Late Quaternary uplift and earthquake potential of the San Joaquin Hills, southern Los Angeles basin, California

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ABSTRACT

Analysis of emergent marine terraces in the San Joaquin Hills, California, and ^{230}Th dating of solitary corals from the lowest terraces reveal that the San Joaquin Hills have risen at a rate of 0.21–0.27 m/k.y. during the past 122 k.y. Movement on a blind thrust fault in the southern Los Angeles basin has uplifted the San Joaquin Hills and has the potential to generate an M_w 7.3 earthquake within this densely populated area. Our structural modeling suggests that the fault dips to the southwest and slips at ~0.42–0.79 m/k.y., yielding an estimated minimum average recurrence interval of ~1650–3100 yr for moderate-sized earthquakes. Recognition of this blind thrust extends the known area of active blind thrusts and fault-related folding southward from Los Angeles into coastal Orange County.

INTRODUCTION AND GEOLOGIC SETTING

The Whittier Narrows and Northridge blind thrust faults in the Los Angeles, California, area were recognized only after they generated damaging, moderate-sized earthquakes (M_w 6.0 and 6.7) in 1987 and 1994 (Bullard and Lettis, 1993; Scientists of USGS and the Southern California Earthquake Center, 1994). Blind thrust faults are often associated with active folds (Stein and Yeats, 1989; Ward and Valensise, 1994; Lettis et al., 1997). Indications of late Quaternary folding are present in the San Joaquin Hills at the southern margin of the Los Angeles basin (Fig. 1). We present stratigraphic and geomorphic analyses in combination with ^{230}Th coral dating to calculate rates of uplift and evaluate the potential for blind thrust earthquakes beneath the San Joaquin Hills.

The Los Angeles basin is a northwest-trending structural trough bounded by active reverse and left-lateral faults of the Transverse Ranges to the north and by active right-lateral faults of the Peninsular Ranges to the northeast and southwest (Wright, 1991; see inset map in Fig. 1). The San Joaquin Hills are the topographic expression of a northwest-trending anticline between San Juan Capistrano and Huntington Mesa (Vedder, 1975; Lajoie et al., 1991) (Fig. 1). The Newport-Inglewood fault zone and its offshore extension (Wright, 1991; Fig. 1) bound the San Joaquin Hills on the southwest. The Newport-Inglewood fault zone generated the 1933 M_w 6.4 Long Beach earthquake near the mouth of the Santa Ana River (Hauksson and Gross, 1991).

Uplift of the San Joaquin Hills began in the early Pleistocene (Barrie et al., 1992). A suite of emergent marine terraces is present along the coastal San Joaquin Hills (Vedder et al., 1957). We extended previous mapping of terrace deposits (Barrie et al., 1992) and measured the elevations of shorelines and terrace platforms using geotechnical excavations, borings, natural exposures, and topography (Fig. 2). We correlated coastal terraces with inland terraces by comparing elevation, stratigraphic relationships, degree of dissection, soil profiles, and faunal assemblages (Kanakoff and Emerson, 1959; Peska, 1984).

MEASUREMENT OF UPLIFT RATE

Fossil localities in the northern San Joaquin Hills have been used for zoogeographic correlation and aminostratigraphic dating of upper Quaternary marine deposits in the Los Angeles basin, but there are significant uncertainties in amino acid dating due to temperature sensitivity (Wehmiller et al., 1977; Kennedy et al., 1982; Lajoie et al., 1991). The ^{230}Th dating of solitary corals is a more reliable method of dating marine platforms. It can calibrate amino acid dates and ages of faunal assemblages. Because corals are uncommon in southern California, ^{230}Th ages from the Los Angeles basin have not previously been reported.

We calculated the average late Quaternary uplift rate of the San Joaquin Hills using coral ages from three localities and measurements of paleoshoreline (shoreline angle) elevations (Fig. 2). Coral U and Th concentrations, isotopic ratios, and ^{230}Th ages (Table 1) were determined by thermal ionization mass spectrometry using the methods of Edwards et al. (1987) and Cheng et al. (1999).

Three subsamples of a single *Paracyathus pedroensis* skeleton (sample FP-28) from terrace 2, on the east side of upper Newport Bay, yielded similar ages and initial δ^{234}U values only slightly higher than the modern marine value of 146‰ ± 2‰ (Cheng et al., 1999). Near-primary uranium isotopic composition and agreement among the radiometric ages imply minimal diagenetic alteration. The ages (Table 1) correlate well with the last interglacial period (Edwards et al., 1987), marine oxygen isotope substage 5e.

Three solitary corals (*Balanophyllia elegans* samples 12654-0, 12654-1, and 12654-2; Table 1) from the second terrace along the coast of the San Joaquin Hills (Fig. 2) had initial δ^{234}U values significantly higher than the modern marine value, suggesting diagenetic alteration. The range of ^{230}Th/^{238}U values for a set of California solitary corals correlated to the last interglacial period (Stein et al., 1991) is a guide to the magnitude of diagenetic shifts in ^{230}Th/^{238}U values (and ^{230}Th ages). We assume that the range in ^{230}Th/^{238}U activity ratios (0.7516–0.8516) for the Stein et al. (1991) samples is due solely to diagenesis, that the same percentage spread affected our samples at the 12654 locality, and we then center this spread on the mean ^{230}Th/^{238}U ratio of the 12654 samples. The lowest ^{230}Th/^{238}U ratio corresponds to an age of about 120 ka, and the highest ratio corresponds to an age of about 240 ka.

A specimen of *Paracyathus pedroensis* from the first terrace (locality GK-90-14, Fig. 2) yielded an age of 106 ka (Table 1). The sample has an initial δ^{234}U value close to the modern marine value, suggesting that the radiometric age is reliable. Barrie et al. (1992) correlated the lowest San Joaquin Hills terrace with substage 5a on the basis of the lack of extralimital southern (i.e., warm water) fossils, the extent of amino acid racemization, and elevation of the shoreline angle. Elevation of the substage 5a highstand was well constrained as –1 m for the southern California coast by Muhs et al. (1994), but they reported –20 m to –1 m elevation of the substage 5c highstand. On the basis of terrace and eustatic sea-level correlations (Fig. 3), we conclude that the substage 5c coral was reworked onto the substage 5a terrace, or the substage 5c and 5a sea stands occupied the same platform.

The elevation difference between the terrace 2 shoreline angle (32–35 m) and substage 5e sea level (6 m; Lajoie et al., 1991) divided by the average age of sample FP-28 (122 ka) yields an uplift rate of 0.21–0.24 m/k.y. Analogous calculations for the 12654 locality yield uplift rates of 0.24–0.25 m/k.y. for a substage 5e correlation. Using 0.24 m/k.y. as our best estimate of uplift rate during the Quaternary, the age of the highest shoreline (305 m) is ca. 1.3 Ma, and several inter-

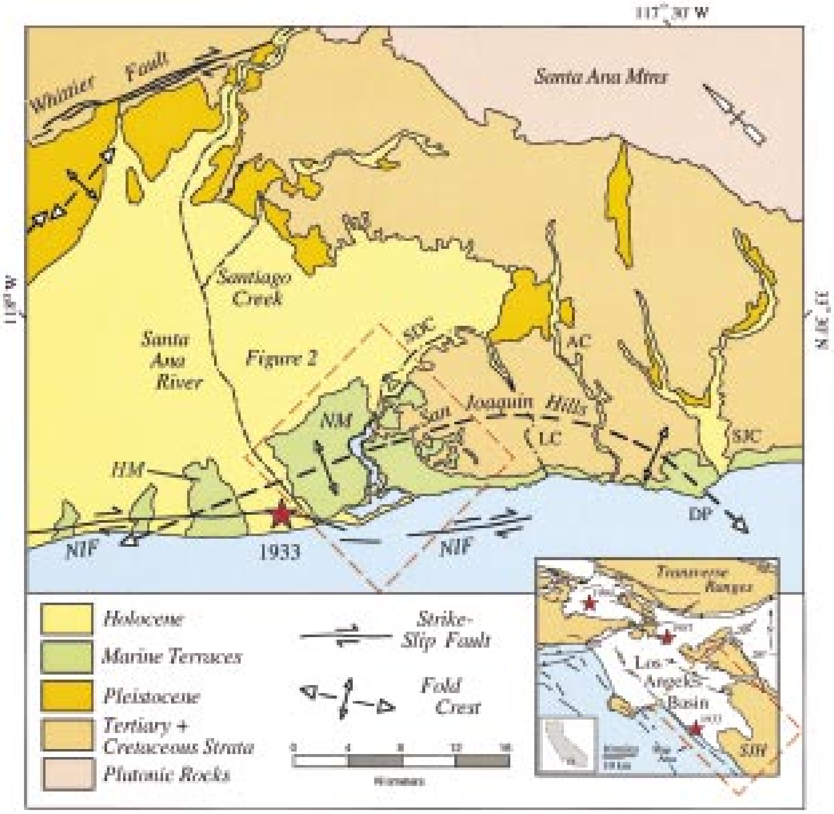


Figure 1. Regional map of San Joaquin Hills (SJH) showing approximate location of fold crest of San Joaquin Hills anticline. Other features: AC—Aliso Canyon, DP—Dana Point, HM—Huntington Mesa, LC—Laguna Canyon, NIF—Newport-Inglewood fault, NM—Newport Mesa, SDC—San Diego Creek, and SJC—San Juan Capistrano. Epicenters of 1933, 1987, and 1994 earthquakes are marked by stars. Modified from Vedder et al. (1957). Inset map shows greater Los Angeles region.

mediate terraces were probably occupied by multiple highstands (Fig. 3).

RECENCY OF UPLIFT

The location and thickness of Holocene sediments in the San Joaquin Hills suggest that tectonic uplift continued during the middle to late Holocene. Isopach and structure contour maps of the Holocene Talbert aquifer beneath the Santa Ana River (Sprotte et al., 1980) suggest that the aquifer has been deformed. The distribution of fluvial and estuarine sediments southeast of the Santa Ana River also suggests that Holocene uplift occurred. Newport Bay was incised at least 36 m below present sea level during the last glacial maximum, but rapid sea-level rise at the close of the Pleistocene inundated coastal drainages and induced sedimentary infilling with Holocene sediments (Stevenson, 1954). Stevenson concluded that an elevated bench of former marsh deposits in Newport Bay was created during the late Holocene by emergence. Stevenson speculated that the emergence was due to tectonic uplift and, based on elevation profiles, the uplift reflected anticlinal folding along a northwest-trending fold axis.

DISCUSSION

The late Quaternary uplift rate, anticlinal structure, and indications of Holocene uplift imply that the San Joaquin Hills are the surface expression of an active contractile fold (see Fig. 1), formed above a potentially seismogenic thrust fault (Stein and Yeats, 1989; Lettis et al., 1997; Shaw and Shearer, 1999). Geomorphic analysis of the San Joaquin Hills provides some constraints on the geometry of the proposed blind fault. A fault-bend fold model with movement on a northeast-vergent thrust fault best explains the elevation of marine terraces on the northeast limb of the San Joaquin Hills anticline, as shown schematically in Figure 4. Anticlinal structure of the San Joaquin Hills and northeast vergence of the underlying fault are supported by structural data of Vedder (1975) and our terrace mapping.

The maximum-magnitude earthquake that could occur on the San Joaquin Hills thrust can be estimated from empirical relationships between magnitude and subsurface fault-rupture length, as defined by the areal distribution of Quaternary uplift. This method does not require assumptions about fault geometry. The area of uplift extends at least ~38 km, from northwestern Huntington Mesa southeast to Dana Point, and therefore the

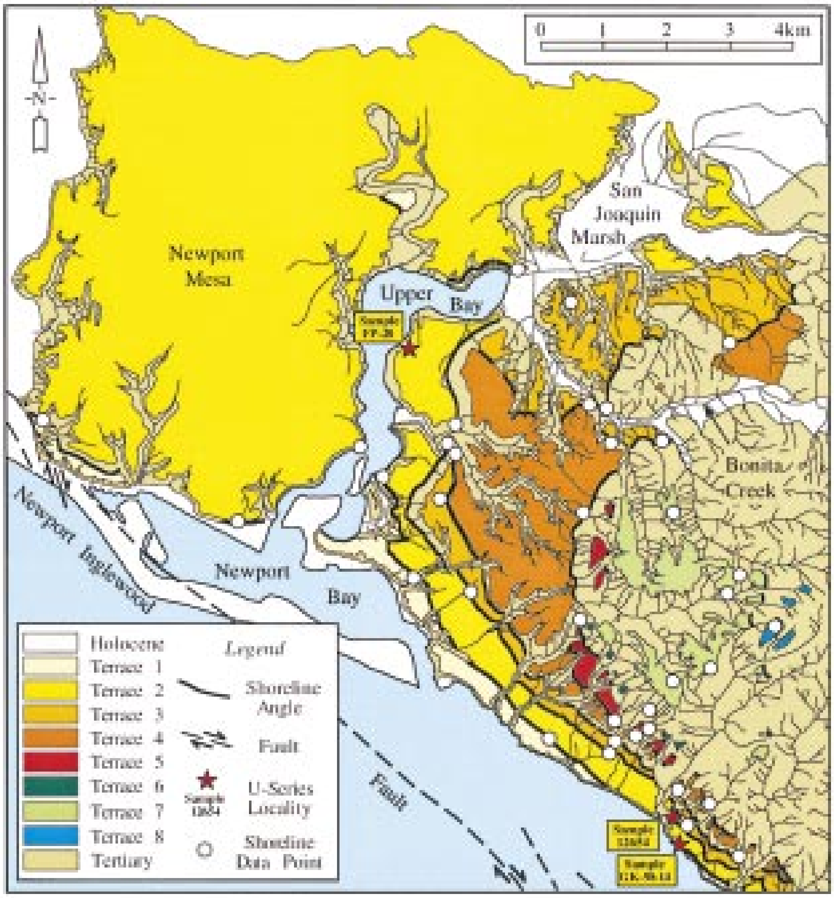


Figure 2. Map of marine-terrace platforms, location of measured shoreline elevations (open circles), and fossil localities (stars). See Figure 1 for location.

Table 1. URANIUM AND THORIUM ISOTOPIC COMPOSITIONS AND CONCENTRATIONS OF SOLITARY CORALS

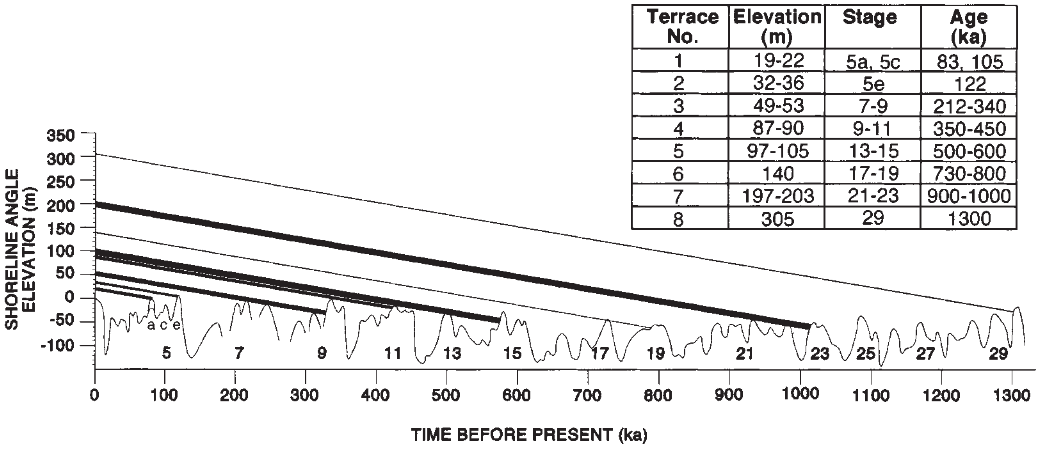
Locality*/ sample number	Species	Sample/shoreline elevation (m)	^{238}U (ppm)	^{232}Th (ppb)	^{230}Th/^{238}U (activity ratio)	^{230}Th age † (ka)	δ^{234}U § initial	Stage or substage
SDSU 3812/FP-28a	*Paracyathus pedroensis*	24/33-34	3.471 (7)	37.9 (3)	0.7616 (26)	122.6 (1.0)	157 (4)	5e
SDSU 3812/FP-28b	*Paracyathus pedroensis*	24/33-34	3.678 (4)	61.8 (6)	0.7717 (68)	124.1 (2.1)	165 (3)	5e
SDSU 3812/FP-28c	*Paracyathus pedroensis*	24/33-34	3.327 (3)	74.5 (5)	0.7563 (48)	120.4 (1.6)	159 (3)	5e
GK-90-14	*Paracyathus pedroensis*	16 – 17/21	4.681 (6)	129.6 (1.1)	0.7131 (24)	105.6 (0.7)	173 (3)	5c
LACMNH 12654/12654-0	*Balanophyllia elegans*	29-30.5/35-36	3.702 (7)	283 (4)	0.9448 (47)	172.8 (3.1)	247 (6)	5e or 7
LACMNH 12654/12654-1	*Balanophyllia elegans*	29-30.5/35-36	3.691 (4)	419.6 (2.3)	0.9430 (36)	167.7 (2.2)	258 (4)	5e or 7
LACMNH 12654/12654-2	*Balanophyllia elegans*	29-30.5/35-36	3.618 (22)	179.6 (1.1)	0.8509 (57)	137.6 (5.0)	230 (26)	5e or 7

Note: The first three analyses are different fragments of the same individual coral skeleton. All other analyses are on individual corals. Decay constants for ^{234}U and ^{230}Th are new values from Cheng et al. (1999): $\lambda_{230} = 9.1577 \times 10^{-6}$/y and $\lambda_{234} = 2.8263 \times 10^{-6}$/y. The decay constant for ^{238}U is referenced in Cheng et al. (1999): $\lambda_{238} = 1.551 \times 10^{-10}$/y. 2σ errors are in parentheses and represent errors in the last significant figures.

*Locality data available from E. C. Allison Center, Department of Geological Sciences, San Diego State University (SDSU), San Diego, California; Invertebrate Paleontology Section, Los Angeles County Museum of Natural History (LACMNH), Los Angeles, California.

† Calculated from isotope ratios using the standard age equation (e.g., Edwards et al., 1987), with correction for initial ^{230}Th assuming an initial ^{230}Th/^{232}Th value of (4.4 ± 4.4) x 10^{-6}, the bulk Earth thorium isotopic value with an arbitrarily assumed error of ±100%. For all samples, the correction is small and error introduced by the correction is small compared to analytical error.

§ $\delta^{234}U = ([^{234}U/^{238}U] - 1) \times 1000$; brackets indicate an activity ratio. Initial δ^{234}U value is calculated from the measured value by using the ^{230}Th age.



Terrace No.	Elevation (m)	Stage	Age (ka)
1	19-22	5a, 5c	83, 105
2	32-36	5e	122
3	49-53	7-9	212-340
4	87-90	9-11	350-450
5	97-105	13-15	500-600
6	140	17-19	730-800
7	197-203	21-23	900-1000
8	305	29	1300

Figure 3. Correlation of shoreline-angle elevations of coastal marine terraces with oxygen isotope record of eustatic sea-level highstands using methodology of Merritts and Bull (1989). Ages of terraces are estimated by their correlation with sea-level highstands, assuming constant 0.24 m/k.y. rate of uplift (slope of line) based on substage 5e terrace. Sea-level curve compiled from Chappell and Shackleton (1986) with modifications from Muhs et al. (1994) and Gallup et al. (1994). Oxygen isotope stages are numbered. Maximum and minimum reported sea-level elevations for oxygen isotope substages 5a and 5c are both shown. Width of correlation line corresponds to range in mapped shoreline angle elevations.

fault could generate a M_W 6.8 earthquake, using the length regression of Wells and Coppersmith (1994). Alternatively, the magnitude of a maximum credible earthquake is estimated by assuming that the San Joaquin Hills thrust extends to the base of the seismogenic crust at 17 km, dips between 20° and 30°, and extends upward to within 2 km of the surface. In this interpretation the San Joaquin Hills thrust is a backthrust that soles into the Oceanside detachment (Bohannon and Geist, 1998) as part of a wedge-thrust structure. The dip of the San Joaquin Hills fault is modeled after the offshore segment of the San Joaquin Hills anticline, south of Dana Point (e.g., Fisher and Mills, 1991). In this model, rupture of the entire fault area could generate a M_W 7.2–7.3 earthquake, using the regression of Dolan et al. (1995). The late

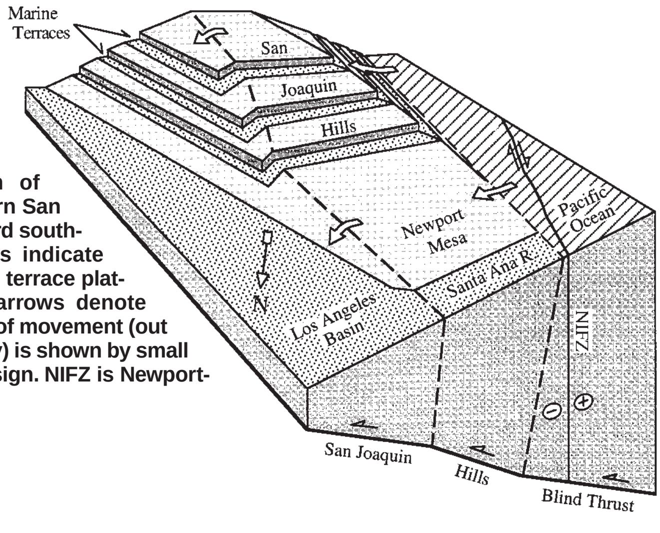


Figure 4. Block diagram of marine-terraces on northern San Joaquin Hills (viewed toward southwest). Heavy dashed lines indicate active axial surfaces where terrace platforms are folded. Large arrows denote sense of folding. Direction of movement (out of or into page, respectively) is shown by small arrows and plus or minus sign. NIFZ is Newport-Inglewood fault zone.

Pleistocene slip rate of 0.42–0.79 m/k.y. is estimated from inferred fault dip (20°–30°) and the measured uplift rate of 0.21–0.27 m/k.y.

The recurrence time for earthquakes is estimated from the equation $T = D/V$, where T is the average recurrence time, V is the slip rate, and D is the average displacement per earthquake. We use D = 1.3 m of average uplift (Grant and Ballenger, 1999) for the most recent event and the slip rates (0.42–0.79 m/k.y.) to calculate average recurrence times of 1650–3100 yr for moderate-magnitude earthquakes.

We prefer to interpret movement of the San Joaquin Hills blind thrust to be the product of partitioned strike slip and compressive shortening across the southern Newport-Inglewood fault zone, similar to partitioned slip reported by Hauksson (1990) along the western Los Angeles basin. Grant et al. (1997) reported multiple surface ruptures on the southern Newport-Inglewood fault zone during the Holocene, but other than observations of an elevated marsh bench in Newport Bay and sparse microseismicity, we do not have direct evidence for Holocene activity of the San Joaquin Hills thrust.

However, on July 28, 1769, Gaspar de Portola, the first Spanish explorer into southern California, camped on the eastern bank of the Santa Ana River, ~15–20 km north of the San Joaquin Hills. A violent earthquake occurred at noon, followed 10 minutes later by a severe aftershock and two other strong aftershocks later that day. Aftershocks continued for the next five days (Smith and Teggart, 1909). Although there are many active faults in southern California that could have generated the 1769 earthquake, Portola's location makes a blind San Joaquin Hills source worthy of serious consideration.

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Late Quaternary uplift and earthquake potential of the San Joaquin Hills, southern Los Angeles basin, California: Comment and Reply

COMMENT

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Grant and et al. (1999) rather unequivocally demonstrated that the San Joaquin Hills, located in Orange County, California, have risen at a rate of 0.021–0.027 mm/yr over the past 122 k.y. Based largely on geomorphic evidence, they attribute this uplift as a fault-bend fold above a southwest-dipping blind thrust fault. The main structural feature in the San Joaquin Hills area has often been described as a complexly faulted, northerly plunging anticline with the Capistrano syncline bordering it on the east (Vedder, 1970; 1975; Vedder et al., 1957). However, this "anticlinal" structure is generally based on the relative regional arrangement of bedding attitude in the Topanga Formation, which was created by faulting rather than by folding (Bode, 1934; Miller and Tan, 1976; Tan and Edgington, 1976). In fact, the dominant structure in the area is faulting, most of which is subparallel to the regional northwesterly fabric of the San Andreas fault zone and other parallel fault zones to the west. Within the San Joaquin Hills, these include the Pelican Hill, Shady Canyon, and the southern part of the Laguna Canyon fault zones, as well as the offshore Newport-Inglewood fault zone. North-trending faults such as the northern portion of the Laguna Canyon fault, and east-trending faults, such as the Temple Hill fault, are also present. Of these, the dominant fault in the area is the Shady Canyon fault, which nearly bisects the area in a northwesterly direction, and has a stratigraphic throw of approximately 5,000 feet (1,524 m) (Bode, 1934; Vedder, 1970; Morton et al., 1974). The Shady Canyon fault is nearly vertical and clearly separates the area into an upthrown block exposing early Miocene and older rocks on the east, and a downthrown block exposing rocks of middle Miocene and younger age to the west (Bode, 1934; Duggan, 1961; Sullwold, 1940). One of the more interesting aspects of the displacement along the Shady Canyon fault is that the Topanga Formation and most of the Vaquers Formation are missing on the uplifted northeast block (Duggan, 1961), suggesting that this side may have been emergent as far back as the middle Miocene. The entire area appears to be defined by a combination of fault blocks, each with homoclinal structure (Miller and Tan, 1976; Tan and Edgington, 1976), that form overall anticlinal-synclinal patterns, essentially without folding. The lack of overall folding and the predominance of faulting in the area appear to make a blind thrust model unattractive.

Alternatively, the nearby Newport-Inglewood fault zone is a broad structural zone of en echelon, northwest-trending folds and vertical faults extending from the southern edge of the Santa Monica Mountains southeastwardly across the Los Angeles basin to the offshore area near Newport Beach. Faults having similar trends and projections occur offshore of San Clemente and in San Diego (the Rose Canyon and La Nacion faults). Harding (1973) suggested that the Newport-Inglewood fault zone was a classic example of a wrench fault. Typically, wrench faulting consists of a relatively narrow, subvertical principal displacement zone at depth, and, within the sedimentary cover, of braided splays that diverge and rejoin both upward and laterally (Christie-Blick and Biddle, 1985). These arrays of upward-diverging fault splays are "flower structures" (Harding and Lowell, 1979). Indeed, such structures have been shown to exist along the Newport-Inglewood fault zone (Harding, 1979; Wright, 1991), and the extensive, nearly vertical faulting observed in the San Joaquin Hills is suggestive of such a structure extending off of the fault zone.

It appears more likely, on geologic grounds, to suggest that the uplift within the San Joaquin Hills is generated by squeezing upward along the Newport-Inglewood fault zone in shortening deformation accompanying northwest-southeast horizontal shear or transpression.

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REPLY

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We welcome the opportunity to further discuss the Quaternary tectonics and earthquake potential of the San Joaquin Hills in response to Bender's comments about our paper. We summarize and address each of his main points below.

Bender contends that there is a "lack of overall folding" in the San Joaquin Hills and the "anticlinal structure . . . was created by faulting rather than folding." The structure of the San Joaquin Hills is complex and was created by at least two phases of deformation. Bender carefully describes older structures. As indicated by the title of the paper, our research focuses on younger Quaternary structures, landforms and relief of the San Joaquin Hills, and their significance for seismic hazard. The pattern of Quaternary uplift and folding of the San Joaquin Hills, as evidenced by the distribution of marine terrace deposits and geomorphology, is significantly less complex than the pre-Quaternary structures. Quaternary uplift, as defined by marine terraces, is superimposed on older Cenozoic structures, basin sediments, and intrusive volcanic rocks related to Miocene extension (Crouch and Suppe, 1993; Wright, 1991). Most of the faults Bender mentions were active prior to deposition of the late Miocene-Pleistocene depositional sequence of the Los Angeles basin (Yeats, 1973; Wright, 1991) and their last movements predate development of the seismically active strike-slip Newport-Inglewood fault zone, which initiated movement in the Pliocene (Yeats, 1973). Latest movement of the Shady Canyon fault was in late middle or early late Miocene (Tan and Edgington, 1976). With the exception of the Pelican Hill fault zone, none of these faults is known to have moved during the Quaternary.

The slip rate and significance of the Pelican Hill fault zone has been studied by geotechnical consultants Leighton and Associates and summarized by Clark et al. (1986). Strands of the Pelican Hill fault zone displace Quaternary terrace deposits. We have observed approximately 8 m of vertical separation of terrace 7 (age 900–1000 k.y.) at Pelican Hill, approximately 1 m of vertical separation of terrace 3 (age 212–340 k.y.) immediately north of Laguna Beach, and no deformation of terrace 2 (age 122 k.y.) anywhere along the coast. At the head of upper Newport Bay, meter-scale displacements were mapped in the terrace 2 deposits (122 k.y.), but they were overlain by undisturbed Holocene deposits (Clark et al., 1986). (Terrace numbers and ages from Grant et al., 1999.) From these observations, the Pelican Hill fault zone appears to be an abandoned secondary structure that ruptured infrequently in response to uplift of the San Joaquin Hills, movement of the Newport-Inglewood fault zone, or both.

Bender's conclusion that uplift within the San Joaquin Hills is generated by squeezing upward along the Newport-Inglewood fault zone by shortening that accompanies northwest-southeast horizontal shear (i.e., transpression) agrees with our statement that, "We prefer to interpret movement of the San Joaquin Hills blind thrust to be the product of partitioned strike-slip and compressive shortening across the southern Newport-Inglewood fault zone," (p. 1034, Grant et al., 1999). However, we disagree with Bender's assertion that the structure of the San Joaquin Hills and proximity to the Newport-Inglewood fault make a blind thrust model unattractive. His interpretation is based on a model of the Newport-Inglewood fault zone as a classic example of a wrench fault (Harding, 1973). The wrench fault model was defined by Wilcox et al. (1973). In that classic paper, the authors describe the San Andreas fault in central California as an example of a wrench fault with a series of en echelon folds on the eastern side of the fault. These folds (anticlines) are now known to be underlain by seismogenic blind thrust faults (Stein and Yeats, 1989; Stein and Ekstrom, 1992) created by transpressive strain partitioned across western California (Lettis and Hanson, 1991). A similar structural relationship probably exists between the Newport-Inglewood fault zone and the San Joaquin Hills.

Our data and geomorphic analysis do not provide detailed constraints on the geometry of the San Joaquin Hills blind thrust, as we acknowledged in our paper. Research into the structural relationship between the San Joaquin Hills blind thrust, the Newport-Inglewood, or other regional faults is ongoing. Our data do provide strong evidence that the San Joaquin Hills are rising in response to a potentially seismogenic, underlying blind fault, and we suggest that this potential earthquake source should be included in regional seismic hazard models.

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