

Tectonic geomorphology of marine terraces: Santa Barbara fold belt, California

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ABSTRACT

Uplifted marine terraces are common landforms in coastal regions where active tectonics are an important component of landscape evolution, such as along the coastal stretches of southern California. The pattern and elevation of shoreline angles on active folds provide information about rates of uplift and fold growth, which is important for defining tectonic models. A particularly impressive succession of marine terraces are developed across the Santa Barbara fold belt (SBFB) in southern California, which comprises an east-west linear zone of active folds and (mostly) blind faults on the coastal piedmont and in the Santa Barbara Channel. The fold belt is characterized by several flights of emergent late Pleistocene marine terraces uplifted and preserved on the flanks of active anticlines. At several locations along the fold belt, the first emergent marine terrace is numerically dated by methods that include uranium-series dating on terrace corals, ¹⁴C dating on terrace shells and detrital charcoal, optically stimulated luminescence of marine terrace sands, and oxygen isotopic signatures ($\delta^{18}\text{O}$) of mollusks. Individual marine terraces have as many as four ages, using up to three different dating methods, providing confidence in terrace chronology. Ages of higher terraces are estimated assuming a constant rate of uplift for a particular flight. Of the 31 terraces, 22 formed during a time of falling sea level, with 9 forming at or near marine oxygen isotope stage (MIS) 3 or 5 highstands.

Ages and rates of uplift of the first emergent terrace vary systematically from west (younger

and higher) to east (older and lower). The first emergent marine terraces in the westernmost SBFB are approximately 45 ka (MIS 3), and the rate of local surface uplift is ~2 m/k.y. In the central part of the belt, first emergent terraces date to 60–70 ka (MIS 5), and uplift rates decrease to ~1.2 m/k.y. First emergent marine terraces preserved in the easternmost fold belt range from 70 ka to 105 ka (MIS 5), with rates of local surface uplift of ~0.5 m/k.y. Lower rates of uplift in the eastern end of the fold belt result from the MIS 5 terrace being tilted down into the Carpinteria syncline. Rates of vertical uplift in the western end of the fold belt are about six times higher than previously reported, suggesting the seismic hazard is also greater.

INTRODUCTION

Tectonic geomorphology is the application of geomorphic processes and landforms to crustal deformation problems, which typically involves measuring deformation of landforms such as marine terraces, folds, and fault scarps. Understanding the formation of these geomorphic surfaces provides the necessary information to explain the processes that formed them. Once Quaternary chronology is established, rates of surface processes and rates of active tectonics may be estimated. Measuring deformation of landforms is relatively straightforward; however, obtaining numerical ages is commonly the most difficult part of tectonic geomorphology studies. With no established ages, there are no estimated rates, and, therefore, applying results of tectonic geomorphic analysis to other areas of inquiry such as seismic hazard analysis is hindered. Marine terraces are common landforms in many coastal environments throughout the world that, when numerically dated, offer

a means to calculate rates of uplift relative to global sea level (approximating the geoid). Deriving rates of uplift from marine terraces for a particularly tectonically active stretch of the San Andreas–Gulf of California transform plate boundary, the Santa Barbara fold belt (SBFB), is the focus of this paper.

The SBFB is a linear belt of young east-west folds located on the south flank of the western Transverse Ranges on the Santa Barbara coastal piedmont and offshore (Keller et al., 2007) in the Santa Barbara Channel (Fig. 1). The SBFB is a continuation of the Ventura fold belt to the east. The SBFB is bounded north and south by the strike-slip Santa Ynez and Santa Cruz Island faults, respectively. Namson and Davis (1992) argued that the Santa Ynez anticlinorium, the principal topographic structure of the fold belt, is related to a low-angle, north-dipping ramp of a detachment or décollement at a depth of 10–12 km. If this hypothesis is correct, then slip on the décollement is transferred to the north-verging structures (backthrusts) on the coastal piedmont (including offshore structures) of the SBFB (Keller and Gurrola, 2000). Shortening across the western Transverse Ranges is the result of strain partitioning associated with right-slip convergence at the “Big Bend” of the San Andreas fault (SCEC, 1995). North-south convergence near Santa Barbara of ~5–7 m/k.y. (Larson and Webb, 1992; Larson, 1993) produces east-west reverse faults and folds.

The tectonic framework of the SBFB on the coastal piedmont consists of three sets of faults: (1) the west-striking, oblique reverse Mission Ridge fault system (MRFS); (2) northwest-striking oblique reverse faults; and (3) north-east-striking lateral tear faults (Gurrola and Kamerling, 1996; Keller and Gurrola, 2000) (Fig. 1). Segments of the west- and northwest-striking faults are defined by geometric, geo-

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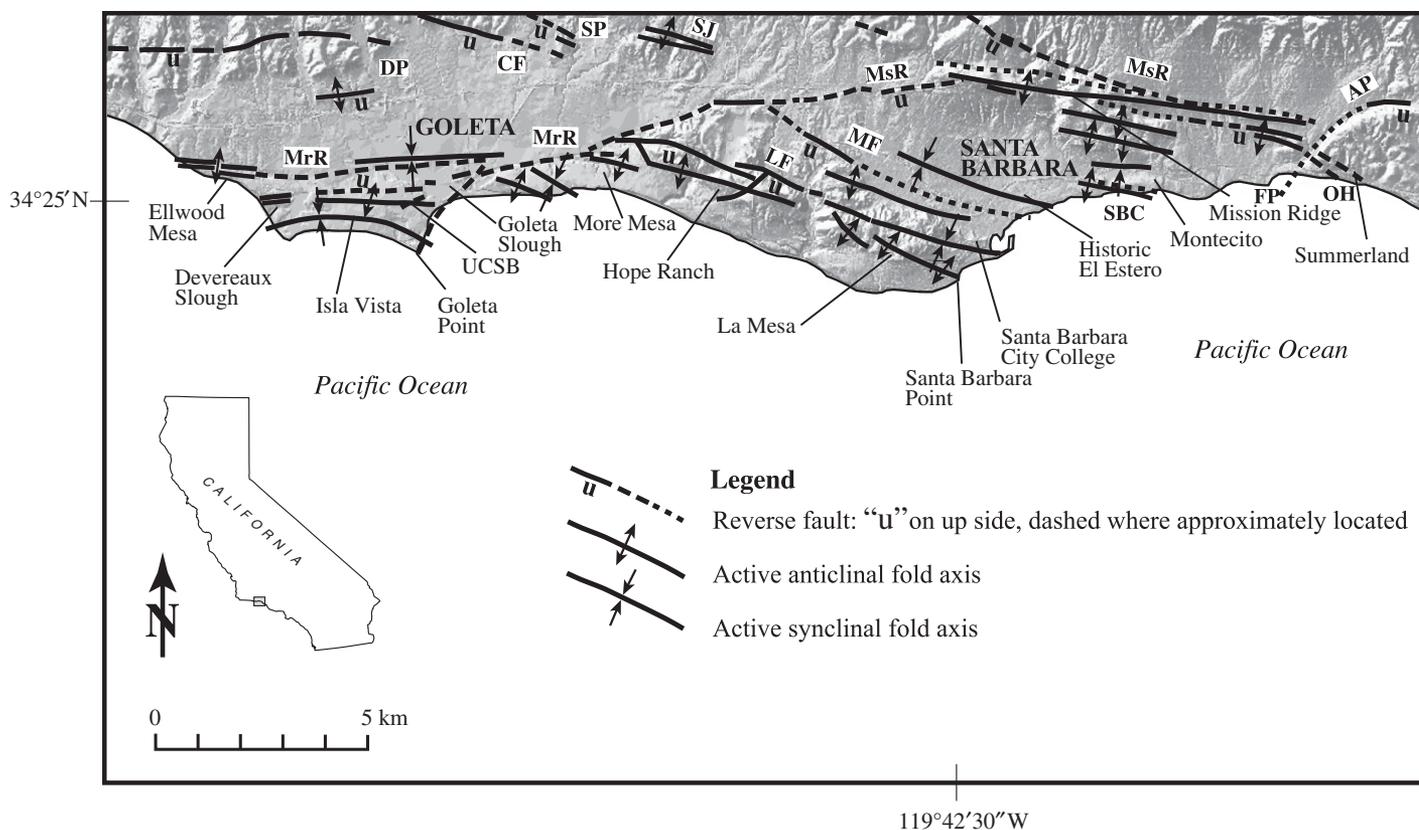


Figure 1. Onshore Santa Barbara fold belt showing south-dipping reverse faults, some of which are blind, with associated north-verging, hanging-wall anticlines and footwall synclines. The marine terrace landforms are preserved on anticlinal folds formed as the result of blind reverse and thrust faulting. The Mission Ridge fault system is subdivided into the More Ranch (MrR), the Mission Ridge (MsR), and the Arroyo Parida (AP) segments. Additional onshore reverse faults include the Dos Pueblos (DP), the Carneros (CF), the San Jose (SJ), the San Pedro (SP), the Lavigia (LF), the Mesa (MF), the Santa Barbara Cemetery (SBC), the Ortega Hill (OH), and the Fernald Point (FP) faults. UCSB—University of California—Santa Barbara.

morphic, and structural characteristics. Segment boundaries of the west- and northwest-striking faults are defined by abrupt changes in geometry, geomorphic expression, structural style of deformation, and termination of folds. These segment boundaries coincide with northeast-striking faults, termed cross faults by Gurrola and Kamerling (1996).

Topographically well-expressed folds are the result of mostly blind, active reverse faulting. Faulted anticlines form linear hills, whereas intervening low areas, such as the city of Santa Barbara and Goleta Valley, are faulted synclines. Coastal erosion has exposed stratigraphy at several of the anticlines. High sea cliffs are associated with anticlines, and synclines form lowland areas where prominent sea cliffs are not present. Thus, the geomorphology of the SBF is clear: where linear hills are encountered, these landforms are actively growing anticlines being uplifted in response to reverse faulting. In contrast, low-lying areas that comprise salt marshes and sloughs are faulted synclines, characterized by subsidence

(Fig. 1). Thus, in general, where a sea cliff is present, the landform is a limb of an anticline; where a sea cliff is absent, a syncline is often present (Keller and Gurrola, 2000; Minor et al., 2009).

The southern flanks of anticlines adjacent to the coast in the SBF generally have flights of marine terraces consisting of wave-cut platforms covered by a thin veneer of sediment that may include beach sands and gravel, dune sands, and/or stream deposits (Upson, 1951; Lajoie et al., 1982; Muhs et al., 1992). When the ages of a marine terrace (wave-cut platform) and associated paleo-sea level are known, the rate of uplift may be estimated (Rockwell et al., 1992). The landward edge of a marine terrace ends with a paleo-sea cliff, and the intersection of the wave-cut platform with the sea cliff defines the shoreline angle, which forms near the mean sea level. Thus, a series of uplifted marine terraces and associated shoreline angles provides a record of past sea levels. An analogy would be a strip recording of sea level (Lajoie et al., 1979, 1982). As a result, the chronology

of a flight of marine terraces can provide a history of uplift of an area.

There is no single global eustatic sea level curve, but there is a eustatic sea volume curve based on marine oxygen isotope stratigraphy that essentially relates to changes in global sea level due to climate change and the waxing and waning of Quaternary glaciers. The California sea level data demonstrate that sea level varies in time and space as a result of both eustatic change and geophysical forcings, including far-field glacial isostatic adjustment (GIA) as determined by modeling (Tamisiea and Mitrovica, 2011). The curve of Chappell et al. (1996) is widely used, but it is a regional curve with a far-field impact of GIA (Tamisiea and Mitrovica, 2011). The GIA component of sea level in southern California has been estimated by Muhs et al. (2012), and the resulting regional sea level curve is used to estimate rates of uplift in our paper. The sea level curve (Muhs et al., 2002) is preferable for our study because it is derived in part from regional studies in southern California

and far-field GIA to provide the best estimates of paleo-sea level for our study area.

The tectonic geomorphic evaluation of marine terraces of the SBFB has several objectives: first, to better understand the geomorphology of marine terraces in an active fold belt (in this case the Santa Barbara fold belt); second, to establish the terrace chronology necessary to estimate rates of tectonic processes (we numerically date several emergent marine terraces, using multiple dating methods to obtain, whenever possible, multiple ages on the same terrace); and third, to estimate rates of late Quaternary uplift of marine terraces to help better constrain the potential earthquake hazard.

METHODS OF STUDY

The late Pleistocene, emergent marine terraces of the SBFB were mapped using A.D. 1928 (1:18,000 scale) stereo aerial photographs. Commonly, the shoreline angle of a particular wave-cut platform is buried, and overlying deposits are exposed in sea cliff, stream-cut, and trench exposures, allowing for three-dimensional mapping, estimation of marine terrace strata thickness, and collection of fossil samples.

Marine terrace fossils are rare but most often are found preserved in a basal conglomerate on a wave-cut platform. Marine terrace fossil deposits were located in sea cliff exposures at Ellwood, University of California–Santa Barbara (UCSB), More Mesa, Santa Barbara Point, and Santa Barbara City College (SBCC) (Fig. 1). We sampled fossil deposits from sea cliff exposures to collect solitary corals for uranium-series age dating and mollusks for oxygen isotopic analysis.

Solitary corals (*Balanophyllia elegans*) are nearly closed systems with respect to the input of uranium from ocean waters following the death of the organism (Muhs, 1992). They can be accurately and precisely dated using uranium-series analysis, providing first-order age estimates of terrace formation (Ku and Kern, 1974). Solitary corals were collected from fossil deposits from the first emergent marine terraces at UCSB and SBCC. Initial $^{234}\text{U}/^{238}\text{U}$ ratios of the coral samples from the SBFB were compared to modern-day seawater to confirm that there was not an influx of secondary uranium. X-ray diffraction analyses of the samples were used to determine if there was any alteration of the original aragonite composition. Marine terrace corals at both sites were determined to be more than 99% aragonite, with no secondary calcite detected. The corals were prepared and analyzed in the Division of Geological Sciences at the California Institute of Technology and in the Isotope Laboratory at the U.S. Geological Survey using

the TIMS (thermal ionization mass spectrometry) method (Chen et al., 1986). The corals provide numerical ages for the first emergent marine terraces at UCSB and SBCC.

Marine terrace fossil deposits rarely contain solitary corals; therefore, alternative age-dating methods were employed. These included radiocarbon analyses of marine terrace fossil mollusks and detrital charcoal, both of which require calibration due to reservoir effects. The fossil mollusks were calibrated using the ^{14}C correction factor of Voelker et al. (1998). Calibration of detrital charcoal reservoir effects was accomplished using Cal-Pal software based on Jöris and Weninger (1998) and Weninger and Jöris (2008).

Marine terrace sand samples were collected for optically stimulated luminescence (OSL) dating of potassium feldspar and quartz grains. OSL dating is a radiometric method based on the time-dependent accumulation of electrons at traps within the crystal lattice of minerals, such as quartz and feldspar (Aitken, 1998). Natural ionizing radiation, due to cosmic rays and radioisotopes within the sediment, is essentially responsible for the gradual increase in the number of trapped electrons in the crystal lattice of the mineral over time, until a saturation level is reached. The release of the trapped electrons upon stimulation by heat and/or light results in a detectable luminescence signal. The intensity of the luminescence is a measure of the amount of radiation-induced electrons, which is dependent upon the rate of ionizing radiation (dose rate) and duration of burial. The OSL data yielded maximum ages of deposition of the sands for the Ellwood Mesa, UCSB, More Mesa, Santa Barbara Point, Santa Barbara Cemetery, and Summerland terraces (Fig. 1).

Fossil mollusks, specifically *Olivella biplicata*, record the marine oxygen isotope signatures of paleo-ocean temperatures for the sea level highstand when the marine terrace formed. Fossil mollusk shells were collected at the Ellwood, UCSB, More Mesa, Santa Barbara Point, and SBCC marine terraces for marine oxygen isotope ($\delta^{18}\text{O}$) analysis (Trecker et al., 1998; Trecker, 1999). The isotopic signatures are associated with the late Pleistocene $\delta^{18}\text{O}$ sea level curve and assist in the correlation of marine terraces throughout the region. Isotopic analysis was undertaken in the laboratory of James Kennett at the University of California. From the work of Trecker (1999), it is clear that $\delta^{18}\text{O}$ values for MIS 3a ($\delta^{18}\text{O} = 1.0$ per mil) are very different than those for MIS 5a ($\delta^{18}\text{O} = -0.7$ per mil). By way of comparison, modern *Olivella* at Campus Point (UCSB) have $\delta^{18}\text{O}$ values of 0.0 ± 0.2 per mil (Trecker, 1999). In our paper, values of $\delta^{18}\text{O}$ are used to help distinguish MIS 3 from MIS 5.

Rates of uplift were estimated by dividing the sum of the elevation of the shoreline angle and the paleo-sea level by terrace age. Elevations of terrace shoreline angles are measured with an uncertainty of $\sim 1\text{--}2$ m, as are paleo-sea levels. Elevations reported, unless otherwise noted, are in meters above or below present mean sea level. The uncertainties for the numeric ages are listed in Table 1.

The method of Bull (1985) is used to estimate ages of older, higher marine terraces in the SBFB. Limitations of the method are considered in the discussion section of the paper.

STRATIGRAPHY

Pre-Quaternary Stratigraphy

Pre-Quaternary strata of the SBFB consist of a section of Eocene through Pliocene sedimentary rocks that were deposited in a continental margin setting. These rocks include, from oldest to youngest, the Coldwater Sandstone, Sespe Formation, Vaqueros Sandstone, Rincon Formation, Monterey Formation, and Sisquoc Formation. The Sespe, Rincon, Monterey, and Sisquoc Formations typically form the rocks of the mountain slopes and the rocks of the coastal piedmont (Arnold, 1907; Dibblee, 1966; Lian, 1952; Minor et al., 2009; Olson, 1982; Upson, 1951). In some cases, these rocks are locally uplifted in the cores of anticlines and along faults (Minor et al., 2009).

Quaternary Stratigraphy

Quaternary strata of the SBFB consist of a succession of Pleistocene marine and non-marine strata. The Pleistocene strata were deposited on pre-Quaternary strata on the coastal piedmont. The Quaternary units, from oldest to youngest, include the Santa Barbara Formation, the Casitas Formation, late Pleistocene–Holocene marine terrace deposits, fan conglomerate deposits, and other alluvium (Gurrola, 2005; Minor et al., 2009). Our discussion will focus on the late Pleistocene marine terrace and younger deposits.

Late Pleistocene Marine Terrace Deposits

Wave-cut platforms in the SBFB are eroded on pre-Quaternary strata, such as the Sisquoc and Monterey Formations and the Pleistocene Santa Barbara and Casitas Formations. The platforms are commonly overlain by a thin, basal cobble to pebble conglomerate (boulder line) with overlying terrace deposits ranging from a 2-m- to a 5-m-thick section of marine sands with an aeolian cap. Terrace fossils preserved in the conglomerate or in locally

TABLE 1. NUMERICAL DATES FOR MARINE TERRACE DEPOSITS IN THE SANTA BARBARA FOLD BELT

Sample location—terrace site	Sample number	Uranium-series age (ka)*	Measured ¹⁴ C age (RCYBP) [†]	Calibrated age (yr)#	Measured luminescence age [§] (ka)	
					Quartz	K-feldspar
University of California, Santa Barbara—Isla Vista terrace	IV-1-96	47 ± 0.5	43,790 ± 770	45,356 ± 1665		40 ± 3
	IV-2-98	49 ± 1.7				
Ellwood Mesa	C-5		35,860 ± 570	38,700 ± 966		
Ellwood Mesa	C-12		37,000 ± 570	39,905 ± 413		
Ellwood Mesa	C-14		47,020 ± 1500	48,767 ± 2601		
Ellwood Mesa	Bell Canyon				36 ± 3	
Ellwood Mesa	Golf course				45 ± 4	
More Mesa terrace	MM-1-96		36,830 ± 330	39,821 ± 330		53 ± 7
	MM-2-98					
Santa Barbara City College terrace	SBCC-1-98	70 ± 2.0			109 ± 23	
	SBCC-2-98					
Santa Barbara Point	SBP-1-98					58 ± 11
Santa Barbara Cemetery	SBC-1-98					79 ± 10
Summerland terrace	LP-2-98				105 ± 15	

*Uranium-series and luminescence ages are reported as 1 ka = 1,000 years before present; J. Chen at the California Institute of Technology and K. Simmons and D. Muhs with the U.S. Geological Survey provided data and performed the analysis. Both used the thermal ionization mass spectrometry method.

[†]Radiocarbon samples were submitted to Beta Analytic Laboratory (Miami, Florida) for accelerator mass spectrometry analysis and ages are designated as radiocarbon years before present (RCYBP).

[§]Optically stimulated luminescence age estimates are based on analysis of quartz and potassium feldspar grains (L. Owen's lab, formerly at the University of California, Riverside; now at the University of Cincinnati).

[#]Radiocarbon ages in RCYBP are calibrated using the Cologne Radiocarbon Calibration Programme (CalPal) at www.calpal.de.

fossiliferous units were sampled to obtain solitary corals for uranium-series age-dating analysis. Three solitary corals from the UCSB and the SBCC marine terraces were analyzed (Table 1).

Late Pleistocene Alluvial and Fanglomerate Deposits

Pleistocene alluvial fan deposition on the coastal piedmont occurred in south-flowing streams from the Santa Ynez Mountains. Fanglomerates are generally composed of coarse boulders and gravels, whereas alluvial deposits generally range from siltstone and sandstone to cobble-gravel conglomerate, which may overlie marine terrace deposits. The ages of late Pleistocene alluvial and fanglomerate units are mostly unknown, but they are younger than those underlying the Casitas Formation, and, therefore, were most likely formed during the mid- to late Pleistocene. Alluvial fan gravels merge at the coast with marine terraces of similar age.

Holocene Alluvial, Fluvial, and Colluvial Deposits

Holocene alluvium typically consists of clay-rich, siltstone and sandstone and conglomerate units that cap late Pleistocene marine terrace units. Holocene colluvial units generally consist of brecciated, matrix- to clast-supported conglomerates and are deposited at the base of fold, fault, and sea cliff scarps. Holocene fluvial units typically consist of clay, silt and sand, and gravel to cobble conglomerate units deposited along active south-flowing stream channels on the coastal piedmont. These deposits are assumed to be Holocene because of their young morphostratigraphic positions and general lack of soil development, but they were not dated in our study of marine terraces.

TECTONIC GEOMORPHOLOGY OF MARINE TERRACES

Marine Terraces

Several flights of marine terraces are preserved in the SBBF. They likely reflect the interaction of paleo-sea level and tectonic uplift (Matthews, 1973; Kern, 1977; Lajoie et al., 1982; Muhs et al., 1992, 2002). Emergent marine terraces originate as eroded, wave-cut platforms forming unconformities on the underlying bedrock. Commonly, as tectonic uplift occurs, a thin veneer of (regressive) marine sands is preserved on the marine platform, producing an unconformity that is subsequently covered by alluvial and colluvial sediments.

The intersection of a former sea cliff with the wave-cut abrasion platform defines the terrace shoreline angle (Lajoie et al., 1979). The shoreline angle approximates the position of former sea level within one or two meters of mean (high) sea level for that platform level and is the preferred reference to past sea levels. However, the shoreline angle is typically buried beneath beach deposits, sea cliff colluvium, and/or alluvium, and, as a result, the elevation of the shoreline angle is estimated based on proximal exposures and known subsurface data.

Santa Barbara Coastal Marine Terrace Morphology

Marine terraces are some of the most obvious landforms on the Santa Barbara coastal piedmont. Elevations of wave-cut platform shoreline angles range from ~25 m to greater than 200 m above present mean sea level. Expressions of paleo-shoreline angles are relatively poor, but

associated paleo-sea cliffs often form moderately to well-expressed scarps. Paleo-shorelines are often laterally discontinuous across streams that dissect terraces, are deformed by folds, and/or are buried beneath alluvial fan and colluvial deposits (Fig. 2).

A succession of marine terraces at a specific site is discussed with respect to the first emergent marine terrace, which is at the seaward edge. The first emergent marine terraces at Ellwood, UCSB, Santa Barbara Point, SBCC, More Mesa, Santa Barbara Cemetery, and Summerland have estimated ages based upon several chronological methods. A more detailed discussion of the marine terraces is provided in Gurrola (2005). The results are summarized below.

Marine Terrace Chronology and Rates of Uplift

Establishment of the marine terrace chronology is fundamental to the estimation of the rate of uplift. Dating of terrace fossil fauna directly overlying the abrasion platform determines a minimum age of platform formation. Commonly, along the California coast, first emergent marine terraces are formed during the high sea levels of MIS 5 (80 ka to 120 ka) (Muhs et al., 2002, 2012). Muhs et al. (2012) used numerical simulations at global scale that include GIA-induced sea level changes over the past 120 k.y. Terraces formed during high sea levels of MIS 3a (ca. 45 ka) are present along the Santa Barbara and Ventura coasts (Lajoie et al., 1982; Gurrola et al., 1996, 1997). MIS 3 terraces are the broadest and best developed in the SBBF. Tables 1–3 summarize the chronology and dates of uplift for marine terraces of the SBBF.

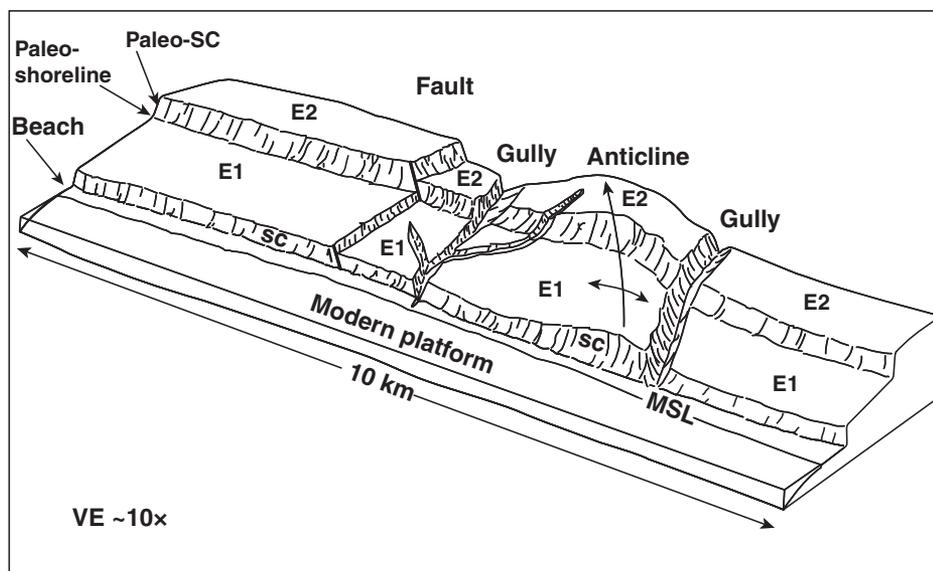


Figure 2. Idealized diagram of the modern wave-cut platform and associated sea cliff (SC) and relations to uplifted marine terraces and associated morphology. The first emergent marine terrace is E1, and the second emergent marine terrace (E2) is the next higher marine terrace. The elevation of the terrace shoreline angle is measured in order to calculate total amount of vertical surface uplift. Note that the uplifted marine terraces are discontinuous and folded, complicating their correlation (modified after Trecker et al., 1998). VE—vertical exaggeration.

Ellwood Terrace

The Ellwood Mesa marine terrace is the first emergent terrace west of Devereaux Slough (Fig. 3). At Devereaux Creek, the marine terrace is anticlinally folded on the hanging wall of the More Ranch segment, whereas to the west, the marine terrace is faulted and vertically offset in a sea cliff exposure (Fig. 4). Although the Ellwood marine terrace is deformed across the More Ranch segment of the MRFS, the marine abrasion platform can be mapped across the fault. The Ellwood marine terrace strandline is poorly preserved north of the More Ranch segment (Fig. 3). Aerial photographs from 1929 reveal that the strandline is moderately well expressed and can be mapped across the Ellwood marine terrace westward to where it trends offshore, west of the fault exposure.

The elevation of the first emergent Ellwood marine terrace is ~24 m asl (above present-day mean sea level). Detrital charcoal sampled from the basal terrace unit yielded a radiocarbon age of 48.8 ± 2.6 ka, and OSL measurements of the quartz from marine terrace sands yielded age estimates of 36 ± 3 and 45 ± 4 ka (Table 1). Oxygen isotopic signatures ($\delta^{18}\text{O} > 1.1$) of terrace mollusks (*Olivella biplicata*) sampled from the fossil site indicate a cool paleo-ocean temperature (J. Kennett, 2009, personal commun.), which is consistent with the numerical ages

from radiocarbon and OSL analysis. Based on the estimated elevation of the shoreline angle, the amount of total, vertical uplift for MIS 3a is ~86 m. Sea level for California at 47 ka was close to 62 m below the present-day mean sea level (Muhs et al., 2012), yielding an estimated local rate of uplift of ~1.8 m/k.y. (Table 2).

Higher flights of terraces are preserved above present-day mean sea level near Goleta (Fig. 3). The shoreline angles associated with these marine terraces are moderately to poorly preserved and, in places, buried by ~2.5–4 m of alluvium. To the west, the highest marine terrace (Table 3) caps north-south-trending ridges, and to the east, caps the crests of active folds. As a result, this marine terrace is laterally discontinuous due to numerous deeply incised drainages, but, by position, it appears to be the same marine terrace surface from Goleta Valley to the western study area. The marine terrace surfaces are mostly stripped, with little or no marine terrace sediments preserved.

UCSB Terrace

The first emergent marine terrace at UCSB extends from Devereaux Slough to Goleta Slough and is bounded by the More Ranch fault to the north and the Coil Oil Point fault to the south (Figs. 3, 5). A marine terrace fossil assemblage is exposed on the sea cliff at Isla Vista beach on the first emergent UCSB marine ter-

race (Fig. 3). The fossil site was sampled, and a solitary coral was obtained for uranium-series and radiocarbon analyses. Two well-preserved, fossil solitary coral *Balanophyllia elegans* were collected and yielded uranium-series ages of 47 ± 0.5 ka and 49 ± 1.7 ka and a calibrated radiocarbon age of 45.4 ± 1.7 ka (from coral) (Table 1).

Marine terrace sands were sampled at the Isla Vista fossil site to measure potassium feldspar grains for OSL dating (Fig. 3). OSL measurements of the terrace sands yielded an age estimate of ca. 40 ± 3.0 ka (Table 1).

Oxygen isotopic signatures ($\delta^{18}\text{O} > 1.1$) of terrace mollusks (*Olivella biplicata*) sampled from the fossil site indicate a cool paleo-ocean temperature (Trecker et al., 1998; Trecker, 1999), which is consistent with the numerical ages from uranium-series, radiocarbon, and OSL analysis. Therefore, the UCSB terrace is assigned a best-estimate age from the uranium-series dates to ca. 48 ka (MIS 3a).

The paleo-shoreline associated with the UCSB terrace is buried on the footwall of the More Ranch fault segment. The maximum observed elevation of the marine platform is ~14.0 m above present-day mean sea level. Assuming sea level at 48 ka was ~62 m below the present-day mean sea level (Muhs et al., 2012), we estimate a vertical surface uplift of 76 m and a vertical surface uplift rate of 1.6 m/k.y. (Tables 2 and 3). This local uplift rate is the result of folding and faulting on several adjacent structures, including the More Ranch fault segment to the north.

More Mesa Terraces

More Mesa is the most laterally continuous and well-expressed marine terrace in the SBFB (Fig. 6). The More Mesa marine terraces are continuous from Las Positas west to Goleta Slough. More Mesa is located on the hanging wall of the More Ranch fault, and the north margin is bounded by the More Ranch segment, which truncates several marine terrace shorelines.

The first emergent marine terrace is preserved on the axis of a Quaternary syncline, and the marine terrace surface is tilted and down-warped to the north (Fig. 6). The marine terrace forms a 4-km-long and nearly 1-km-wide surface. The shoreline angle of the first emergent marine terrace is buried, due to the synclinal warping of the marine terrace, and is the least discernible of all marine terraces.

A fossil locality was discovered on the first emergent marine terrace in a gully at a sea cliff re-entrant (Fig. 6). The age of the marine terrace is estimated by radiocarbon dating of a pholad shell, OSL of potassium feldspar in marine

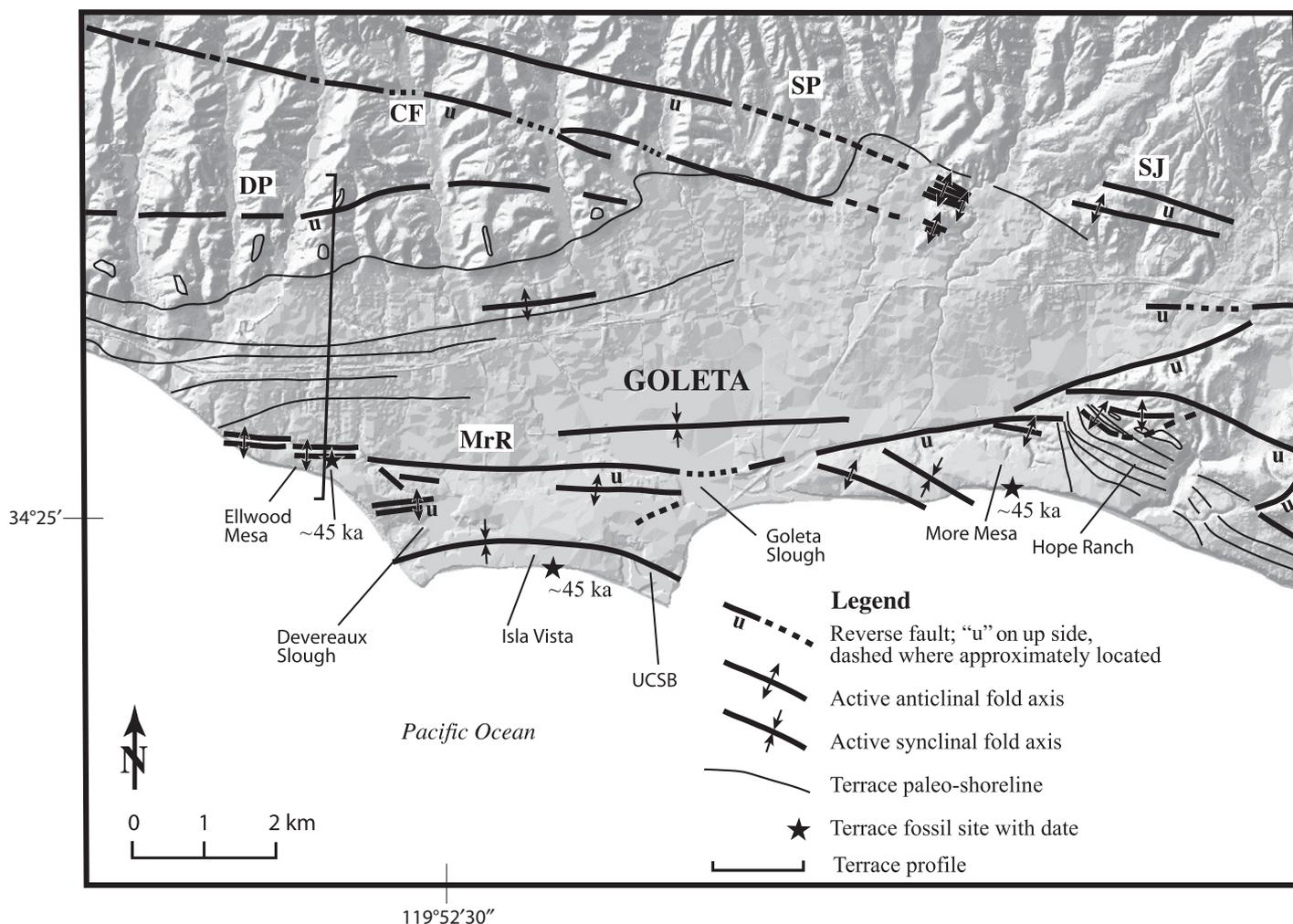


Figure 3. Map of the Ellwood and University of California–Santa Barbara (UCSB) campus area showing major structures, shoreline angle, and the positions of the associated paleo-shorelines. Note that the paleo-shorelines are discontinuous at drainages and eroded across the More Ranch fault (MrR). Other faults include the Carneros (CF), the Dos Pueblos (DP), the San Jose (SJ), and the San Pedro (SP) faults.

terrace sand, and correlation by isotopic signatures of mollusks.

A fossil pholad shell obtained from a rock borehole in growth position was sampled. Initial SEM (scanning electron microscopy) analysis determined that the shell material was unaltered aragonite. The shell yielded a calibrated ^{14}C age of 39.8 ± 0.3 ka (Table 1); however, Voelker et al. (1998) reported a large fluctuation in the calibration of ^{14}C ages between 32 and 34 ka and determined a ^{14}C age offset (correction factor) of ca. 5 ± 1 ka for the pholad age, which results in a calibrated ^{14}C age of ca. 45.5 ± 1.4 ka.

Oxygen isotope signatures ($\delta^{18}\text{O} > 1.1$) of fossil mollusks sampled from the More Mesa marine terrace indicate a cool paleo-ocean temperature signature correlating to the UCSB site (Trecker et al., 1998). Additionally, terrace sands were sampled at the fossil site for OSL dating to estimate an age for potassium feldspar

grains. The OSL analysis estimated an age of 53 ± 7 ka for marine terrace sands (Table 1). Unfortunately, the large uncertainty does not allow us to distinguish whether the sands were deposited during MIS 3a or MIS 3c. However, the calibrated ^{14}C age of the fossil pholad and the isotopic signatures of the fossil mollusks, combined with the OSL age, suggest the More Mesa terrace correlates to MIS 3a at ca. 48 ka. The estimated age of the More Mesa marine terrace is consistent with other terraces (i.e., Ellwood and Isla Vista–UCSB) uplifted on the hanging wall of the More Ranch fault.

Elevations and estimated ages of the More Mesa terraces are shown in Table 3. Higher terrace strandlines correlate with MIS 3 and 5. Total surface uplift for the first emergent marine terrace is ~97 m. A surface uplift rate of 2.0 m/k.y. is estimated based on the age of 48 ka, the elevation of the shoreline angle, and Muhs

et al.'s (2012) estimate of sea level at 48 ka of ~62 m below present-day mean sea level (Tables 1 and 2).

La Mesa Terraces

East of the More Mesa terraces, the La Mesa marine terraces and associated strandlines are continuous from the outlet to Los Positas Canyon along the southern flank, eastward across the Mesa anticline (Figs. 7–9). The marine terraces are uplifted along the south limb of the La Mesa and Lavigia anticlinal folds on the hanging walls of the blind La Mesa and Lavigia reverse faults, respectively. The marine terraces and associated strandlines are truncated east of SBCC by the Mesa fault and subsequent erosion from Mission Creek.

A series of 7 marine terraces with associated shorelines is preserved at Santa Barbara Point on La Mesa (Fig. 7). The highest marine abrasion

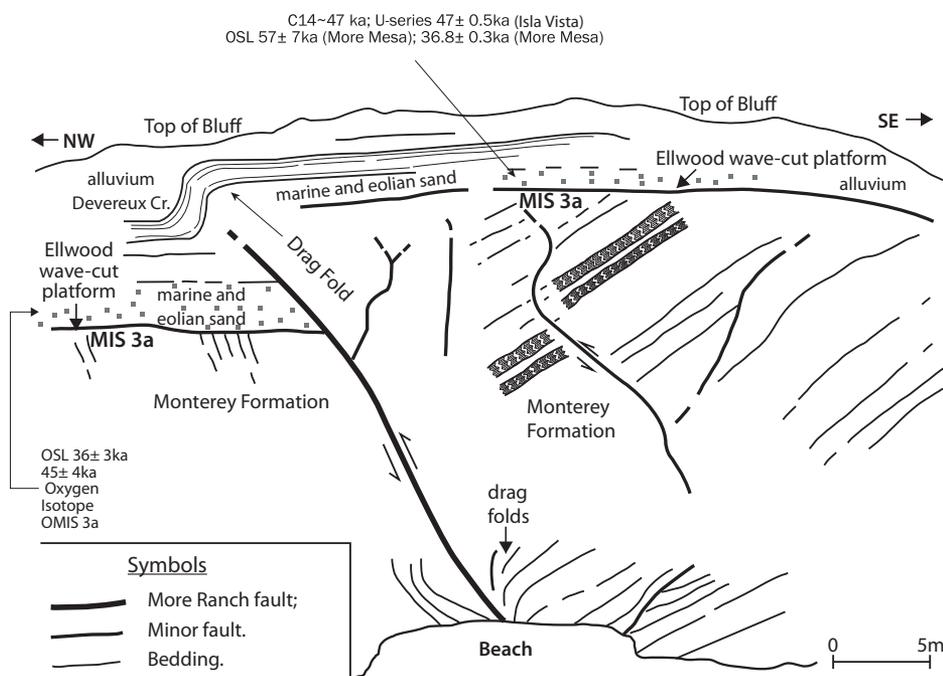


Figure 4. Cliff exposure showing the More Ranch fault at Ellwood Mesa with numerical ages for deformed strata. Modified from Metcalf (1994) and Keller and Gurrola (2000). MIS—marine oxygen isotope stage; OSL—optically stimulated luminescence.

platform with the strandline absent is preserved at an elevation of ~148 m above present mean sea level (Table 3).

The paleo-shoreline of the first emergent marine terrace at Santa Barbara Point is discontinuous. To the west, the paleo-shoreline trends offshore, and to the east, it is buried by alluvial fan–delta deposits. Several marine terrace shoreline angles are mappable at SBCC. Based on mapping and correlation, the second emergent marine terrace at Santa Barbara Point is the 70 ka marine terrace shoreline at SBCC (Fig. 7).

OSL measurements of quartz grains sampled from terrace sands at Santa Barbara Point yield an age of 58 ± 11 ka for the first emergent marine terrace (Fig. 9; Table 1). Given the large uncertainty associated with the OSL age, it is

not possible to determine whether the marine terrace formed during MIS 3a (ca. 45 ka) or 3c (ca. 58 ka). Oxygen isotope data from fossil mollusks from Santa Barbara Point indicate a cool ocean temperature (Trecker et al., 1998).

Based on the OSL age of terrace sands, the isotopic signatures of fossil mollusks, and the position of the second emergent terrace at Santa Barbara Point which correlates with the first emergent terrace at SBCC dated at ca. 70 ka, the first emergent terrace likely is correlated to MIS 3c (58 ka) and, hence, a local rate of surface uplift of 1.2 m/k.y. is estimated (Table 2). Sea level for California at 58 ka was ~55 m lower than present-day mean sea level (Muhs et al., 2012). Estimated ages of higher terraces are shown in Table 3.

Along the south limb of the fold at SBCC, a marine terrace fossil assemblage is exposed in the sea cliff on the first emergent marine terrace at SBCC, formerly known as Bathhouse Beach (Fig. 7). A fossil coral was obtained from the paleontology collection at the Department of Earth Science at UCSB. The coral was a well-preserved, solitary coral (*Balanophyllia elegans*) sampled from the sea cliff exposure at the Bathhouse Beach fossil site. Uranium-series analysis of the fossil coral yielded an age of 70 ± 2 ka (Table 1). The oxygen isotope analyses ($\delta^{18}O > 0.73$) of fossil mollusks indicate warmer ocean water signatures than the UCSB site (Trecker et al., 1998). Sea level at 70 ka was ~44 m below present-day mean sea level (Muhs et al., 2012).

At SBCC, there are five uplifted marine terraces with associated paleo-shorelines and one abrasion platform with the strandline removed by erosion, preserved in the same marine terrace flight as the SBCC site. A rate of local surface uplift of ~1.1 m/k.y. is estimated, based on the uranium-series age of 70 ka for the first emergent marine terrace at SBCC and Muhs et al.'s (2012) estimate of paleo-sea level of 44 m below present mean sea level and a total surface uplift of ~74 m (Table 2). This is in agreement with the rate at Santa Barbara Point. Ages of higher marine terraces at SBCC are shown in Table 3 (Fig. 7).

Santa Barbara Cemetery

The first emergent marine terrace is a 1–2-km-long by 300-m-wide surface in the Montecito area, which is truncated by surficial drainage and is deformed across the Santa Barbara Cemetery anticlinal fold (Fig. 10). The maximum elevation of the marine terrace is ~25 m above present-day mean sea level.

A steep, south-facing paleo-sea cliff is preserved north of the fold at an elevation of ~25 m above present-day mean sea level. The next higher marine terrace is preserved on the south limb of the Mission Ridge anticline. The shoreline angle of this marine platform is buried or eroded due to faulting, and the maximum plat-

TABLE 2. ESTIMATED UPLIFT RATES OF FIRST EMERGENT TERRACES OF THE SANTA BARBARA FOLD BELT

Terrace Location	Approximate elevation of first emergent terrace shoreline (m)	Approximate age (ka)*	Uplift rate	
			California regional sea level (m)†	Uplift rate (m/k.y.)
University of California–Santa Barbara (Fig. 3)	14	48	–62	1.6
Ellwood Mesa (Fig. 3)	24	48	–62	1.8
More Mesa (Fig. 6)	35	48	–62	2.0
Santa Barbara Point (Fig. 7)	15	58	–55	1.2
Santa Barbara City College (Fig. 7)	30	70	–44	1.1
Santa Barbara Cemetery (Fig. 10)	25	80	–10	0.4
Summerland (Fig. 10)	34	105	–14	0.5

*See numerical ages of terraces shown in Table 1.

†California sea level for each terrace age shown is relative to present-day sea level (Muhs et al., 2012): 47 ka (–64 m); 58 ka (–57 m); 70 ka (–39 m); 80 ka (–6 m); 105 ka (–15 m).

TABLE 3. LIST OF MARINE TERRACE FLIGHTS, FROM WEST TO EAST, IN THE SANTA BARBARA FOLD BELT

	Terrace flight number	Elevation (m)	Age, nd, est*	Uplift rate (m/k.y.) ^{††}	Relative sea-level change at terrace formation
Ellwood Mesa (Fig. 3)	1	23.5 ± 1.5	48,767 ± 2601 ^{††}	1.8	Falling sea level
	2	31.5 ± 2.0	52,000 ± 500		Falling sea level following highstand
	3	39.0 ± 2.0	55,000 ± 1000		Highstand
	4	44.0 ± 2.5	58,000 –2000/+5000		Rising sea level near highstand
	5	63.0 ± 3.0	67,500 ± 500		Falling sea level
	6	131.0 ± 3.25	80,000 +11,000/–1000		Falling sea level near highstand
University of California–Santa Barbara (Fig. 3)	1	14.0 ± 0.5	48,000 ± 1100 [§]	1.6	Falling sea level
More Mesa (Fig. 6)	1	35.0 ± 1.5	39,821 ± 330 [†]		Falling sea level
	2	40.0 ± 1.5	53,000 ± 7000 ^{**}	2.0	Falling sea level
	3	50.0 ± 2.0	40,750 ± 250		Falling sea level
	4	59.0 ± 2.0	44,000 ± 500		Falling sea level
	5	81.5 ± 3.0	47,500 ± 500		Falling sea level
	6	106.5 ± 3.0	56,000 ± 1000		Highstand
	7	118.5 ± 3.0	67,000 ± 500		Falling sea level
	8	187.5 ± 3.0	79,000 ± 500		Falling sea level
	9	91,750 ± 500	Falling sea level		
La Mesa: Santa Barbara Point (Fig. 7)	1	15.0 ± 1.0	58,000 ± 11,000 ^{**}	1.2	Rising sea level near highstand
	2	27.0 ± 1.5	67,000 ± 500		Falling sea level
	3	37.5 ± 2.0	69,000 ± 500		Falling sea level
	4	47.0 ± 2.0	70,500 ± 500		Falling sea level
	5	58.0 ± 3.0	72,500 ± 750		Falling sea level
	6	76.0 ± 3.5	76,000 +250/–750		Falling sea level
	7	147.5 ^{§§}	118,000 ± 1000		Falling sea level
La Mesa: Santa Barbara City College (Fig. 7)	1	30 ± 1.5	70,000 ± 2000 [§]	1.1	Falling sea level
	2	43.5 ± 2.0	72,000 ± 250		Falling sea level
	3	61.5 ± 2.0	76,000 ± 250		Falling sea level
	4	76.0 ± 3.0	80,000 ± 250 or 92,500 ± 250		Highstand or falling sea level
	5	125.5 ± 3.5	120,000 ± 250		Highstand
Santa Barbara Cemetery (Fig. 10)	1	25.0 ± 1.5	79,000 ± 10,000 ^{**}	0.4	Highstand
	2	31.5 ± 2.0	95,000 +1000/–250		Falling sea level
Summerland (Fig. 10)	1	33.5 ± 1.5	105,000 ± 15,000 ^{**}	0.5	Highstand
	2	50.0 ± 2.5	115,000 +500/–250		Falling sea level

*nd—first emergent terrace is numerically dated; est—ages of older terraces are estimated using the method of Bull (1985) and sea level curve of Muhs et al. (2012). See Table 1 for all numerical dates.

[†]Denotes maximum ¹⁴C age of the samples obtained from terrace units. ¹⁴C date is calibrated using CalPal correction software, www.calpal.de.

[§]Denotes average of two uranium-series ages of terrace fossil corals.

[¶]Uranium-series age.

^{**}Optically stimulated luminescence age.

^{††}See Table 2.

^{§§}Terrace platform which is stripped of terrace deposits.

form elevation is estimated to be ~32 m above present-day mean sea level.

Marine sands were sampled from the first emergent terrace along the modern sea cliff at Montecito to measure OSL of potassium feldspar. The OSL analysis indicates an age of ca. 80 ka for the terrace sand (Table 1). A local uplift rate of ~0.4 m/k.y. is estimated, based on the maximum elevation of the first emergent marine terrace at ~25 m above present-day mean sea level and Muhs et al.'s (2012) estimate of sea level at 80 ka of ~10 m below present-day sea mean level, and hence, a calculated total uplift of ~35 m (Table 2).

Summerland Marine Terrace

The first emergent marine terrace at Summerland is uplifted and preserved on the hanging wall of the Arroyo Parida segment of the MRFS (Fig. 10). The shoreline angle of the first emergent marine terrace extends 2 km from the Ortega Hill anticline eastward to where it trends offshore.

A marine platform and associated shoreline angle is exposed in a railroad-cut exposure on the south flank of the Ortega Hill anticline

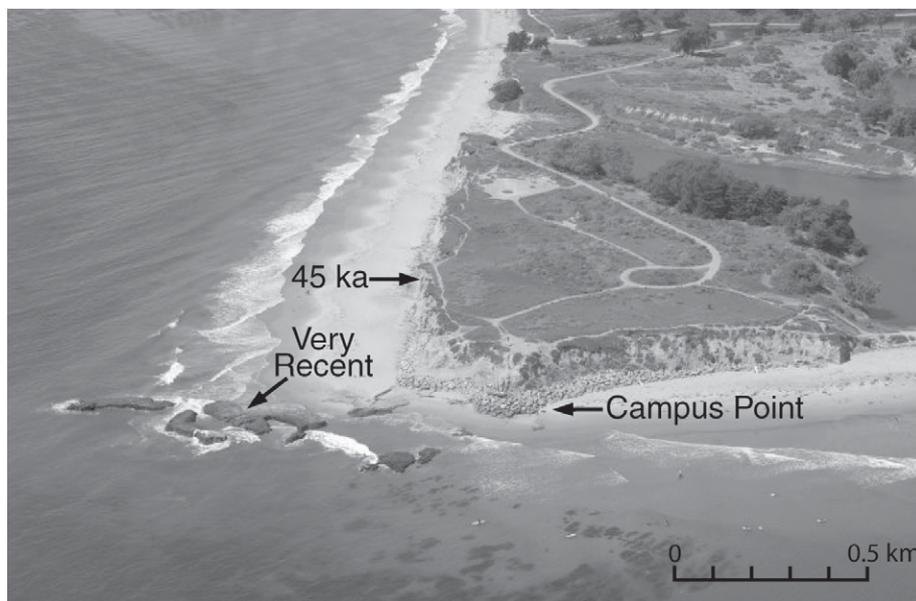


Figure 5. University of California–Santa Barbara marine terrace. The campus is mostly sited on the ca. 45 ka terrace. At Campus Point, a very young wave-cut platform is present. This platform was probably uplifted during a recent earthquake. Modified after California Coastal Records Project, 2002–2007 (www.californiacoastline.org). Image courtesy of Kenneth and Gabrielle Adelman.

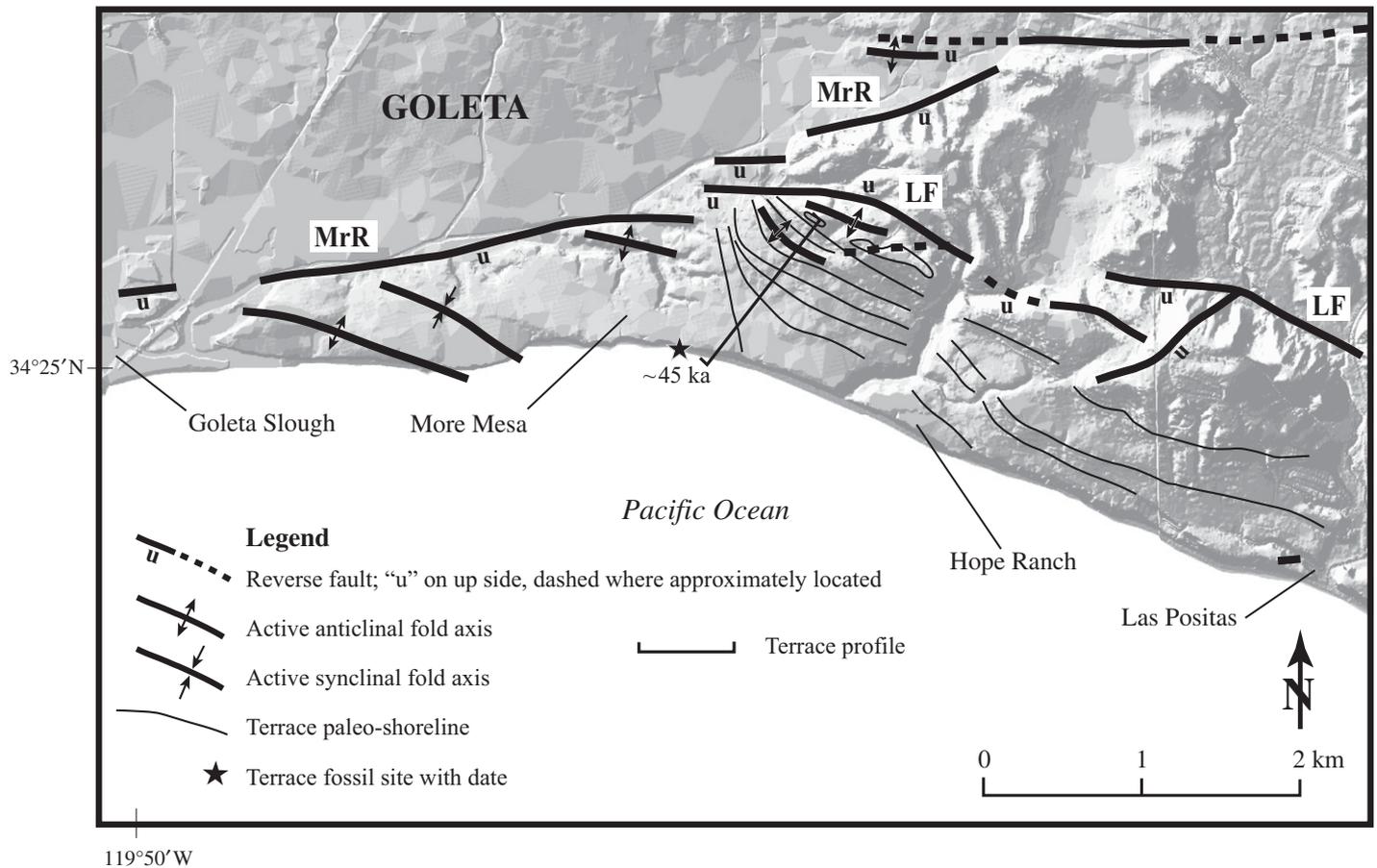


Figure 6. Map of the More Mesa marine terraces on the hanging wall of the More Ranch (MrR) and Lavigia (LF) faults. The positions of the five emergent marine terraces and associated paleo-shorelines are shown.

(Fig. 10). The wave-cut abrasion platform is inclined $\sim 2^\circ$ to 4° to the southeast and is denoted by a cobble bed 0.2–1 m thick. The cobbles have occasional pholad borings, indicating a nearshore beach depositional environment. The cobble bed is overlain by a thin, discontinuous 0.5-m-thick bed composed of well-sorted, medium to fine (beach) sand. The cobble bed is terminated against steeply south-dipping, non-marine Casitas strata (paleo-sea cliff), forming a buried wave-cut notch at an elevation of $\sim 23 \pm 1.0$ m above present-day mean sea level (Fig. 11). The age of this marine platform and terrace is unknown, but it probably correlates with the Summerland terrace.

The first emergent marine terrace near Summerland is exposed along the modern beach sea cliff. The elevation of the shoreline angle is ~ 34 m above present-day mean sea level. The marine terrace is synclinally folded, and its surface drops steadily in elevation to the east until it passes below sea level into the Carpinteria syncline. Marine terrace sands were sampled for OSL dating and yielded an age of 105 ± 15 ka (Table 1). Paleo-sea level at 105 ka was ~ 14 m

below present-day mean sea level (Muhs et al., 2012). The estimated amount of surface uplift is ~ 48 m, and the estimated uplift rate is ~ 0.5 m/k.y. (Table 2).

DISCUSSION

Rates of uplift of marine terraces in southern California tend to be relatively low at 0.1–0.3 m/k.y. (Muhs et al., 1992; Rockwell et al., 1992). A notable exception is in the vicinity of Carpinteria to Ventura where rates likely exceed 8 m/k.y. (Lajoie et al., 1979). The very high rates near Ventura result from a rate of convergence that approaches or exceeds 10 m/k.y. (Rockwell et al., 1992). The rates of uplift of the SBBF vary from ~ 0.5 to 2 m/k.y., which at the higher rates are several times that of most of southern California. The highest rates are near More Mesa and westward to Ellwood Mesa. These high rates are associated with the presence of a MIS 3a marine terrace, which extends for a number of kilometers along the coast. For this marine terrace to be even present, a rate of uplift exceeding 1 m/k.y. is needed.

In this paper, we use a variety of dating techniques and have attempted to obtain multiple dates on the same marine terrace. For example, for the Isla Vista terrace, we have two uranium-series ages on solitary coral, a ^{14}C age from the crushed coral, and an OSL age. The ages are essentially the same, and, so, we have considerable confidence that the UCSB–Isla Vista marine terrace formed during MIS 3a. For the Ellwood marine terrace, we have several radiocarbon and OSL ages and information from oxygen isotopes ($\delta^{18}\text{O} > 1.0$) on the gastropod *Olivella biplicata*, all of which suggest that the Ellwood terrace formed during MIS 3a (see Table 1). Chronology of marine terraces that are higher and older than the first emergent marine terrace at a particular site is rare.

The regional rates of uplift of the Santa Barbara coast estimated in this paper result from displacement and folding on several known faults, the slip rates of which remain mostly unknown. The method of Bull (1985), with the sea level curve of Muhs et al. (2012), assumes a constant uplift rate (not constant rate of faulting) and was evaluated using terrace flights

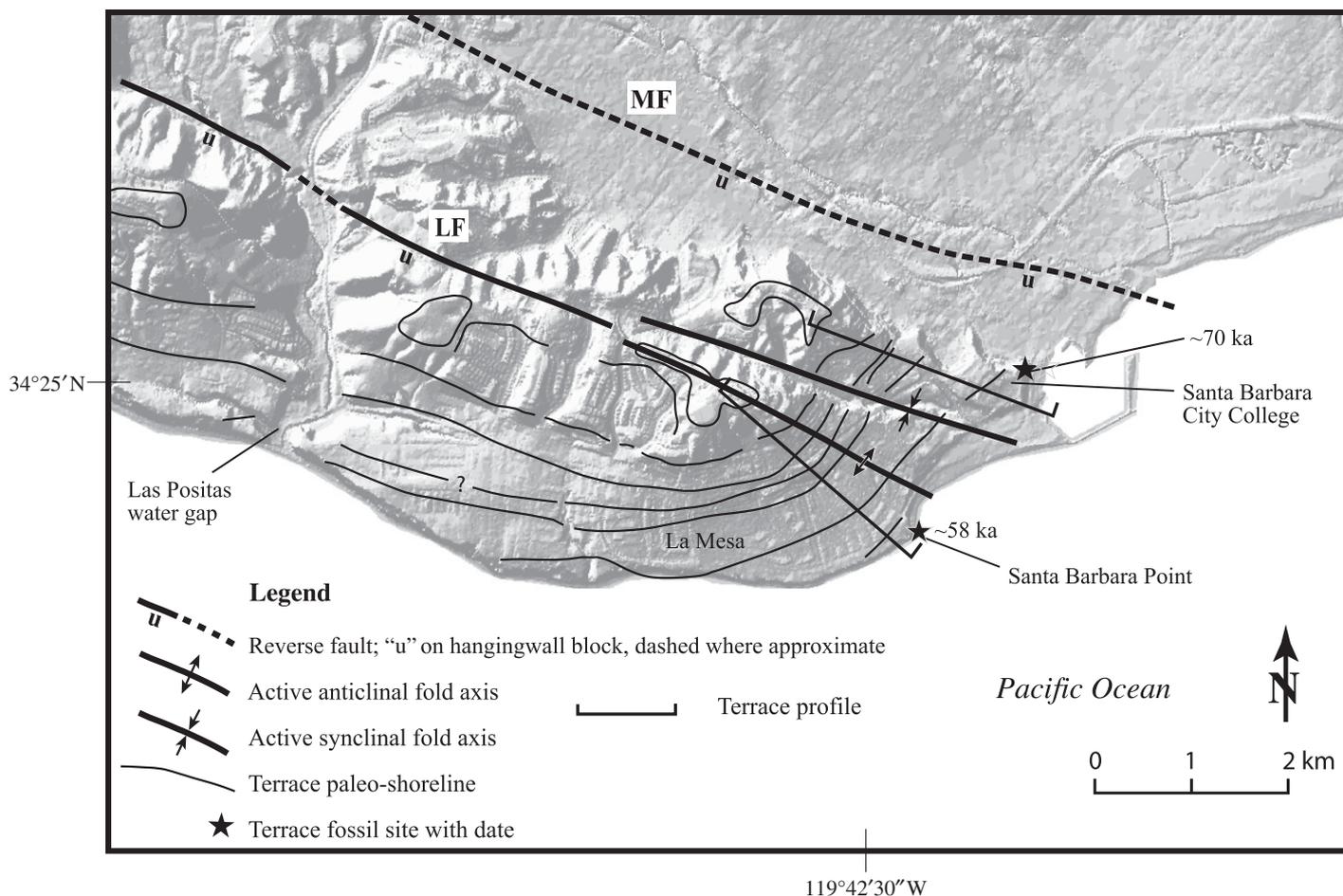


Figure 7. Map of the La Mesa anticline and uplifted marine terraces (MF—La Mesa fault; LF—Lavigia fault). Flights of marine terraces are preserved on the south flank and the nose of the east-plunging La Mesa anticline. Sites where uranium-series and optically stimulated luminescence age-dates are labeled are correlated across the Las Positas water gap. The blind, south-dipping MF truncates the marine terraces. The LF forms a well-expressed fold scarp east of the Las Positas water gap and is expressed as an anticlinal-synclinal fold sequence to the west.

for Santa Barbara Point (SBP) and Santa Barbara City College (SBCC) (Table 3). The first emergent terrace at SBCC is ca. 70 ka, and that at SBP is ca. 58 ± 11 ka (Table 1). The uplift rate for both is nearly the same, at 1.2 m/k.y. at SBP and 1.1 m/k.y. at SBCC (Tables 2 and 3). Based on mapping, terrace 2 at SBP is correlated to terrace 1 at SBCC. If we use the method of Bull (1985), we predict the age of terrace 2 at SBP to be ca. 67 ka (numerical age is 70 ka). Terrace 7 at SBP is estimated to be ca. 118 ka, and the same terrace at SBCC is estimated to be ca. 120 ka (Table 3). Thus we present limited evidence to support the method of Bull (1985). For relatively young marine terraces, the assumption that uplift rates are constant may be satisfactory, as rates of uplift over periods of ~45–100 k.y. may not change significantly. This suggests that estimated ages of higher terraces in other flights in the SBF

using the method of Bull (1985) are reasonable estimates.

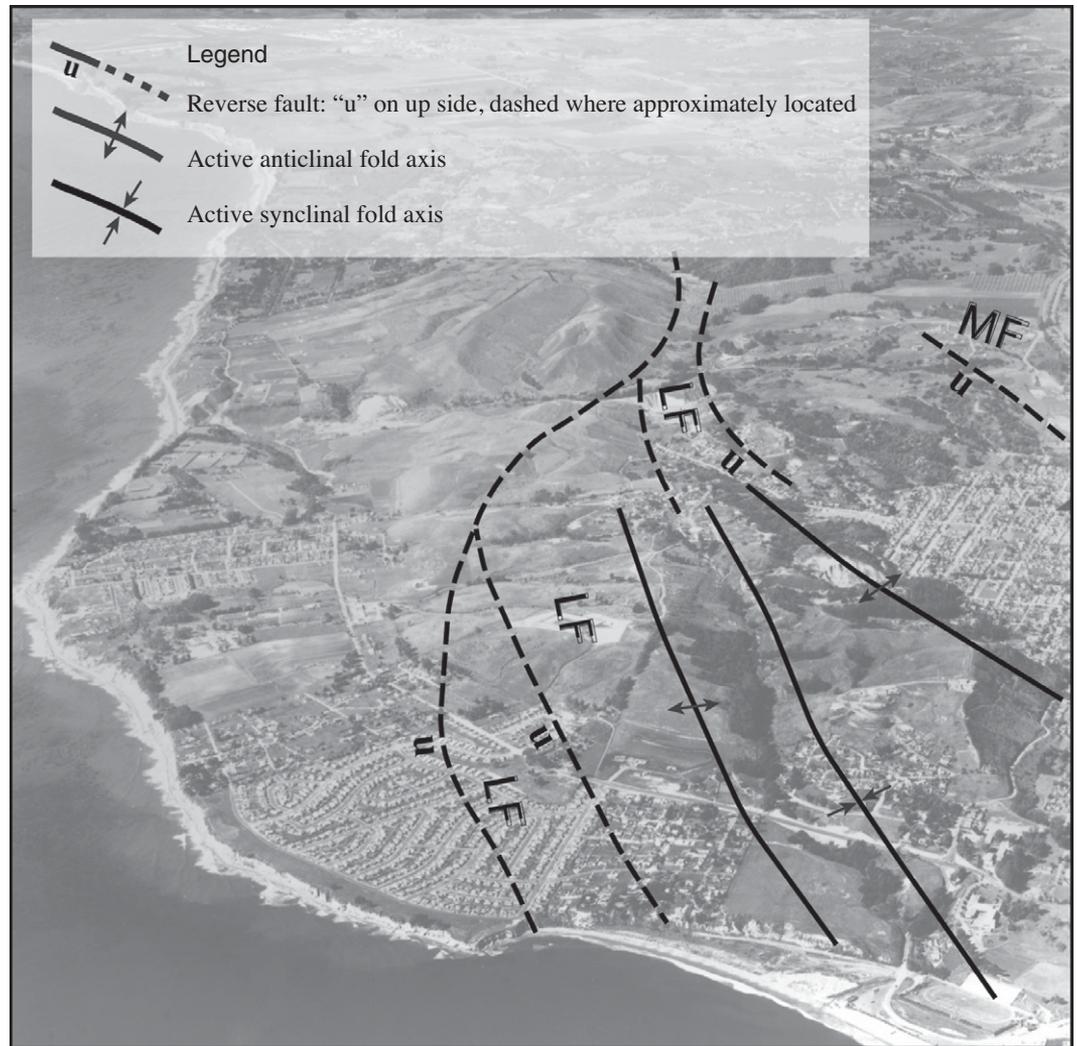
The gradient in uplift rates from west to east is related to tectonics that deform (drop down) MIS 5 terraces as they trend into the western limb of the Carpinteria syncline (Gurrola, 2005; Minor et al., 2009). The MIS 5 terrace is at an elevation of ~34 m above present mean sea level at Summerland, and its elevation steadily decreases to the east to below sea level at Carpinteria. Farther east, the 45 ka terrace emerges above present mean sea level west of Carpinteria and rises to an elevation of ~200 m above present mean sea level a few kilometers east at La Conchita (Lajoie et al., 1979; Gurrola et al., 2010).

When we apply the method of Bull (1985), we can identify most wide marine terraces of MIS 3 and 5. The most prominent and widest terraces in the Santa Barbara area are those

correlated to MIS 3a (ca. 48 ka). With small change in sea level over 20,000 years during MIS 3, there is a higher probability of a broad terrace forming.

There are intermediate marine terraces that are smaller and with less vertical separation. At La Mesa and Ellwood, we suggest these marine terraces were most likely produced during earthquakes. A paleoseismic trench excavated across the More Ranch fault at Ellwood Mesa (Keller and Gurrola, 2000) suggests a cluster of three earthquakes between ca. 36 ka to 47 ka. Figure 12 shows flights of terraces at Santa Barbara Point and Ellwood. Seven terraces can be recognized at Santa Barbara Point (Fig. 12A), and, using Bull's (1985) method, the oldest terrace formed at ca. 120 ka during MIS 5c. At Ellwood (Fig. 12B), six terraces are recognized; the oldest is ca. 80 ka (MIS 5a), using the methods of Bull (1985). These flights of terraces have

Figure 8. Oblique aerial photograph looking west at the La Mesa anticline and fault (MF). The Lavigia fault (LF) bifurcates into two splays, one of which terminates into anticlinal and synclinal folds. The La Mesa anticline is dissected across the crests, and the south limb is inset with marine terraces. The La Mesa fault is located north of the eroded forelimb near downtown Santa Barbara that can be seen in the far right of the photograph. Image courtesy of the University of California–Santa Barbara Map and Imagery Library, Mark Hurd Collection.



mostly formed with falling sea level or sea level highstand. We suspect that earthquakes occurred during periods of rising sea level, which produced small terraces, but they would not have remained long in the landscape, due to coastal erosion that occurs with rising sea level. In the SBF, we have identified 31 terraces in 7 flights of terraces; of these, 22 formed during falling sea level and 9 formed during a highstand (Table 3). The methodology presented by Bull (1985) assumes uplift of a particular terrace sequence is constant. What is necessary to use the method is a paleo-sea level curve, elevations of shoreline angles, and a numerical age on at least one terrace (for the SBF, this is the first emergent terrace, and in one case, the first and second emergent terraces). The small, young terrace (assumed to be MIS 1) at Goleta Point (Fig. 5) is eroding quickly (personal observation by Keller over 30 years). Bull's (1985) method of estimating age of terraces, while useful, provides only estimates, as the method assumes constant

uplift. Therefore, future work should endeavor to drill older marine terraces and obtain cores and materials for dating as many marine terraces in a given flight as possible.

The growth of folds is a dominant process controlling marine terrace evolution in the SBF, although each fold is likely underlain by a buried reverse fault. The best location in the SBF to observe a late Pleistocene faulted terrace is in the sea cliff at Ellwood Mesa where the More Ranch fault is exposed (Fig. 4). At that location, the More Ranch fault vertically displaces the 48 ka marine terrace by ~9 m, suggesting a vertical slip of ~0.2 m/k.y. However, based upon the elevation of the wave-cut platform and the estimated age of the terrace, this suggests the rate of uplift is ~9 times that amount. Therefore, the coastal area of Ellwood Mesa is being uplifted by structures other than the More Ranch fault. This suggests that when studying rates of uplift of marine terraces, the rate we estimate is often a regional rate, not

directly related to any particular structure that might deform one marine terrace.

The drainage pattern associated with active folding can provide information on lateral propagation of individual folds. For example, at More Mesa (Fig. 6), streams from the north are continually diverted to the west, suggesting that the young (45 ka) More Mesa anticline is propagating westward (Melosh and Keller, 2013). The pattern of marine terrace morphology may also be used to help shed light on the lateral growth of folds. Just north of Santa Barbara Point (Fig. 7), for example, a flight of terraces—the youngest being ca. 58 ka (MIS 3) and the oldest being ca. 120 ka (MIS 5c), based on Bull (1985)—clearly change direction from east-west to northeast-southwest. These marine terraces are bent around the end of the Mesa anticline, which suggests that the fold has propagated laterally to the east ~2 km. If the two ages are correct, then the rate of lateral propagation is ~32 m/k.y. (2 km of lateral propagation in 62 ka.



Figure 9. Wave-cut platform at Santa Barbara Point that is dated to 58 ± 11 ka (marine oxygen isotope stage 3a or 3c). Modified after California Coastal Project, 2002–2007 (www.californiacoastline.org). Image courtesy of Kenneth and Gabrielle Adelman.

If this estimate is right, then the rate of lateral propagation is very rapid compared to other folds such as Wheeler Ridge in the southern San Joaquin Valley (Keller et al., 1998, 1999). However, there are not enough data on rates of lateral propagation for active folds for us to strongly argue that the rate of lateral propagation of the Mesa anticline is unusual.

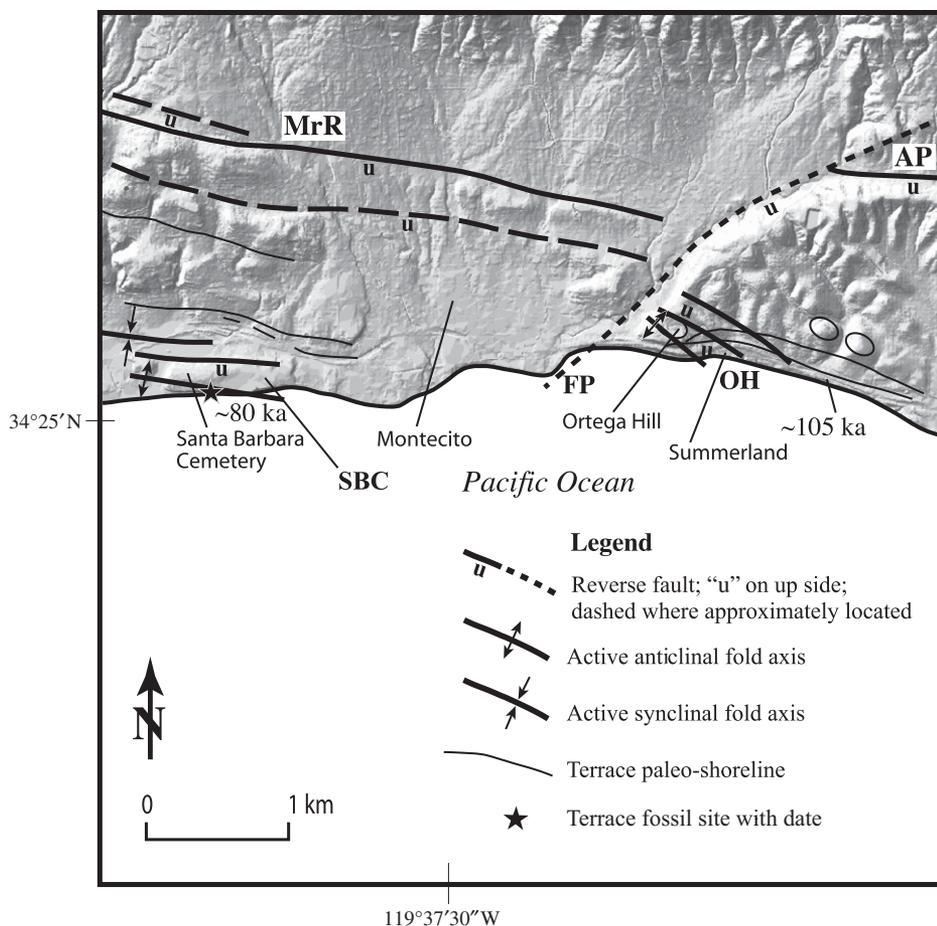
During the course of this research, we established with numerous ages that the Ellwood marine terrace formed during MIS 3a at ca. 48 ka. The Ellwood marine terrace is folded near where the More Ranch segment of the Mission Ridge fault extends from the land to the offshore (Fig. 3). There is a pronounced ~4-m-high fold scarp on the south side of the More Ranch fault, and we dated the marine terrace on both sides of the fault and completed oxygen isotope work on mollusks (Fig. 4). All the data suggest that the age of this marine terrace is ca. 48 ka.

In contrast to our ages for the first emergent marine terraces, Rockwell et al.'s (1992) study on marine terraces from roughly just west of Ellwood to Point Conception, using amino

acid racemization and uranium-series methods, assigned an age of 85 ka to the Gaviota marine terrace. However, amino acid racemization is primarily a relative dating tool and does not provide an unequivocal age for a marine terrace, and the U/Th and U/Pb uranium-series dates on bones are controversial (Kennedy et al., 1992). Having said that, we accept our younger terrace ages just west of Goleta, and although we do not correlate terraces westward to Point Conception, we reject (with the exception of the uranium series dates west of Gaviota Canyon) the ages suggested by Rockwell (1992) until more numerical ages are obtained. Our age estimate for the first emergent terrace at Ellwood and Gaviota is important because of its implications for the earthquake hazard. Rockwell et al.'s (1992) study provides an estimated uplift rate of ~0.3 m/k.y., whereas using our younger age results in a rate of 1.8 m/k.y. Younger terraces with higher rate of uplift obviously impact assessment of the earthquake hazard. Assessing earthquake hazard, however, is beyond the scope of this paper, and we direct readers to

Keller and Gurrola (2000) for more in-depth discussions. Alternatively, the differences in marine terraces ages and uplift rates between the SBF and the Gaviota terraces may be the result of the southern branch of the Santa Ynez fault, which may juxtapose terraces of different ages. Regardless, it is apparent that parts of the coastline may be rising at a much faster rate than previously thought, and, clearly, further work is needed, particularly to the west, to test this view and to define the nature of uplift and seismic hazard. It is possible that there is no inconsistency in rates, insofar as our ages are for locations that are far to the east of most of those of Rockwell et al. (1992).

Upson (1951) identified smaller, low marine terraces, ~2 m above present mean sea level along the Gaviota Coast. Upson (1951) also identified what appeared to be wave-cut notches at about the same elevation. Interestingly, Upton's (1951) observations are consistent with the small terrace Campus Point at UCSB, which is ~2 m above present mean sea level (Fig. 5). Two hypotheses have been presented to explain



these small low marine terraces. One is that there was a mid-Holocene sea level highstand, which cut the terraces. A late Holocene highstand (~3 m above present mean sea level) has been identified in the equatorial Pacific (Mitrovica and Milne, 2002) but has not been identified in southern California. The second hypothesis, which we prefer due to the active tectonic setting of the SBF and apparent presence of late Holocene earthquake terraces near Ventura (Lajoie et al., 1979), is that an earthquake suddenly uplifted the coastal area producing a small terrace at Campus Point at UCSB. In order to have uplift of 2 m, the earthquake would have to have had a magnitude of at least 7.0 (Wells and Coppersmith, 1994).

The Campus Point terrace was (Fig. 5) not uplifted sufficiently to produce a dead zone, and so dating of that marine terrace has been problematic. It is feasible that similar features to the west of Gaviota might be dated, but that would have to be the subject of further study. Such study is important, however, as the Gaviota Coast is facing future development, and the possibility of magnitude 7.0 earthquakes in the Santa Barbara area is worrisome. Several hundred thousand people live in the area today, and such an event would likely cause widespread damage, as well as a local tsunami.

CONCLUSIONS

Based upon the development of Quaternary stratigraphy, rates of uplift for marine terraces in the SBF, and investigation of active folding and faulting, we conclude:

Figure 10. Map of the eastern Santa Barbara fold belt from Santa Barbara eastward to Summerland. Uplifted marine terraces and the associated paleo-shoreline are shown. The Mission Ridge (MsR), the Fernald Point (FP), the Arroyo Parida (AP), the Santa Barbara Cemetery (SBC), and the Ortega Hill (OH) faults are shown.

Figure 11. Railroad-cut exposure of the paleo-sea cliff of the third emergent marine terrace at Summerland, California (possibly correlates to marine oxygen isotope stage 5c). The basal marine terrace deposit consists of a cobble conglomerate (black dashed line) excavated on mid- to late Pleistocene southeast-dipping Casitas Formation (on the north limb of the Ortega Hill anticline). The ca. 105 ka marine platform terminates against the steeply north-dipping Casitas Formation where it forms a buried wave-cut notch (arrow). The notch is ~1 m deep by 1 m high.

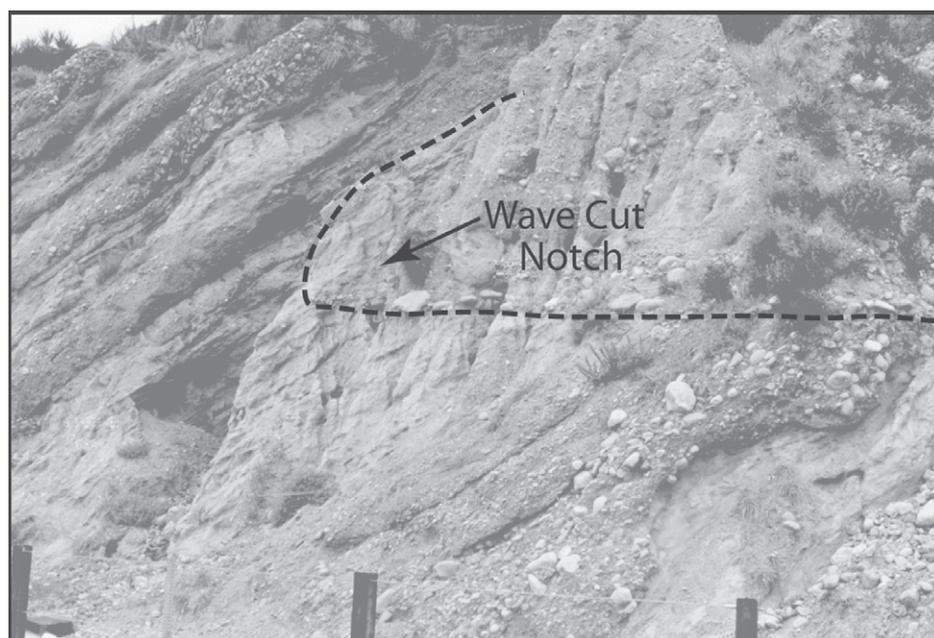
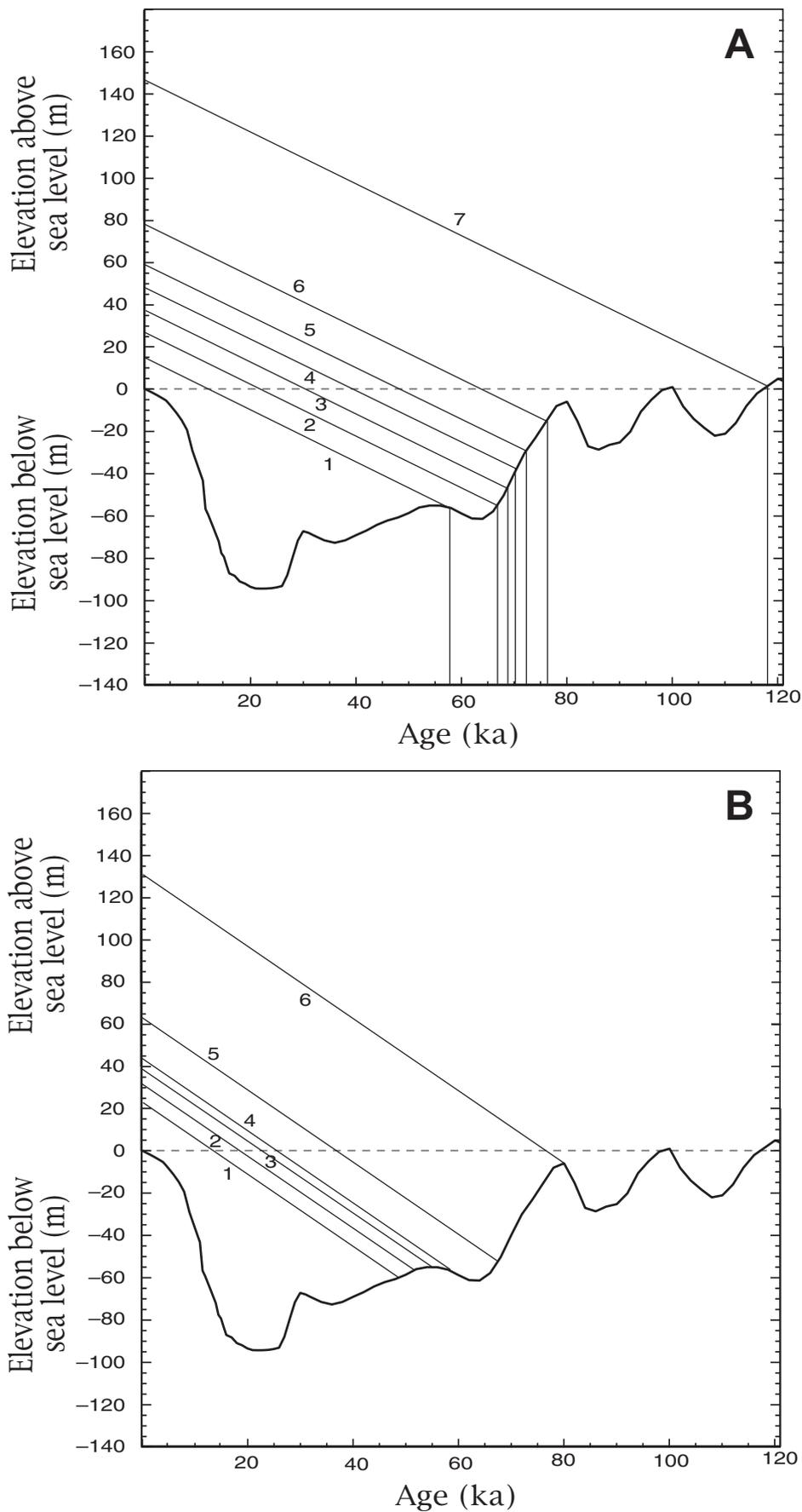


Figure 12. Marine terrace flights at (A) Santa Barbara Point and (B) Ellwood Mesa. The elevations and ages of the first terrace flight are correlated to the associated paleo-sea level MIS 3 or 5 highstands. Application of the Bull (1985) method assumes a constant rate of uplift, which permits correlation of higher terrace flights (i.e. 2, 3, 4, etc.) to the sea level curve of Muhs et al, (2012).

1. First emergent marine terraces in the SBF range in age from 48 ka to 105 ka, that is, MIS 3 or 5. The 48 ka terrace is particularly well established by several methods of numerical dating.
2. Marine terraces in the SBF are younger with a greater rate of uplift (~1.6–2 m/k.y.) in the westernmost part of the study area at Ellwood Mesa. Terraces near the central part of the fold belt (Mesa area of the city of Santa Barbara) are 60–70 ka, with uplift rate of ~1.1–1.2 m/k.y. Terraces at the eastern end of the fold belt are strongly tilted to the east into the Carpinteria syncline and are older (80–105 ka), with rate of uplift of ~0.4–0.5 m/k.y.
3. Rates of uplift in the SBF are very high compared to most areas of active tectonics.
4. High rates of uplift (~1.8 m/k.y.) in the far western end of the fold belt are ~6 times greater than previously thought, suggesting the seismic hazard there is likely greater than previously thought.
5. Multiple marine terraces at several locations suggest that they mostly formed during drops in sea level and are likely due to coseismic uplift as a result of clustering of earthquakes.
6. Lateral propagation of the Mesa anticline is apparently very rapid compared to known rates of lateral propagation of Wheeler Ridge in the southern San Joaquin Valley.

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