location). (B) Diagrammatic sketch of landscape surfaces in photo A. Compare with Smith's (1933) Fig. 4. (C) Topographic profiles of ridge crests within the "embayment", which show gentle seaward slopes and apparent concordance of surfaces up to an elevation of approximately 200 m. Vertical exaggeration approx. 2.5×.

Fig. 5. (A) Fossil-bearing gravel deposit exposed on "Ben Weston Beach Overlook" ridge. Finger and arrow indicate fossil shell fragments. (B) Fossiliferous volcaniclastic sandstone and conglomerate exposed in Cottonwood Canyon. Part of pocketknife in lower left of photo is approximately 3 cm long. (C) Wave-rounded pebble–cobble conglomerate on south slope of Cottonwood Canyon, about 30 m above roadcut shown in photo B. Pen is approximately 15 cm long. (D) Discoid cobbles from south slope of Cottonwood Canyon. (E) Rounded and angular pebbles in the deposit at Samaras and Gellura's (1979) site TS-4 (see Fig. 2 for location). Mattock head is 25 cm long. (F) Alluvial fan deposits in Avalon Canyon.

approximately 15 m thickness that includes abalone shells associated with midden deposits. Vedder et al. (1979) sampled the same deposit and assigned it a Miocene to Pliocene age based on the fossil assemblage, also concluding that it represents a mid-bathyal (500–1000 m water depth) biofacies, ruling out both a Quaternary age assignment and a marine-terrace depositional environment. Another exposure of presumably the same deposit in a roadcut on the south slope of Cottonwood Canyon, approximately 1 km northeast of the "Ben Weston Beach Overlook" location, consists of tan to dark-brown, fossiliferous, volcaniclastic sandstone and conglomerate at an elevation of approximately 150 m. This exposure contains more, but considerably smaller, fragments of pectinids and echinoid spines in a carbonate-cemented matrix (Fig. 5B). In a more thorough examination of this exposure, Vedder et al. (1979) also identified ostracode and foraminifera tests, as well as fragments of bryozoans, barnacles, and brachiopods, assigning the assemblage a mid-Miocene (Mohnian) age and inferring a sub-littoral inner shelf (<200 m water depth) depositional environment. Numerous rounded pebbles and cobbles (Fig. 5C), some highly discoid in shape (Fig. 5D) suggesting wave rounding, are found on the surface of the ridge crest approximately 30 m above the roadcut. However, no marine fossils were found associated with this gravel deposit. This leads us to conclude that the present topography of this area, which strongly resembles dissected marine terrace surfaces, is younger than, and not related to, the underlying fossiliferous marine sediments, implying that there was at least one marine incursion of the island since the end of the Miocene.

Smith (1933) also noted a fossiliferous marine deposit near the middle of the island, approximately 1.5 km southwest of Mount Orizaba (actually on the northeastern slope of Mount Banning, which was probably unnamed when Smith carried out his studies). This deposit, thought by Smith to be of Pleistocene age, was later determined by its faunal assemblage to be Miocene (Shepard et al., 1939; Bailey, 1941; Vedder et al., 1979).

Loop (1973) observed that ridges in the Little Harbor area have broad, nearly flat surfaces indicative of terraces, and described rounded pebbles and cobbles on the surface of the ridge just to the south of Little Harbor. He found similar rounded cobbles in trenches he dug into the surface of the ridge, but he did not specify the depth of the trenches so the thickness of the cobble layer is not known. The presence of rounded cobbles in the subsurface may at least partially contradict the assertions of several authors that the cobbles were brought upslope from the modern beaches and discarded by the pre-European contact Tongva (also called Gabrieliño) people (Shepard et al., 1939; Davis, 1984, 2004). Nevertheless, given the large number of identified middens on Santa Catalina (Glassow, 1980) an archeological origin likely explains at least some of the cobbles found at a number of locations.

The presence of water-rounded pebbles and cobbles on many land surfaces is one of the most disputed forms of evidence for marine terraces on Santa Catalina Island. Although some of these cobble deposits are in place, particularly those in the subsurface that are exposed in roadcuts and embankments, many are described as being strewn across the land surface, thus depriving them of stratigraphic context. Using the methodology of Dobkins and Folk (1970) whereby the maximum projection sphericities of pebbles and cobbles were measured and compared, Samaras and Gellura (1979) determined that three cobble-gravel deposits, located in or near the mouth of Cottonwood Canyon, contained dominantly wave-rounded cobbles. They collected and measured 107 cobbles and pebbles from their site TS-4 and determined that there was a greater than 76% probability that clasts in the deposit were wave-worn (Samaras and Gellura, 1979). We visited this site, which is in a roadcut on the south slope of Cottonwood Canyon (Fig. 2) at an elevation of 90 m. Here, the gray to tan, matrix-supported gravel includes both angular and rounded rock fragments of mixed lithologies (Fig. 5E), but an absence of marine fossils or pholad borings that would aid in a definitive determination of a marine origin for the deposit. A lack of discernible bedding raises the possibility that the deposit may have been reworked.

3.4. Avalon Canyon

The other area identified by Smith (1897) as possibly of marine origin is in the middle part of Avalon Canyon (Fig. 2), where he described a broad platform with a gentle seaward slope that steepens in an up-canyon direction. Bailey's (1941) geologic map of the island identifies these features as marine terrace deposits, but Smith (1897) and Davis (2004) interpreted them as remnants of an alluvial fan, based on the geomorphic expression of the surface and the presence of both rounded and subangular rock fragments in the deposit.

We examined these deposits in Falls Canyon (a tributary of Avalon Canyon) and along the south side of Avalon Canyon adjacent to the golf course. In both areas, matrix-supported cobble gravels contain a mixture of angular and rounded, locally derived clasts composed dominantly of diorite with minor amounts of andesite (Fig. 5F). Some of the clasts are imbricated in a down-valley direction, and crude fining-upward bedding can be seen in places, indicating a fluvial origin, whereas in other places the clasts are poorly sorted and more angular, suggesting a debris-flow depositional environment. We found no fossils, marine deposits, or any indication of marine reworking in this area. Therefore, we also interpret these deposits to be of alluvial fan (or fan delta?) origin. Entrenched alluvial terraces and fans are also found on the northern Channel Islands (Brumbaugh, 1980; Woolley, 1998). The planar shape and seaward slope of their upper surfaces can be attributed to adjustments of the fluvial system to postglacial rising sea level. A similar history is quite plausible for the Avalon Canyon deposits. The reason for subsequent entrenchment is less well understood. Vegetation stripping by grazing sheep has been postulated as one possible cause on Santa Cruz and Santa Rosa islands (Brumbaugh, 1980; Woolley, 1998). Although sheep and cattle ranching occurred on Santa Catalina Island, we found no specific mention of ranching in Avalon Canyon.

3.5. "Notched salients"

Smith (1933), in revisiting the marine terrace issue, suggested that three areas of Santa Catalina Island were especially likely to exhibit evidence of marine terracing: (1) a "prominent salient" at the northwest end of the island; (2) the rounded southwestern part of the island from about 3–5 km south of Little Harbor to the area around Silver Canyon Landing; and (3) ridge crests at the southeastern end of the island. He constructed topographic profiles along ridge crests ("spurs") using U.S. Coast and Geodetic Survey (USCGS) topographic maps of Santa Catalina Island produced between 1853 and 1873 with contour intervals ranging from 20 to 100 ft (6–30 m). The presence of notches in the profiles with flat, bench-like sections and steeper, cliff-like sections were interpreted as remnants of marine terraces. Smith noted that these "notched salients" exist only on seaward-facing slopes, and that some of the benches have rounded cobbles on their surfaces. He also noted similarities in the shape and form ("step-like appearance") of notches at similar elevations on different ridge crests. At the southeastern end of the island (roughly from Silver Canyon southeastward), Smith (1933) described step-like features on several ridge crests at multiple elevations, and found rounded cobbles on benches at the 1000 ft (305 m) and 1060 ft (323 m) elevations, which he verified with a barometric altimeter. Along the southwestern "bulge" of the island (between Cottonwood and Silver canyons), Smith (1933) noted "benches on many of the ridges and spurs". Benches cut into ridges formed in volcanic rocks and in the Catalina Island pluton appear to be better defined than those on ridges formed in the Catalina Schist (Smith, 1933). However, Bailey (1941), like Shepard et al. (1939), was not convinced that the bench-like features on ridge crests described by Smith (1933) were sufficiently prominent or continuous to be of wave-cut origin. Bailey (1941) pointed out that many landslides on the island have steep slipfaces and relatively flat runouts that could superficially resemble terraces in profile.

One of the limitations of Smith's (1933) topographic analysis of ridge crests on Santa Catalina Island is the resolution of the elevation data available at the time. Several topographic maps were used in combination to cover the island, with contour intervals of 20, 40 or 100 ft (6, 12 or 30 m). The larger contour intervals, in particular, may have provided an oversimplified or distorted representation of the topography. In 2006, high-resolution LiDAR was flown for Santa Catalina Island on behalf of the Los Angeles Region Imagery Acquisition Consortium (LAR-IAC; http://planning.lacounty.gov/LARIAC/). The USGS acquired a version of the dataset with 3 m horizontal spatial resolution. This DEM dataset provides a consistent representation of elevation across the island at a considerably higher resolution than the maps available to Smith in his 1933 study.

Using the LiDAR-based DEM, topographic profiles were constructed along ridge crests and ocean-facing slopes in an attempt to determine the validity of Smith's assertion that "notched salients" are remnants of marine terraces. Fifteen profiles were constructed along ridge crests in the areas discussed by Smith (1933): on the ocean-facing side of the northwest part of the island (northwest of Two Harbors); along ridges radiating from Little Harbor (Fig. 4); on the ocean-facing sides of the southeast part of the island (generally south and east of Silver Canyon), and along the southwest "bulge" of the island between Salta Verde Point and China Point (Fig. 2). Four of these profiles are shown compared with Smith's (1933) profiles of the same ridge crests in the southeastern part of the island (Fig. 6).

With the greater detail shown by the DEM data, smaller topographic irregularities are displayed, so the ridge profiles are not as smooth, and some notches appear less distinct and less prominent than in Smith's (1933) profiles constructed from the early contour maps. The DEM profiles also show some areas in which the sub-horizontal "bench" areas slope landward, suggesting the surface of a rotational landslide. These are generally found northwest of Two Harbors, and between China Point and Silver Canyon (not shown in Fig. 6), both areas with steep slopes and abundant landslides. Nevertheless, many of the profiles also show notched areas on ridge crests and hillslopes with flat or gently seaward-sloping benches backed by steep cliffs. A number of these notches can be

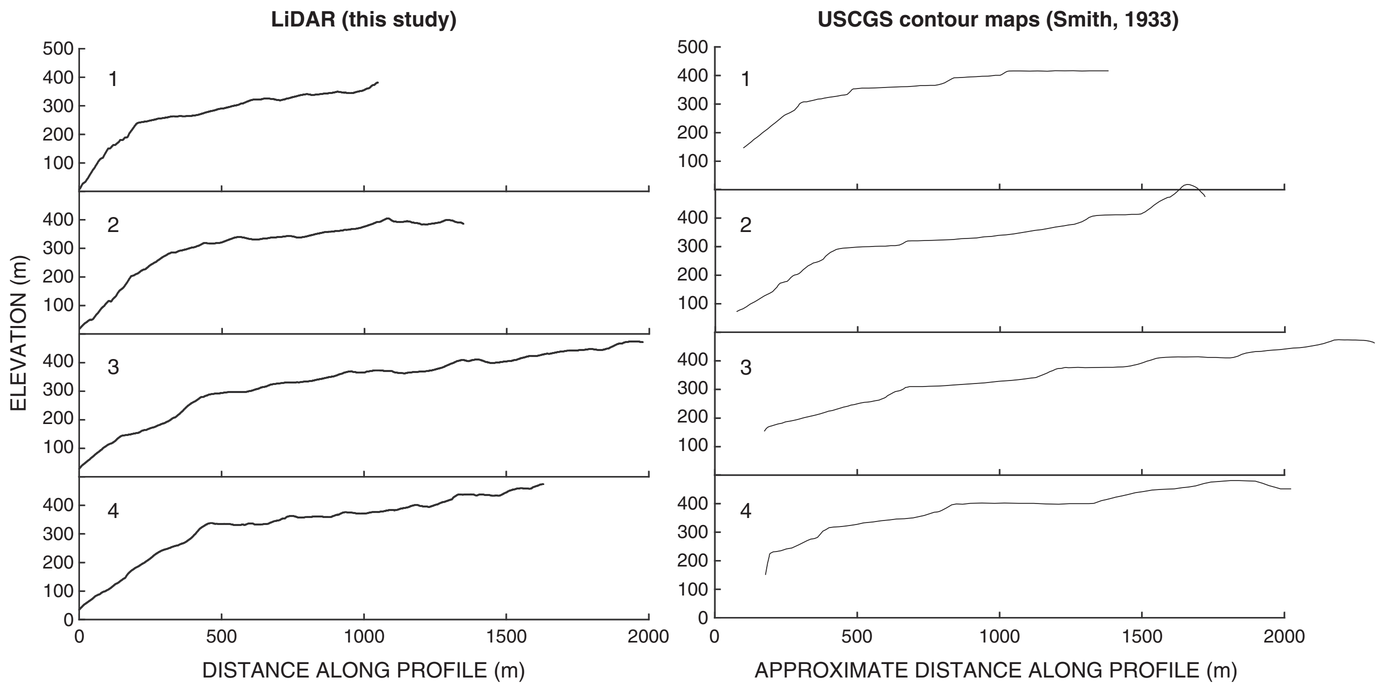

Fig. 6. Topographic profiles along ridge crests in the southeastern part of Catalina Island. See red lines and numbers in Fig. 2 for locations of ridges. Left column of figure — new (this study) profiles generated from LiDAR data; right column — profiles of same ridge crests redrawn from Fig. 3 of Smith (1933).

observed at elevations of approximately 30, 90, 120, 180 and 335 m on multiple ridges, suggesting the possibility that some of these features may be terrace remnants.

3.6. Salta Verde Point and Thunder Beach

Samaras and Gellura (1979) reported that the surficial deposits within the shallow basin-like area above Salta Verde Point contained a mixture of dominantly fluvially-rounded pebbles and a lesser number of wave-rounded cobbles. Few larger-sized cobbles were found, and many of those were broken or chipped, possibly in a deliberate manner by the island's aboriginal inhabitants to form tools. This led Samaras and Gellura to conclude that most of the larger, wave-rounded cobbles had been removed from the site, and to interpret this site as a marine terrace remnant. It is equally possible, however, that most or all of the wave-rounded cobbles that Samaras and Gellura (1979) found were instead brought to Salta Verde Point by the aboriginal Tongva people. If there were marine terrace deposits at this location, they would likely have been buried beneath the landslide deposits presently covering the surface. The slopes above Salta Verde Point, which rise to elevations of more than 400 m, are extensively modified by landslides (Fig. 3), and several small intermittent drainages flow into and across the shallow basin just above the Point. This would account for the preponderance of fluvially-rounded pebbles found by Samaras and Gellura (1979). The shallow basin-like topographic expression of Salta Verde Point resembles that of a landslide runout, terminating in an elevated, wave-eroded toe. The underlying sediment consists of poorly-sorted, unconsolidated, angular pebble-to-cobble gravel with no discernible bedding. Although we cannot entirely rule it out, the lack of tangible evidence suggests that it is unlikely that Salta Verde Point is a marine terrace remnant.

Bailey (1941) described a strand line of rounded pebbles at an elevation of 7.6 m (25 ft) along the shore extending for several miles east of Silver Canyon, as well as another terrace below the strand line at an elevation of 3 m (10 ft), located midway between the mouths of Silver and Bullrush canyons. We believe that he must have meant that the strand line extended to the west, because Bullrush Canyon is west of Silver Canyon, and for the 7 m strand line to lie above the 3 m terrace it must also extend west from the mouth of Silver Canyon. This seems more likely because the steep cliffs of the Palisades, with no discernible beach, extend east from the mouth of Silver Canyon, and it is unlikely that terrace deposits would be preserved there.

The beach between Salta Verde Point and the mouth of Silver Canyon is called Thunder Beach, so named because it is a cobble- and pebble-dominated beach composed almost entirely of locally-derived clasts of Catalina Schist (Fig. 7A) that make a dramatic rumbling sound when moved about by wave action. A small intermittent stream terminates on Thunder Beach just below the beach's parking area. Here, alluvium from this stream overlies a layer of beach cobbles (Fig. 7B). A polystyrene foam cup embedded in the alluvium dates the layer as no more than 50–60 years old. The elevation of the cobble layer at its landward edge is 2.8 m, so it is possible that this or a similar wave-cut bench was the “10 ft strand line” described by Bailey (1941). An apparently modern storm bench occurs at roughly this elevation, making it highly doubtful that Bailey identified a Pleistocene marine terrace at this location and elevation.

The highest beach ridge preserved on Thunder Beach is mantled with a 10 to 15 cm-thick layer of sandy silt, locally covered by a thin cobble layer (Fig. 7C). Its GPS-determined elevation of 6.2 m corresponds roughly to the height of the “25 ft strand line” described by Bailey (1941). Its surface morphology is that of a flat-topped bench backed by bedrock sea cliffs, colluvial wedges, and landslides. Shells of *Olivella*, *Serpulorbis*, *Conus*, *Balanus*, and *Antisabia* were found in the silty layer mantling the surface of the bench. Radiocarbon dating of three samples of mollusk shells from this bench yielded essentially modern ages (Table 1). The bench appears to be above the reach of most storm waves, and the presence of the sandy silt mantle and unbroken mollusk shells is in stark contrast to the pebble- and cobble-dominated lower beach ridges, but given its modern age, this feature is most likely a storm bench.

3.7. Northwestern Santa Catalina Island

Bailey (1941) described a terrace-like area immediately west of Parson's Landing (Fig. 2), at an elevation of approximately 100 ft

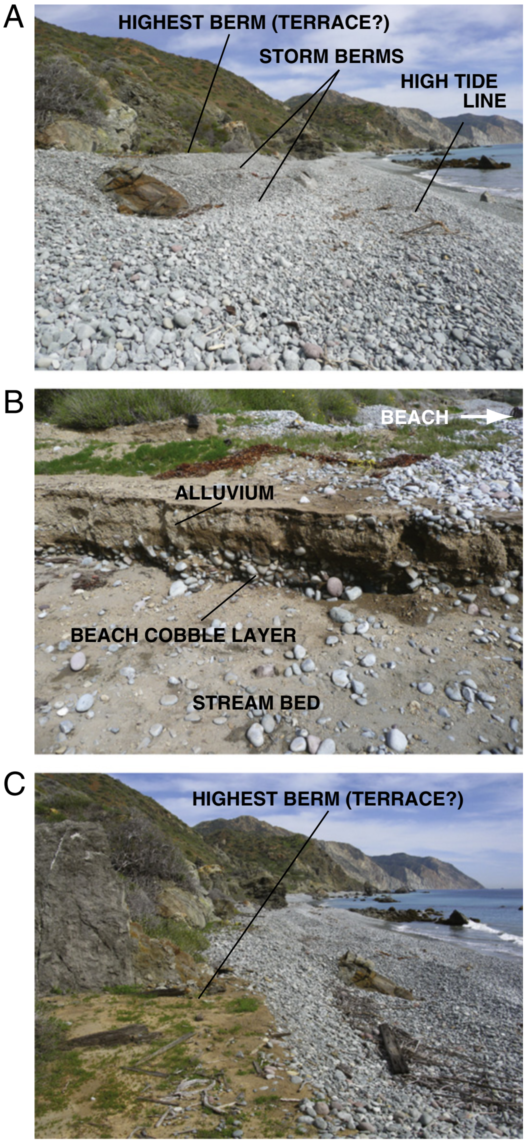

Fig. 7. (A) View looking eastward along Thunder Beach from near Salta Verde Point. The Palisades in background. See Fig. 2 for location. (B) Beach cobble deposit overlain by younger alluvium at Thunder Beach. (C) View looking eastward showing highest beach ridge at Thunder Beach, at an elevation of approximately 6 m. This could correspond to the "25 foot strand line" of Bailey (1941).

(30 m), as dissected and mantled with fluvial deposits. Although he thought the terrace surface to be of marine origin, from his description it seems more likely that it is entirely of fluvial origin. A deeply gullied but otherwise relatively smooth-surfaced area to the west of the hummocky surface of the Parson's Landing landslide was referred to as "non-marine terrace deposits" by Slosson and Cilweck (1966), who drilled 12 test borings to depths of 22 m and apparently found no marine deposits in or near the landslide area. The topography of the area resembles that of an alluvial fan, the toe of which was eroded by wave action, which probably initiated landsliding.

Although they did not identify marine terrace deposits at Parson's Landing, Slosson and Cilweck (1966) noted the presence of "a slightly elevated beach deposit" just north of Emerald Bay. We observed what appear to be remnants of a marine bench in a small cove in the same area (Fig. 8). The bench fragments are cut into Catalina Schist bedrock at an estimated elevation of 6 m. No fossils, rounded cobbles, or other definitive evidence of marine terraces were found on the surfaces of the ledges, so we cannot identify them as such with any degree of certainty. The elevation of these ledges is, however, approximately the same as that of the highest strand line at Thunder Beach.

Bailey's (1941) geologic map of Santa Catalina Island shows a small exposure of marine terrace deposits just to the north of White's Landing (Fig. 2). He does not discuss it in the text of his dissertation, and there does not appear to be any topographic expression of a terrace at this location. No other authors mention the White's Landing area as having possible marine terraces, and we did not visit the locality.

Table 1
Radiocarbon ages of mollusk shells collected from the highest beach ridge (elevation 6.2 m) at Thunder Beach, Santa Catalina Island. Dates are corrected for $\delta^{13}C$.

Sample ID	Description	^{14}C age (yr BP)
CAT-2010-03A-01	*Olivella biplicata* shell	Modern
CAT-2010-03A-02	*Antisabia panamensis* shell	675 ± 30
CAT-2010-03B-01	*Serpulorbis squamigerus* shell	Modern

4. River profiles

Due to the apparent lack of marine terraces, a higher degree of fluvial system development than San Clemente Island or the Palos Verdes hills, and the paucity of beaches relative to steep sea cliffs, Lawson (1893) postulated that Santa Catalina Island is not experiencing uplift like neighboring areas, but instead may be actively subsiding. In contrast, many other authors conjectured that the island has experienced uplift during the Quaternary (Smith, 1897, 1933; Bailey, 1941; Emery, 1960; Loop, 1973). Other Channel Islands, as well as parts of the mainland California coast that are known to be actively uplifting, exhibit similar amounts of fluvial dissection but retain marine terrace remnants. Moreover, rivers in an actively subsiding area would be expected to aggrade rather than incise in response to a rising base level (Mackin, 1948; Alexander, 1953; Schumm, 1993). This does not appear to be the case on Santa Catalina Island, as the streams are

Fig. 8. Remnants of wave-cut benches in small cove north of Emerald Bay. Approx. 2 m-tall person standing on top of wave-cut bench remnant in each photo for scale.

primarily cut to bedrock and have minimal or highly localized accumulations of alluvium in the channels of all but the largest drainages, such as Middle Canyon, which has aggraded upstream of an artificial impoundment at Thompson Reservoir, and Avalon Canyon.

Rivers are dynamic systems that respond relatively quickly to changes in base level, making them good indicators of recent tectonic or eustatic changes. To compensate for base-level changes, a river may adjust by aggrading or degrading its bed, or by altering its channel pattern, roughness, or shape (Leopold and Bull, 1979; Schumm, 1993). In bedrock-floored valleys, such as the majority of those on Santa Catalina Island, lateral movement of stream channels is restricted, so rivers are most likely to adjust their gradients through incision or deposition. This is reflected in the longitudinal profile of a stream, making stream profile analysis an excellent tool for detecting recent or ongoing uplift or subsidence of an area (Merritts and Vincent, 1989; Whipple and Tucker, 1999, 2002; Schumm, 2000; Kirby and Whipple, 2001; Wobus et al., 2006). The idealized longitudinal profile of a channel in steady-state equilibrium with hydraulic and tectonic conditions tends to approach a concave-upward, logarithmic shape, though not necessarily because it is in a "graded" condition as defined by Mackin (1948) and Hack (1960). Deviations from the idealized profile may be caused by differences in erodibility of the rocks over which the river flows, by local base levels such as lakes, reservoirs, rock or landslide dams, or by forcings external to the river system such as tectonic or eustatic changes in local (e.g., domes, basins, faults) or absolute (sea level) base level.

Landscape evolution, as exemplified by the development of river systems, is a product of erosional and depositional processes acting on tectonically-created land surfaces, expressed in the morphology of river channels and drainage basins (e.g., Howard, 1994; Howard et al., 1994; Whipple and Tucker, 1999). Relatively easily-measured topographic parameters of river systems yield a descriptively and diagnostically useful mathematical relation whereby local channel slope S is a function of contributing drainage area A (a proxy for discharge):

$$S = k_s A^{-\theta}$$

where k_s and θ represent the steepness and concavity indices, respectively (Flint, 1974; Howard and Kerby, 1983; Howard, 1994; Wobus et al., 2006). Whereas many streams tend to exhibit a single slope-area relation along their entire lengths, segments of a profile characterized by different values of k_s, θ, or both may indicate disequilibrium conditions due to tectonic modifications, along-stream changes in erosional resistance of rock, climatic changes, base-level changes, or exceeding intrinsic thresholds. Numerical modeling of the relation between channel gradient and contributing area indicates that the concavity index, θ, is independent of rock uplift rate if uplift is uniform across the entire drainage basin, whereas the steepness index, k_s, is positively correlated with uplift (Wilgoose et al., 1991; Howard, 1994; Whipple and Tucker, 1999; Wobus et al., 2006). However, upstream migration of nickpoints in response to a drop in base level, such as that caused by uplift, increases concavity (Phillips and Lutz, 2008). Segments of a gradient-area curve with negative slope (negative concavity index) are associated with concave reaches of a stream profile; segments with positive slope (positive concavity index) indicate convexity. Transitions from convex to concave profile segments are commonly marked by nickpoints. The uppermost parts of the profile are usually associated with hillslope runoff or debris-flow processes rather than in-channel processes, which only become active downstream of a critical contributing drainage area (Whipple and Tucker, 2002; Wobus et al., 2006), so the upstream parts of the slope-area graphs are generally not considered useful for analyses.

To facilitate analysis of Santa Catalina Island stream profiles in this study, topographic and hypsometric data were generated using the LiDAR-based DEM of the island discussed earlier, using software tools in Environmental Systems Research Institute, Inc.'s (ESRI) ArcGIS program (use of trade, firm, or product names is for descriptive purposes only and does not constitute endorsement by the U.S. government). River courses were generated by routing and concentrating flow in a downslope direction across each grid cell of the DEM; long profiles were plotted from the resulting stream lines. Topographic contours were generated at a 10-m contour interval and areas between adjacent contours calculated by ArcGIS. Stream gradients were calculated at 10-m vertical intervals, using a 20-m moving window.

Many of the streams on Santa Catalina Island exhibit transient, or disequilibrium, profiles (Fig. 9). Of the six stream profiles shown in Fig. 9, five of them, all draining to the southwestern and western sides of the island, exhibit convex reaches and have markedly steeper gradients in their downstream reaches. The profiles are arranged roughly from northwest to southeast in Fig. 9, beginning with an unnamed canyon in the Little Harbor embayment (see Fig. 2 for location). Both the long profile and the area-gradient plot for this drainage show a convex reach downstream of a small reservoir, and upstream from a nickpoint at approximately 50 m elevation and approximately 1800 m upstream of the river's mouth. The stream exhibits a concave profile downstream of the nickpoint (Fig. 9). The river's profile is also concave upstream of the reservoir. Data for Buffalo Springs Canyon show two apparent nickpoints at 70 and 130 m elevation, with a convex profile reach above each (Fig. 9). The reach between the two nickpoints and the reach downstream of the lower nickpoint have roughly the same slope. Both segments are steeper than the reaches upstream of the nickpoints. The reach directly upstream of the upper nickpoint has a slightly convex shape, indicated by a positively-sloping segment of the slope-area graph.

Cottonwood Canyon does not exhibit any obvious nickpoints in the lower part of its profile, but the convex shape of the lower ~3 km indicates that the stream is in a disequilibrium state (Fig. 9). There appears to be a nickpoint at approximately 270 m elevation. The valley is narrower and deeper at this location, suggesting active or recent incision. A nickpoint is approximately 3 km upstream of the mouth of Middle Canyon at an elevation of about 140 m. The stream profile is steeply concave downstream of the nickpoint, whereas it has a convex shape between the nickpoint and Thompson Reservoir (Fig. 9). The valley floor is covered by alluvial fill for several km upstream of the reservoir, and this reach has a gently concave-upward profile, suggesting that this part of the stream is adjusted to the local base level of the reservoir. A small convexity is also seen in the profile of Middle Canyon at an elevation of about 280 m.

Most of Silver Canyon's profile is slightly concave, with a steeper concave reach downstream from an inflection point at about 40 m elevation to the river's mouth at sea level. A second nickpoint is observed about 4.5 km upstream at an elevation of 280 m, at roughly the same elevation as the nickpoint in Cottonwood Canyon and the possible upper nickpoint in Middle Canyon (Fig. 9).

The long profile of Avalon Canyon, which drains toward the northeast, is concave upwards along its entire length (Fig. 9). It is an alluvial stream in the lower 3 km of its 4-km length. In its natural state, this would make the stream more capable of adjusting its gradient through changes in channel shape or sinuosity, but most of the alluvial reach is channelized around the golf course, which was constructed in 1892 (Pedersen, 2004), as well as where the stream flows through the city of Avalon. The slightly steeper deviations from the straight line of the slope-area plot for Avalon Canyon may be created artificially by this channelization, or may represent recent natural downcutting of the stream in lieu of channel pattern or shape adjustment.

Streams in canyons northwest of Two Harbors (not shown in Fig. 9) have longitudinal profiles that fall similarly into two main groups. Streams draining toward the northeast generally have uninterrupted concave-up profiles, whereas those draining toward the southwest have straighter profiles that steepen downstream from inflection points at elevations of 100–150 m.

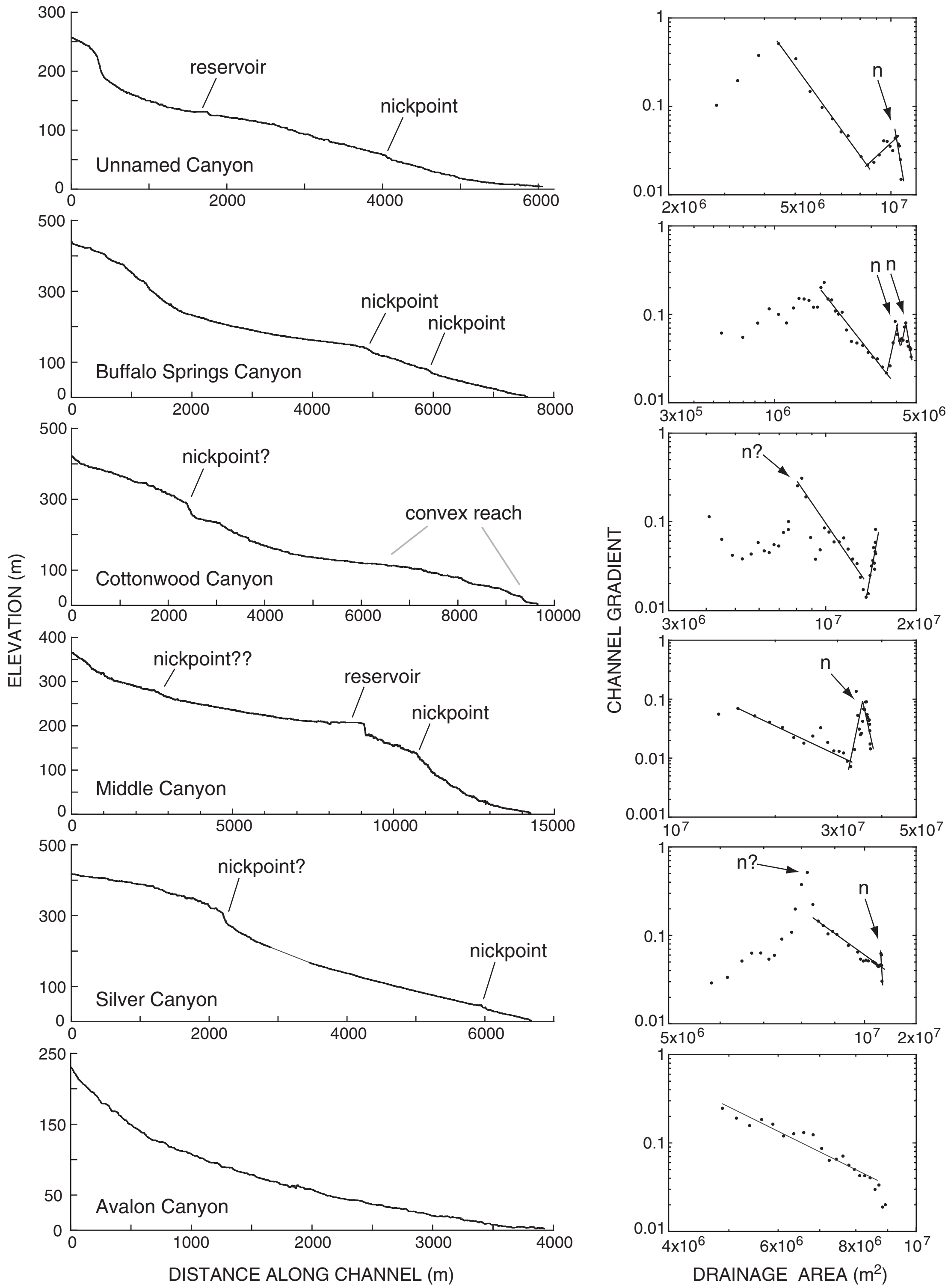

Fig. 9. Longitudinal profiles and corresponding slope-area plots of selected stream channels on Santa Catalina Island. See Fig. 2 for locations of streams. Vertical exaggeration varies between profiles. In slope-area plots, negatively-sloping segments of the plot (trending down toward the right) correspond to concave reaches of the long profile; positively-sloping segments (upward to the right) correspond to convex reaches. "n" indicates position of nickpoint.

5. Submerged terraces

Late Quaternary subsidence is a viable explanation for a lack of emergent marine terraces on Santa Catalina Island, as suggested more than a century ago by Lawson (1893). Recently acquired multibeam bathymetry data (Caldwell et al., 2010; Divins and Metzger, 2010) shows submerged terrace-like landforms surrounding Santa Catalina Island (Fig. 10). At least 5 distinct submerged terrace-like benches can be identified with inner edge depths of approximately 12, 70, 115, 150 and 225 m (Fig. 11A). Emery's (1958, 1960) interpretation of depth sounding profiles off Santa Catalina Island identified additional postulated marine terraces with inner edges at depths of approximately 30 and 45 m.

From interpretations of seismic reflection profiles, Francis et al. (2010) suggest that the contact between the marine sedimentary

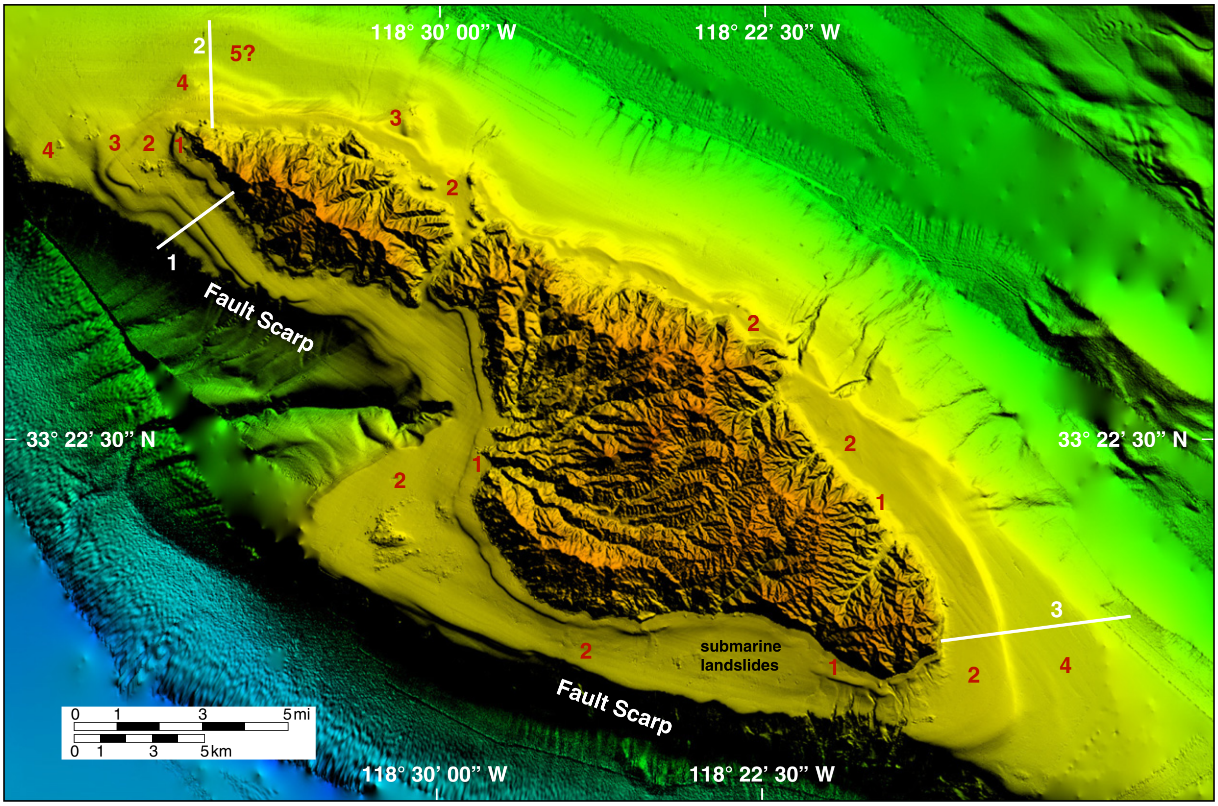

Fig. 10. Shaded-relief bathymetric-topographic image of Santa Catalina Island and the surrounding offshore area. Approximate depths (below present sea level) of the "inner edge" of numbered terraces are as follows: 1–12 m; 2–70 m; 3–115 m; 4–150 m; 5–225 m. Numbered lines indicate locations of topographic profiles in Fig. 11. Data from Divins and Metzger (2010).

sequence and the underlying schist basement rock offshore of Santa Catalina Island at depths of 400–500 m below present sea level forms a gently sloping surface resembling a marine terrace bench. Although they offer no evidence for it, Francis et al. (2010) hypothesize an age of 600 ka for this surface. This age corresponds to one of the lowest lowstands of the Quaternary, that of marine isotope stage (MIS) 16, during which sea level is estimated to be at most 20–30 m lower (Shackleton, 1987; Rohling et al., 1998) than the local Last Glacial Maximum (LGM; MIS 2) lowstand.

The LGM lowstand is estimated to have been −120 m to −140 m below present sea level, based on data from Barbados, a far-field locality with respect to glacial-isostatic adjustment (GIA) effects (Bard et al., 1990; Peltier and Fairbanks, 2006). GIA modeling shows that relative sea level differs in near- or intermediate-field localities located closer to continental ice sheets such as the ones that covered a large part of North America (Kendall et al., 2005; Milne and Mitrovica, 2008). Southern California is situated in an intermediate-field region, where there are significant GIA effects on the record of relative sea level. Sea-level models that account for GIA effects produce an estimate of about −90 m for relative LGM sea level off the southern California coast (Muhs et al., 2012). Because older glacial-period marine lowstands are estimated to have been, at most, no more than a few tens of meters lower than the MIS 2 level (Shackleton, 1987; Rohling et al., 1998), the presence of submerged marine terraces at depths to about −120 m could be attributed solely to glacio-eustatic sea-level changes without requiring tectonic uplift or subsidence (but not necessarily excluding either one). The submerged terrace-like surface surrounding Santa Catalina Island at ~−225 m (Figs. 10, 11A), or the hypothesized terrace at ~−400 m (Francis et al., 2010), however, cannot be explained solely by glacio-eustatic sea level lowering. A hypothesized MIS 16 marine

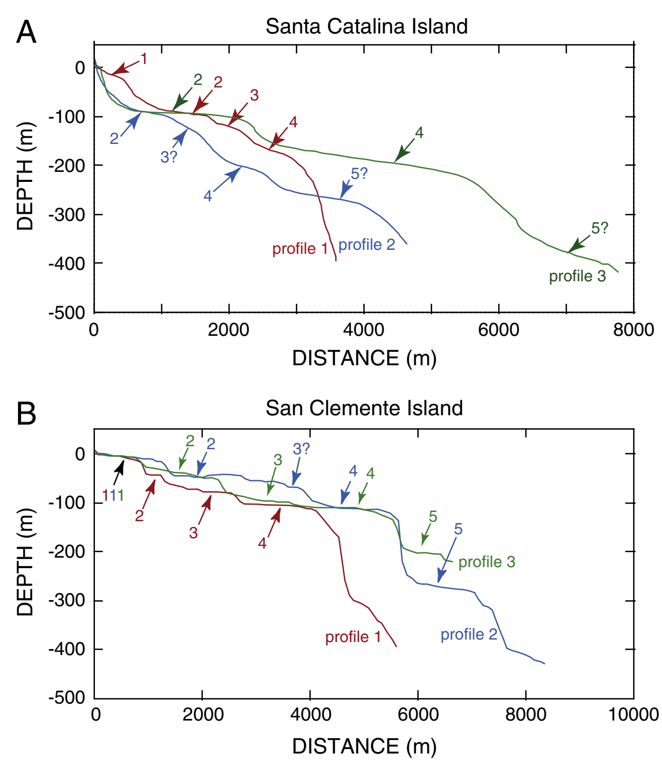

Fig. 11. Topographic profiles of submerged shelf areas surrounding (A) Santa Catalina Island, and (B) San Clemente Island. See Figs. 10 and 12 for locations. Numbers of major terrace-like surfaces arbitrarily assigned and do not suggest relative age relationships or correlations between islands.

terrace at a present depth of 400 m or more would suggest that the Santa Catalina Island block has subsided more than 300 m during the middle to late Quaternary. A definitive age assignment, and indeed, positive identification of this feature as a marine terrace surface, would require coring of the sea floor to this depth and finding marine terrace sediments with dateable fossils at the contact.

Submerged terraces surround the other Channel Islands as well. Bathymetric images for the area around San Clemente Island, created from gridded multibeam sounding data (NOAA National Geophysical Data Center, 2011), also indicate the presence of multiple submerged terraces (Fig. 12), in agreement with previous studies by Emery (1958, 1960). At least four major terraces with inner edge depths of approximately 5, 40, 70 and 90 m are seen (Fig. 11B). The outer edge of the San Clemente Island platform stands at approximately −120 m. A possible 5th terrace occurs at a seemingly anomalous inner edge depth of 200–250 m (Figs. 11B, 12), in spite of San Clemente Island's geologic record of continuous uplift throughout the Quaternary (Muhs and Szabo, 1982; Muhs, 1983; Muhs et al., 1992, 2004). The terraces around San Clemente Island have more variable inner-edge depths, and there are more discontinuous terrace remnants than those surrounding Santa Catalina Island.

Additionally, Chaytor et al. (2008) identified what they postulated as a pre-LGM terrace at approximately −200 m depth north of Anacapa and Santa Cruz Islands. The northern Channel Islands have apparently experienced only uplift during the Quaternary (Pinter et al., 2001), so the existence of a bench at this depth is also anomalous if it is truly a wave-cut platform. The presence of deeper submerged terraces around uplifting Channel Islands suggests that the existence of terrace-like landforms or surfaces at similar or lower depths around Santa Catalina Island does not necessarily constitute evidence of Quaternary subsidence.

6. Discussion

Reanalysis of previous work did not uncover new, definitive evidence of marine terraces on Santa Catalina Island. Thus, this investigation focuses instead on explanations for the anomalous absence of these features. We have discounted erosional resistance of bedrock and total obliteration by landslides as explanations for the lack of marine terrace remnants. Submerged terrace-like features have been identified around Santa Catalina Island. They are similar in appearance to submerged terraces around the other Channel Islands and the mainland coast of southern California. The submerged benches around Santa Catalina Island have been offered by some as evidence of Quaternary tectonic subsidence. Although terrace-like features have been noted at depths below which they could have been formed purely by glacio-eustatic sea-level change, they have not been definitively identified as marine terraces, nor have they been dated.

In contrast, transient stream profiles on Santa Catalina Island provide geomorphic evidence of rapid uplift. Stream profile convexities and nickpoints deviate from typical smooth, concave-up, equilibrium long profiles. Possible causes of disequilibrium conditions include

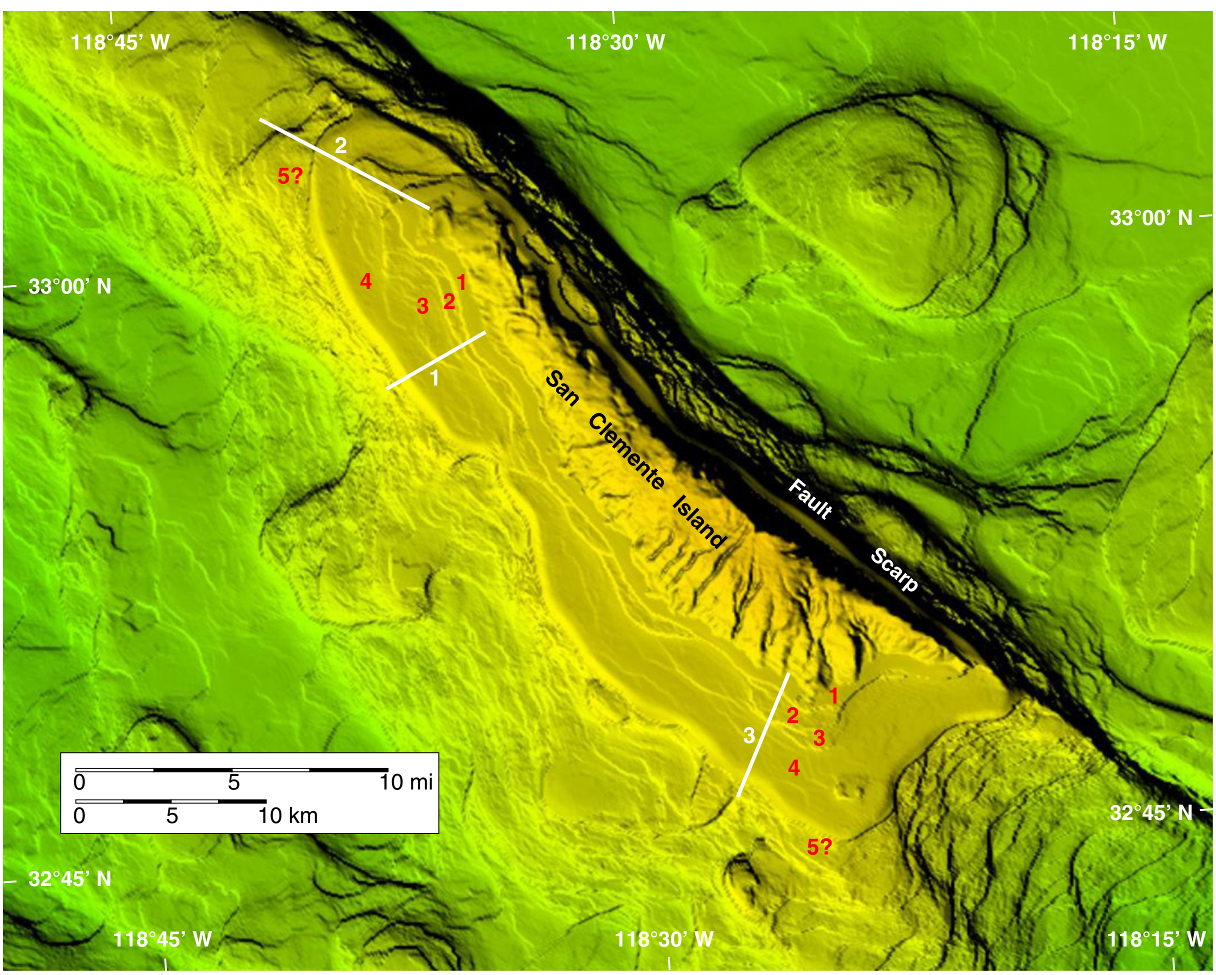

Fig. 12. Shaded-relief bathymetric-topographic image of San Clemente Island and the surrounding offshore area. Approximate depths (below present sea level) of the "inner edge" of numbered terraces are as follows: 1–5 m; 2–40 m; 3–70 m; 4–90 m; 5?—the outer edge of terrace 4 is at ~120 m. Numbered lines indicate locations of topographic profiles in Fig. 11. Data from NOAA National Geophysical Data Center (2011).

differences in the erodibility of the rocks over which the stream is flowing; localized tectonic forcings (uplift or faulting); base-level (e.g., sea-level) lowering; changes in sediment delivery to the channel, for example, by tributaries or landslides; human modifications to river systems such as channelization or impoundments; and changes in the amount of water supplied to the river, such as by climatic changes (Goldrick and Bishop, 2007; Phillips and Lutz, 2008). There are several possible explanations for the steepened lower reaches and convex reaches of the river profiles shown in Fig. 9, keeping in mind that, except for Avalon Canyon, these are not dominantly alluvial rivers and therefore cannot easily adjust their channel shape, pattern, or sinuosity through erosion or deposition of sediment. Nickpoints can form where streams cross faults with a vertical slip component. There are, however, no mapped faults or obvious topographic expressions of faults crossing the streams at or near the locations of the observed nickpoints. Another possible cause is differences in erodibility of the rocks over which the streams flow. In general, the gradient would tend to be steeper and the profile less concave over more resistant rocks (Moglen and Bras, 1995; Duvall et al., 2004; Phillips and Lutz, 2008). "Unnamed" canyon, Buffalo Springs Canyon, and Cottonwood Canyon (Fig. 9) all flow entirely over metamorphic rocks of the Catalina Schist (Bailey, 1941). Although this rock includes greenschist, blueschist, and amphibolite facies, none of the contacts between facies correspond with observed inflection points on the stream profiles. Middle Canyon heads in quartz diorite of the Catalina Island pluton, but the bedrock changes to Catalina Schist in the vicinity of Thompson Reservoir, several kilometers upstream from the nickpoint on its long profile (Fig. 9). Silver and Avalon canyons flow entirely over quartz diorite rocks from their headwaters to mouths. Landslide or rockfall dams also show no systematic correlation with nickpoint positions. This simplified analysis does not take into account other rock properties such as fracture patterns and densities or intraformational lithologic changes, which can also affect erodibility. However, the fact that nickpoints occur consistently in two groups, 40–140 m elevation, and 270–280 m elevation, in multiple drainages, points to a more systematic, regional (island-wide) cause that is independent of local (affecting only one or a few drainages) effects. Upstream migration of nickpoints in response to base-level lowering increases concavity downstream of the migrating nickpoint (Phillips and Lutz, 2008). This effect is clearly seen in the long profiles of streams on the west and southwest sides of Santa Catalina Island (Fig. 9), particularly in lower reaches where more discharge is available to provide erosive power. The higher-elevation (~270–280 m) nickpoints in Cottonwood and Silver canyons appear to be much larger and steeper than their downstream counterparts. The gentler gradients and small contributing areas upstream may not provide sufficient power to incise the bedrock substrate quickly, creating hanging valleys (Wobus et al., 2006).

In the absence of localized within-channel effects, the most likely origin of the nickpoints is base-level change caused by eustatic or tectonic activity. Sea level in the vicinity of the Channel Islands has risen approximately 90 m to its current level over the past 20,000 years (Muhs et al., 2012), but steepening of the stream profiles is consistent with a relative decrease of base level, so eustatic sea-level rise must also be discounted. Tectonic uplift is therefore the most plausible explanation for the shapes of the observed stream profiles, and is not an unreasonable conclusion given the tectonic setting of the island and the documented uplift of all of the other Channel Islands and much of mainland coastal California. Our observations indicate that nickpoints and profile convexities are more pronounced on the west side of the island. The two groups of observed nickpoints suggest two waves of rejuvenation triggered either by surpassing channel

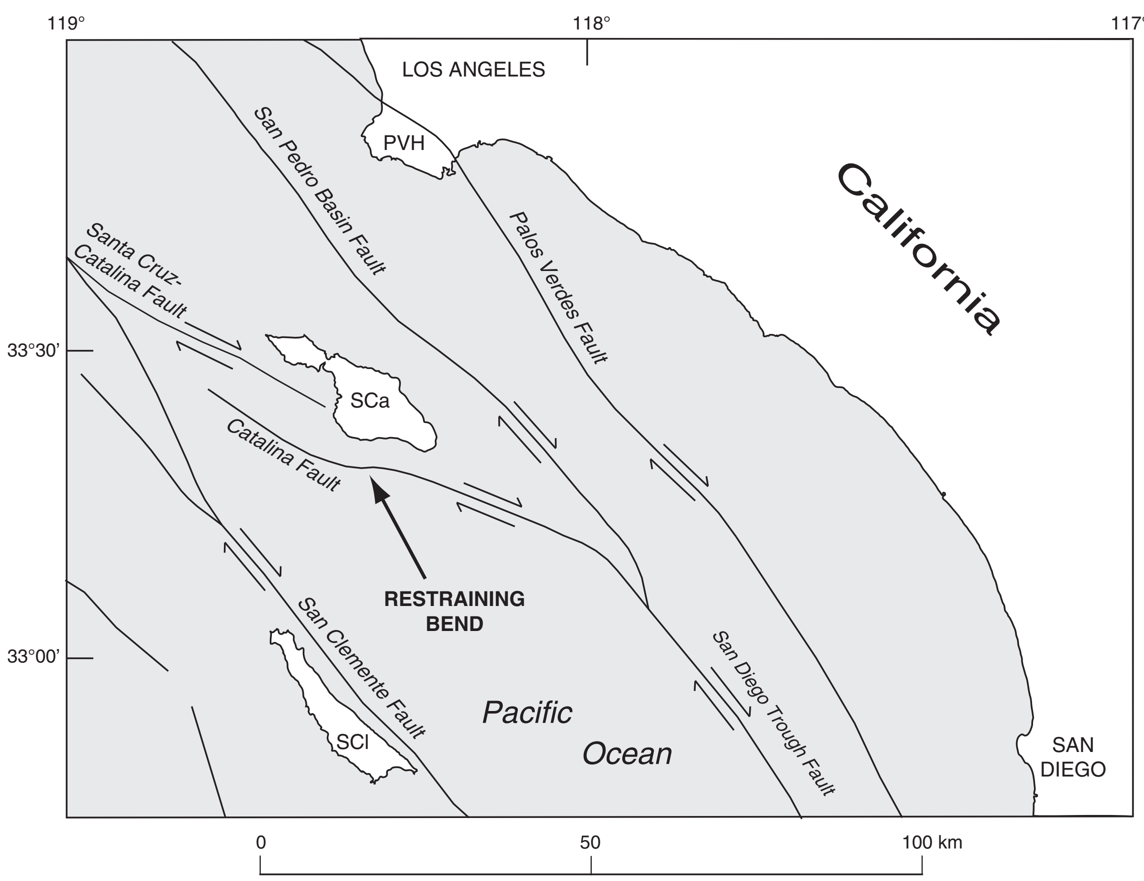

Fig. 13. Simplified structural setting of the southern California Continental Borderland region. Abbreviations: PVH, Palos Verdes Hills; SCa, Santa Catalina Island; SCI, San Clemente Island. After Legg et al. (2007).

gradient thresholds in response to continuous or long-term uplift, or alternatively, by two distinct uplift events. The marked asymmetry of the island's drainage divide toward the northeast (yellow line, Fig. 2) also suggests that the island has tilted in that direction in response to uplift occurring primarily on the west, or southwest, side of the island. Headward stream erosion would presumably be greater on the southwest, more uplifted side of the island, outcompeting headward erosion on the lower northeast side and causing the drainage divide to gradually migrate northeastward. Northeastward tilt of the island was also inferred by Smith (1897), who observed that ridge crests on the southwestern part of the island were generally as much as 60 m higher than those on the northeast side.

Bailey (1941) also plotted several profiles of westward-draining streams using 100-ft (30 m) contours on the same topographic maps used by Smith (1933). He identified nickpoints at similar positions and elevations as those in Fig. 9, and similarly concluded that the most likely explanation for the oversteepening of the lower reaches of the profiles was tectonic uplift of the island.

The deeply dissected topography of Santa Catalina Island, with sharp ridge crests, deep, v-shaped valleys, and abundant landslides (e.g., Smith, 1897; Bailey, 1941; Slosson and Cilweck, 1966; Melchiorre, 1990) provide additional indications that rapid uplift is occurring on the island. Landslides are characteristic of disequilibrium landscapes in which the uplift rate exceeds the lithologically-controlled erosion rate (Schmidt and Montgomery, 1995; Burbank et al., 1996; Montgomery, 2001). Downcutting of streambeds in response to uplift causes steepening of valley walls, leading to instability and landsliding. Smith (1897) also noted that some of the surface drainages meet sea cliffs at hanging valleys, particularly on the northwest and southwest sides of the island where high, steep sea cliffs are most pronounced, again suggesting that erosion is not currently able to keep pace with uplift.

Santa Catalina Island is the emergent part of an uplifted block of seafloor bounded by the Catalina and Santa Cruz–Catalina faults on the west, and the San Pedro Basin fault to the east (Fig. 13). For dextral strike-slip faults, a bend or step of the fault to the right creates an area of divergence and subsidence, whereas a bend or step to the left creates an area of convergence with local folding and (or) uplift (e.g., Legg et al., 2004, 2007). In this model, uplift is concentrated in a zone of transpression created by the restraining bend, also called a “pop-up” structure (Legg et al., 2004, 2007; White et al., 2004). A pronounced left restraining bend in the dextral-slip Catalina fault (Fig. 13) is located offshore of the southwestern “bulge” of Santa Catalina Island where southwestward-trending drainages are diverted toward the northwest (Fig. 2). The restraining bend is also adjacent to The Palisaides, an area of high, steep sea cliffs fronted by massive submarine landslides (Figs. 2, 10, 13). We suggest that localized transpression created by the restraining bend of the Catalina Fault is the most likely cause of the proposed recent (and ongoing?) uplift and, perhaps, northeastward tilting of Santa Catalina Island.

7. Conclusions

From our observations we conclude that landforms resembling marine terraces do exist on Santa Catalina Island, but there is no definitive, dateable, sedimentary or paleontological evidence to confirm that those features are, in fact, remnants of marine terraces. We also conclude that some of the features identified by previous researchers as possible marine terrace deposits definitely are not of this origin, most notably the fossiliferous Miocene deep-water deposits exposed in Cottonwood and Middle canyons and on Mount Banning, and the alluvial fan deposits in Avalon Canyon.

Submerged terraces surrounding Santa Catalina Island appear similar to those around the other Channel Islands as well as offshore of the southern California mainland. Submerged terraces at depths greater than approximately 90–120 m may indicate that Catalina has undergone subsidence during the Quaternary, but if so, it is inconsistent with the inferred uplift caused by the restraining bend in the Catalina fault on the south side of the island, which is supported by the stream profile data. Moreover, the presence of deeper submerged terraces around the other Channel Islands, which are known to have experienced uplift throughout the Quaternary, suggests that the existence of terrace-like landforms at similar or lower depths around Santa Catalina Island is not necessarily anomalous, and may not necessarily constitute evidence of Quaternary subsidence. At this time we cannot explain what these deeper terrace-like features represent. Available modern, high-resolution bathymetric data would facilitate a more rigorous study of these features, but a definitive study would also require sedimentologic and stratigraphically-constrained fossil age data in order to yield meaningful interpretations.

We have explored all the available evidence for the presence or lack of marine terrace landforms and deposits on Catalina, and we conclude that the most plausible explanation for the enigmatic lack of definitive marine terrace remnants is related to past (and present?) tectonic activity. Santa Catalina Island probably has recently experienced, or is experiencing, relatively rapid uplift, causing intense landscape rejuvenation that removed nearly all traces of marine terraces by erosion. The stream-profile evidence presented here supports a recent uplift hypothesis for Santa Catalina Island. Rejuvenation of major drainages on Santa Catalina is evidenced by convexities in stream profiles, steepening downstream of nickpoints, and abundant landslides. These features appear prominently in streams draining the southern and western parts of the island, which may be related to localized transpression, uplift, and northeastward tilting caused by a restraining bend in the Catalina fault.

Although this study did not produce new, definitive evidence of marine terraces on Santa Catalina Island, our new evidence for recent uplift is consistent with its tectonic setting and may explain why marine terraces have not been preserved. In some cases, previous researchers identified important pieces of evidence, but failed to recognize their significance in the larger reference frame of onshore, offshore, and tectonic settings employed in this study. As is often the case, advances in learning and technology made avenues of investigation available to us that did not exist for previous researchers. The ability to evaluate and compare more diverse types of data in this study was made possible in large part by the availability of modern, high-resolution, digital topographic and bathymetric data and modern numerical and statistical techniques of landscape analysis. A similar approach could be applied to investigations of other tectonically active coastlines in which an expected marine terrace record appears to be missing.

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