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Coastal Uplift of the San Joaquin Hills, Southern Los Angeles Basin, California, by a Large Earthquake since A.D. 1635

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Abstract Late Holocene marsh deposits and a shoreline along the coast of the San Joaquin Hills, southern Los Angeles basin, range from 1 to 3.6 m above the active shoreline. Radiocarbon dating of ancient marsh shows that emergence occurred after A.D. 1635. The age, distribution, and geomorphic expression of elevated marsh and shoreline are best explained by tectonic uplift due to a **M** >7 earthquake. Radiocarbon dates and the historic record of seismicity suggest the earthquake occurred between A.D. 1635 and 1855, possibly in 1769. The historic record of earthquakes in the Los Angeles basin begins in A.D. 1769 and contains no other earthquakes greater than **M** 6.7. Therefore, the San Joaquin Hills earthquake may be the largest historic earthquake in the Los Angeles basin.

Introduction

The San Joaquin Hills in coastal Orange County, California, are the surficial expression of a faulted anticline parallel to the active Newport–Inglewood fault zone at the southern margin of the Los Angeles basin (Vedder, 1975; Wright, 1991; Grant *et al.,* 1999) (Fig. 1). The San Joaquin Hills have been rising tectonically at an average rate of 0.21–0.27 m/k.y. during the last 122,000 yr (Grant *et al.,* 1999). Grant *et al.* (1999, 2000) proposed that uplift was generated by movement on an underlying blind thrust fault due to partitioned strike-slip and compressive shortening across the southern Newport–Inglewood fault zone.

Several investigations have addressed the generally low level of seismicity in the Los Angeles basin relative to levels expected from analysis of regional deformation (e.g., Dolan *et al.,* 1995; Working Group on California Earthquake Probabilities [WGCEP], 1995; Stein and Hanks, 1998). The southern Los Angeles basin, including the San Joaquin Hills, has been estimated to have low seismic hazard relative to the greater Los Angeles region (WGCEP, 1995), in part because it has fewer known active faults and historically lower rates of seismicity. Grant *et al.* (2000) suggested that the San Joaquin Hills be considered a seismic source in regional hazard assessment. However, like many blind faults, the recency of movement and Holocene slip rate of the San Joaquin Hills fault was not known. Recognition and characterization of seismogenic blind faults is a major challenge in seismic hazard assessment (Lettis *et al.,* 1997). This article addresses the seismic potential of the San Joaquin Hills by documenting and analyzing evidence of late Holocene uplift. We present data showing that tectonic uplift of the San Joaquin Hills has occurred within the last several centuries and may have generated the largest earthquake in the Los Angeles basin since western explorers reached the area.

Coastal Observations and Measurements

The Marsh Bench

Our investigation was guided by 1950s studies of formation and evolution of salt marsh in upper Newport Bay (Stevenson, 1954; Stevenson and Emery, 1958). Newport Bay is a late Pleistocene erosional gap between the northern San Joaquin Hills and Newport Mesa (Fig. 1). Stevenson (1954) and Stevenson and Emery (1958) described a bench of ancient marsh deposits around the margins of the bay above the active marsh. Stevenson (1954) conducted leveling profiles of the marsh bench on both sides of Newport Bay and reported that the "bench averages 38 inches [0.96 m] above the present marsh on the western shore and 62 inches [1.57 m] on the eastern bank. It is approximately 6 inches [0.15 m] higher in the central part of the Bay than at the north and south ends. This bench contains remnants of marsh flora. . . . " (Stevenson, 1954, p. 36). After comparing the stratigraphy and remnant marsh flora on the bench with the active marsh, Stevenson (1954) concluded that the marsh bench was created by emergence of late Holocene marshland and subsequent death of the elevated marsh community. Stevenson (1954) hypothesized that "the greater height of the 'marsh bench' in the central area is probably the result of movement during Recent time of a major anticline and fault system which cut through the Bay in a NW–SE direction" (p. 36). He reported observations and measurements of the marsh bench to support a tectonic emergence hypothesis so that he could exclude the marsh bench from his primary study of active marsh processes. Stevenson estimated that the marsh bench emerged due to "relative uplift within historic time" (p. 176) a few hundred years before his study, but he did not date it directly.

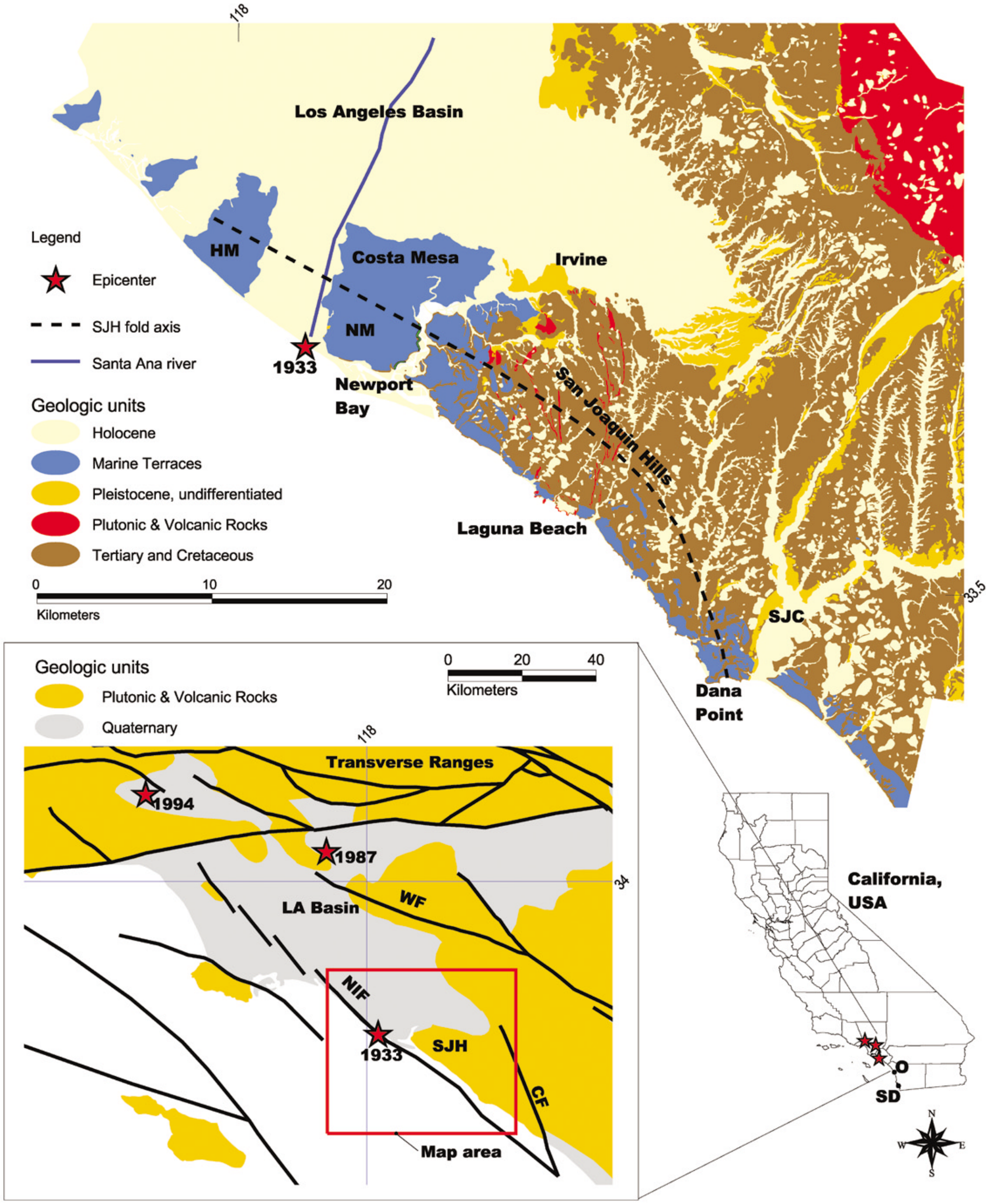

Figure 1. Regional location, major faults, and general geology of the southern Los Angeles basin and San Joaquin Hills (SJH) showing approximate location of the fold axis of the SJH anticline (from Grant *et al.,* 1999) relative to Huntington Mesa (HM), Newport Mesa (NM), Newport Bay, Laguna Beach, San Juan Capistrano (SJC), Dana Point, the Whittier fault (WF), Cristianitos fault (CF) and the Newport–Inglewood fault (NIF) zone. Epicenters of the 1933 **M** 6.3 Long Beach, 1987 **M** 5.9 Whittier Narrows, and 1994 **M** 6.7 Northridge earthquakes are marked by stars. Cities of San Diego and Oceanside are marked by SD and O on inset map of California. Regional map and epicenters from Schruben *et al.* (1999). Geologic units in the southern Los Angeles basin are from Morton and Miller (1981).

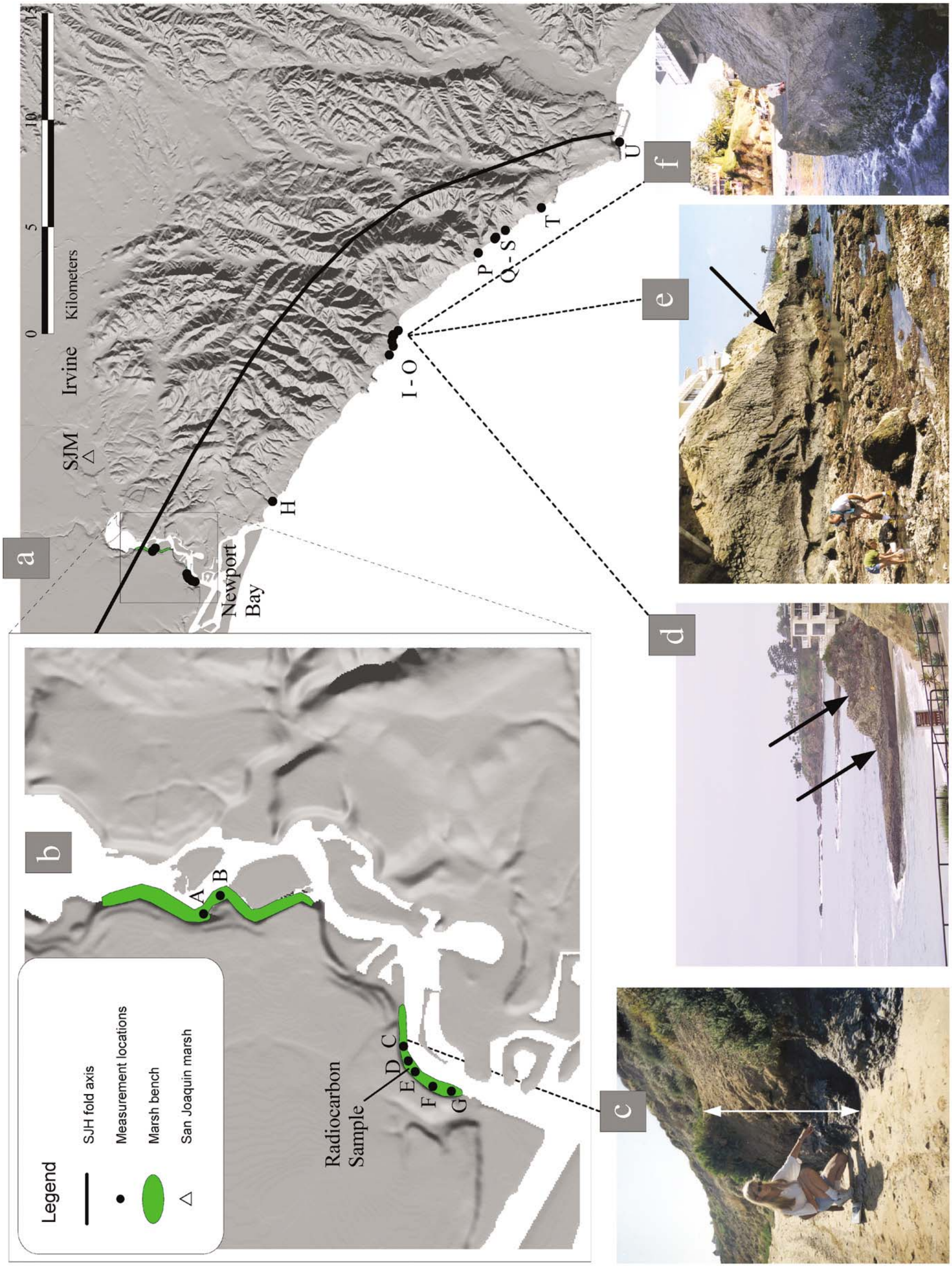
a
Kilometers
0
5
10
15
Irvine
SJM
Newport Bay
H
I - O
P
Q - S
T
U
b
Legend
SJH fold axis
Measurement locations
Marsh bench
San Joaquin marsh
A
B
C
D
E
F
G
Radiocarbon Sample
c
d
e
f

Figure 2. (a) Physiography of the San Joaquin Hills region and locations of measurement sites (dots). Measurement sites lettered A–U correspond to site labels on Figure 3. Triangle shows the location of core sample from San Joaquin Marsh (SJM). See Figure 1 for other abbreviations. Compiled from 10 and 30 m U.S. Geological Survey Digital Elevation Models using Universal Transverse Mercator North American Datum 1927. Shading is approximately 270° azimuth and approximately 45° altitude. (b) Expanded view of Newport Bay showing locations where remnants of the marsh bench were identified (green line), and lettered measurement sites (dots) referenced to Figure 3. Radiocarbon sample location is marked. (c) Photograph of the marsh bench on the west side of upper Newport Bay near radiocarbon sample site. L. Ballenger is on the active shore platform with her knee on the modern shoreline and her foot on bedrock. A few centimeters of sediment blanket the platform and display tidal fluctuation marks. The white vertical bar marks the elevation difference between the modern shoreline (below) and the top of the marsh bench at the base of colluvial slope wash. This is approximately the elevation difference between the older paleoshoreline and the modern shoreline. The true paleoshoreline is buried by colluvium. (d) View of the coast looking northwest at Diver's Cove and Fisherman's Cove in Heisler Park, Laguna Beach, showing the modern wave-cut platform (under water), the lower emergent platform and shoreline (lower arrow), and a suspected older shoreline of unknown age (upper arrow). The prominent, white building is also visible in photos e and f. (e) Examples of erosion features at Fisherman's Cove, Laguna Beach. People are standing on the modern wave-cut platform, exposed at low tide. A modern tidal erosion notch extends along the base of the cliff behind the people. The arrow points to a bench above tidal level, which we interpret as an emergent shoreline. View is looking southeast toward the location of photo f. Location L on Figure 3. (f) L. Ballenger is kneeling on a platform or bench, pointing to a well-defined break in slope, which we interpret as an emergent shoreline. View is looking northwest toward Fisherman's Cove, Laguna Beach. Location M on Figure 3.

The pattern of uplift reported by Stevenson (1954) is consistent with both the geomorphic expression of the San Joaquin Hills (Fig. 2a) and the expected vertical displacement field that would be generated by coseismic growth of the San Joaquin Hills anticline (Fig. 1). If we accept Stevenson's tectonic emergence hypothesis, then the marsh bench and ancient flora may be analyzed to estimate the date and magnitude of most recent tectonic uplift in Newport Bay at the northern margin of the San Joaquin Hills.

We examined, mapped, and radiocarbon dated remnants of the marsh bench in Newport Bay to evaluate the tectonic emergence hypothesis. Since the 1950s, much of the natural salt marsh around the margins of Newport Bay and the coastline of the San Joaquin Hills has been obliterated or modified by residential development and road construction. We reviewed archival and recent aerial photographs, maps, and reports on Newport Bay and surveyed the area on foot and by kayak to find undisturbed portions of the marsh bench.

There are remnants of marsh bench at the base of bluffs on the west side of upper Newport Bay, immediately above the present shoreline (Fig. 2b,c). Comparisons with photographs of the same location in the 1950s (from Stevenson, 1954; Stevenson and Emery, 1958) show that significant growth of vegetation and modest accumulation of colluvium have occurred in the past approximately 50 yr. Vegetation now obscures the marsh bench in many places. Where exposed, the bench consists of locally fossiliferous, unconsolidated sediments above the regional bedrock. An example of marsh bench in a location with minimal vegetation is shown in Figure 2c. Our observations of marsh bench morphology, lithology, and fauna are mostly consistent with Stevenson's descriptions. However, we found only a few remnants of marsh flora because the bench is now covered with dense growth of nonmarsh vegetation, including shrubs and a few trees.

Photographs of the mouth of Newport Bay just south of Stevenson's study area taken in the 1930s to 1950s (Sands, 1990) (UC Irvine Main Library Special Collection, various dates) show a bench that is morphologically similar to the marsh bench. The bench was immediately above the visible shoreline, at the base of the cliffs, at roughly the same elevation as the marsh bench. Stevenson did not describe this bench, for it was outside his main study area, and we have not found records of it other than photographs. However, from its appearance on photographs, the bench in lower Newport Bay may have been contemporaneous and correlative with the marsh bench in upper Newport Bay and may have formed by the same or comparable mechanism.

Alternatively, it could have been formed or modified by the Santa Ana River, which flowed parallel to the coastline through lower Newport Bay between approximately 1861 and 1920 (Stevenson, 1954). The bench in lower Newport Bay was destroyed by development and cannot be investigated. However, if the marsh bench formed by coseismic uplift of the San Joaquin Hills, then additional evidence of uplift might be preserved elsewhere along the coast.

Shorelines and Platforms along the Open Coast

The open coast of the San Joaquin Hills is rocky and subject to relatively high rates of wave erosion (Pipkin *et al.,* 1992). Wave erosion may be comparable to the San Diego area, where Emery and Kuhn (1980) reported erosion rates ranging from 0.03 to 33 cm/yr for shore platforms and sea cliffs (see Fig. 1 for location). In the San Joaquin Hills, wave erosion and coastal processes have formed a suite of shore platforms extending from the modern shoreline up to an elevation of greater than 300 m above sea level, indicating late Quaternary tectonic uplift (Grant *et al.,* 1999). The shoreline (also called strandline, shoreline angle, inner edge, or back edge) is at the intersection of the shore platform and sea cliff (Bradley and Griggs, 1976; Lajoie *et al.,* 1991; Sunamura, 1992). In the San Joaquin Hills, the lowest (modern) shore platform and shoreline at the base of the cliffs is partially exposed during low tide and low sand conditions (see examples Fig. 2c–e). Mean tidal range shown on U.S. Geological Survey topographic maps is approximately 1.2 m.

Emergent coastal erosion features such as notches, shorelines, and shore platforms are indicators of uplift in tectonically active areas (Pirazzoli, 1991; Carver and McCalpin, 1996; Merritts, 1996; Stiros and Pirazzoli, 1998). Shore platforms (also called wave-cut platforms, wave-cut benches, marine abrasion platforms, coastal benches, and various other names) are common along the California coast and in rocky coastal regions of Oregon, New Zealand, Japan, and Australasia (Bradley and Griggs, 1976; Twidale, 1976; Sunamura, 1992). Along the central California coast, where Quaternary uplift rates are comparable to the San Joaquin Hills, wave-cut platforms slope seaward with gradients ranging from 0.007 to 0.04 (Bradley and Griggs, 1976). In protected coastal areas of Australasia, distinctive horizontal "Old Hat" platforms form below modern high-water level and have a seaward drop or low-tide bench (Fairbridge, 1968; Twidale, 1976; Sunamura, 1992). Differences in platform types and morphology in various regions have been attributed to differences in wave energy, weathering rates, rock strength, and other factors (Fairbridge, 1968; Bradley and Griggs, 1976; Twidale, 1976; Sunamura, 1992), but there is common agreement that modern and ancient shorelines are geomorphic indicators of sea level relative to land.

Along the coast of the San Joaquin Hills, the lowest (i.e., modern), wave-cut platform is submerged at high tide, exposed during low tides, and covered with marine life and scattered boulders (e.g., Fig. 2d). There are at least two emergent shorelines (see arrows, Fig. 2d) above the lowest (modern) wave-cut platform in erosion-resistant rock formations such as volcanic dikes and San Onofre breccia. The lower emergent platform has few or no boulders and little marine life except barnacles. Some emergent platforms receive significant wave splash and are submerged by unusually high tides or large swells. These platforms contain tidepool organisms in scattered crevices.

The approximate age of emergent platforms and shorelines can be estimated from their position between the lowest (modern) platform and dated marine platforms at higher elevation. In the northern San Joaquin Hills, Grant *et al.* (1999) measured 19 to 22 m elevation for the shoreline of terrace 1, which they correlated with stage 5a or 5c sea level highstand (age 83 ka or 105 ka, respectively) based on a dated coral and faunal assemblage. To the southeast between Aliso Beach and Dana Point (locations Q and U on Figs. 2 and 3), Shlemon (1978) reported an estimated elevation of 22.6 to 39.1 m for the first emergent terrace, which he correlated with stage 5e sea level highstand (125 ka). Shlemon (1978) also noted the existence of a lower shoreline at 8.3 m elevation in Heisler Park in Laguna Beach (see Fig. 2d for approximate location). He tentatively correlated the 8 m shoreline with stage 3 or 5a sea level highstand because it is below the regionally prominent stage 5e platform.

Along the open coast of the San Joaquin Hills, the lower emergent platform and shoreline are a few meters above the lowest (modern) wave-cut platform and several meters below any previously mapped or dated shoreline (see lower arrow, Fig. 2d). Based on position between the modern shoreline and dated shorelines at higher elevation, the lower emergent shoreline should be younger than 83 ka (stage 5a sea level highstand). It is unlikely to correlate with stage 3 sea level highstand because stage 3 shorelines have only been reported from areas of California with Quaternary uplift rates significantly higher than the San Joaquin Hills (Lajoie *et al.,* 1991; Trecker *et al.,* 1998; D. Ponti, 2001, personal comm.). Therefore, the lowest emergent platform and shoreline (lower arrow in Fig. 2d) are most likely Holocene age (stage 1 sea level highstand).

Most emergent Holocene shorelines in tectonically active areas are less than 6000 yr old and reflect coseismic uplift rather than sea level fluctuation or large storms (Lajoie *et al.,* 1991). If Stevenson's (1954) and Stevenson and Emery's (1958) hypothesis that the marsh bench was created by tectonic emergence is correct, then the lowest emergent or elevated coastal platform and shoreline may be correlative with the marsh bench and may also have formed by tectonic uplift. We evaluated this hypothesis by measuring and com-

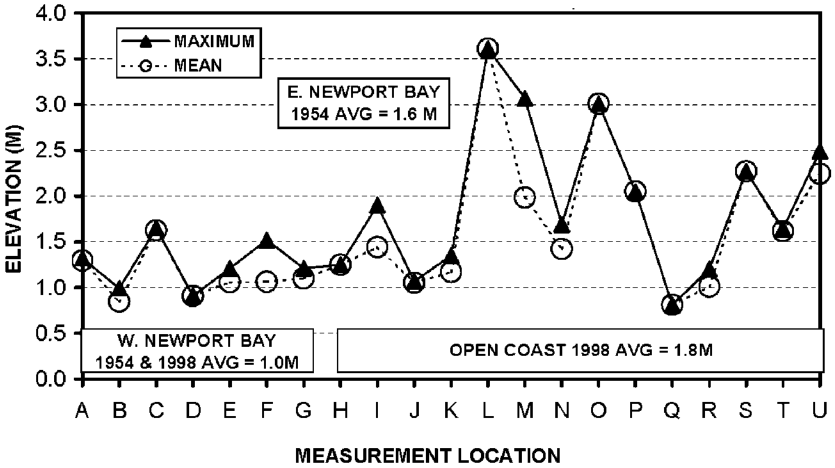

Figure 3. Plot of elevation measurements of the marsh bench on the west side of Newport Bay and emergent shoreline and platform along the open coast. Letters correspond to measurement locations shown on Figure 2. See text for explanation of measurements.

paring the height of the marsh bench today, the height of the emergent coastal shoreline or platform, and the average measurements reported by Stevenson (1954).

Measurements

We used rods and hand levels to measure the height of the marsh bench and lower emergent coastal shoreline or platform above the lowest (modern) shoreline or shore platform exposed at low tide. Most measurements were made during low-sand conditions.

We identified 21 locations where the marsh bench or emergent shoreline are relatively well defined and appear to be in their natural condition (i.e., not modified by humans). At most locations we made multiple measurements, for a total of 61 measurements. Wherever possible we measured the height between the emergent shoreline and the modern shoreline immediately below it. In some locations this was not possible due to restricted coastal access or hazardous conditions. In these cases we measured the elevation difference between the emergent platform and modern shoreline, as close to the emergent shoreline as possible, or we measured platform to platform elevation difference close to the shorelines. Locations of measurement and representative photographs are shown in Figure 2. The greatest density of measurements is in northern Laguna Beach (Fig. 2a). Average and maximum measurements for each location are displayed on Figure 3.

On the west side of Newport Bay, the top of the marsh bench is 1.02 m (on average) above the modern shoreline (Fig. 3). Our measurements in the Bay agree well with Stevenson's (1954) reported average height of 0.96 m on the western shore circa A.D. 1950. A road on the eastern side of the bay covers the marsh bench so it is no longer possible to measure it. Stevenson (1954) reported an average height of 1.6 m for the marsh bench on the eastern side of the bay. Along the open coast, between lower Newport Bay and Dana Point, the average height of the emergent shoreline or platform is 1.8 m above its modern geomorphic equivalent. The maximum measurement is 3.6 m in northern Laguna Beach (Fig. 2e). On average of 61 measurements, the marsh bench and emergent shoreline are 1.6 m above the modern shoreline.

Uplift and Age

Our data agree with Stevenson's (1954) hypothesis that the marsh bench emerged due to tectonic uplift of the San Joaquin Hills. The spatial pattern of emergent shorelines and marsh deposits roughly mimics the topographic expression of the San Joaquin Hills and is consistent with a tectonic origin. Elevation profiles of the marsh bench in Newport Bay reveal an antiformal pattern of uplift nearly perpendicular to the axis of the San Joaquin Hills anticline, with higher average uplift on the east side of the bay where the topographic relief is greater (Stevenson, 1954). The maximum elevation of the coastal shoreline is on the central coast of the San Joaquin Hills near the greatest topographic relief. The marsh bench and coastal benches could not have formed solely by erosion or deposition due to a sea level highstand because the elevations are different at different locations and the average elevations are different on each side of Newport Bay and along the open coast. Therefore, the most plausible mechanism for creating both the marsh bench and coastal platforms is emergence by tectonic uplift. The date of uplift can be estimated from the age of the marsh bench and emergent shoreline.

Age of the Marsh Bench

The age of the marsh bench is constrained by radiocarbon dating and erosion rates. We collected charred plant material and shells (*Ostrea lurida*) from two separate, horizontal layers 5–7 cm apart in marsh bench sediment, 0.7 m above the present shoreline. Some shells may have been in life positions (E. Marks, 2000, personal comm.). The calibrated ages of the plant material (A.D. 1635–1955) and underlying shell (A.D. 1665–1950) (see Table 1) are essentially coincident. The slightly older age of the plant sample may be due to the presence of detrital material or charcoal. Active marsh deposition and growth must have ceased on the marsh bench sometime after our samples were deposited. Assuming the radiocarbon dates represent the true age of the samples, the marsh bench must have emerged from the active marsh after deposition of the dated samples. The earliest plausible date is A.D. 1635, indicating that the marsh bench emerged sometime in the last few centuries.

The calibrated radiocarbon ages of marsh bench samples are consistent with measurements and observations of marsh growth and marsh bench erosion. Stevenson (1954) and Stevenson and Emery (1958) estimated that the marsh bench was approximately 220–300 yr old at the time of their study. Their estimate was based on 4-yr measurements of the rate of growth of new marshland and erosion rates of Newport Bay bluffs and marsh bench. Our field observations also suggest that the fragile marsh bench is not more than a few centuries old. In four years of study, we observed visible changes caused by erosion. We also observed active erosion during winter storms and high spring tides. In addition, there is significantly more vegetation on the marsh bench now than there was in the 1950s, suggesting that it was a younger feature in an earlier stage of ecological succession.

Age of Emergent Shoreline

The emergent coastal shoreline is assumed to be late Holocene (<6 ka), as described previously, because it is below late Pleistocene shorelines and above current sea level (as defined by the lowest wave-cut platform and shoreline). We were not able to apply radiocarbon dating to the emergent shoreline because we were unable to find suitable fossil material. The location, elevation, morphology, and apparent Holocene age of the emergent shoreline suggest that it is correlative with the marsh bench and may be the same age,

Table 1
Radiocarbon Dates

Sample*	Material†	Measured ^{14}C Age‡	^{13}C/^{12}C	Conventional ^{14}C Age‡	Calibrated 2σ Calendar Age
Beta 13095 LG2-9-99A	Charred plants	180 ± 60	−23.2‰	210 ± 60	A.D. 1635–1955
Beta 13096 LG2-9-99C	Shells *(Ostrea lurida)* (six pieces)	330 ± 40	+1.1‰	760 ± 40	A.D. 1665–1910; A.D. 1915–1950

*Samples analyzed by Beta Analytic, Miami, Florida, USA 33155. Age calibration performed by Beta Analytic from procedure by Stuiver *et al.* (1998).

†Sample 13095 pretreated with acid/alkali/acid. Sample 13096 pretreated with acid etch.

‡Dates are reported in radiocarbon years before present (RCYBP) where present = A.D. 1950.

but the correlation cannot be confirmed because much of the coastline has been modified by development.

Historic Earthquakes

If we assume a tectonic origin for the marsh bench and emergent shoreline, then the record of earthquakes in southern California may further constrain the date of uplift. Uplift of the San Joaquin Hills must have occurred after A.D. 1635, the earliest plausible age of the marsh bench. The historic earthquake record begins in 1769 with a strong temblor described by explorer Gaspar de Portola (Townley and Allen, 1939) from his inland location in present day north Orange County, central Los Angeles basin. There are no reported observations of the 1769 earthquake from coastal areas. The mainshock was violent, and at least two dozen earthquakes followed it over the course of several days. The date, location, and apparently large magnitude of the 28 July 1769 earthquake make it a good candidate for the most recent earthquake that raised the San Joaquin Hills coastline (Grant *et al.,* 1999).

Other candidates for the San Joaquin Hills earthquake occurred on 22 November 1800 and 10 July 1855 (Barrows, 1974). Coastal Orange County was sparsely populated in the early to mid-1800s, and little information exists about earthquakes during that time period (Toppozada *et al.,* 1982). The 1800 earthquake cracked walls in San Diego and at the San Juan Capistrano Mission, which started construction in 1797 (Toppozada *et al.,* 1982; Jacoby *et al.,* 1988). The 1855 earthquake generated strong shaking in Los Angeles and San Gabriel and was felt distinctly as far north as Santa Barbara and east to San Bernardino (Townley and Allen, 1939). "Two unusually heavy sea waves" were reported from Dana Point immediately following the last shock (Barrows, 1974, p. 62). The sea waves suggest that a modest tsunami was generated by local disturbance of the sea floor. However, there are numerous reports of damage north of the San Joaquin Hills and none to the south. Yerkes (1985) assigned the 1855 earthquake to the Raymond fault in Los Angeles County. There are no other documented earthquakes that could have generated more than 1-m uplift of the San Joaquin Hills after 1855, so we conclude that uplift and the causative earthquake occurred between A.D. 1635 and 1855.

Earthquake Magnitude and Source Models

If we assume that the marsh bench and emergent shoreline were raised by a single coseismic event, the magnitude can be estimated from measurements of inferred uplift by converting uplift to fault slip and then applying empirical regression relationships between magnitude and slip (Wells and Coppersmith, 1994). The single-event assumption is supported by the young age of the marsh bench, its geomorphic expression as a single bench, and the historic record of earthquakes.

The geometry of the source fault must be known or estimated to convert surficial uplift to fault displacement (e.g., Anderson and Menking, 1994). Several fault models have been proposed to explain uplift and folding of the San Joaquin Hills. Grant *et al.* (1999) developed a model of a blind thrust fault dipping 30° to the southwest. Bender (2000) proposed that uplift is occurring in response to movement of the steeply dipping, strike-slip Newport–Inglewood fault system. Both types of faults may have contributed to uplift during the late Quaternary (Grant *et al.,* 2000). A third model proposed by Rivero *et al.* (2000) attributes uplift to movement of a large regional thrust, the northeast-dipping Oceanside fault extending offshore of the San Joaquin Hills south to Oceanside and San Diego (see Fig. 1).

Because the source fault models are so different, it seems prudent to apply only simple models to estimate fault slip for end-member cases. To account for the range of proposed fault models, we consider two end-member cases for estimating magnitude: pure uplift on a vertical fault and pure thrust on a fault dipping 30°. Our method underestimates magnitude because surface deformation generated by movement of a blind fault is less than displacement on the fault at depth, and both cases neglect strike-slip displacement. If there were a strike-slip component (as suggested by Bender, 2000), then the total fault displacement, and the resulting magnitude, would be even greater.

We estimate minimum magnitude by assuming average and maximum uplift at the surface is the same as average and maximum slip on the fault at depth. As shown in Table 2, the magnitudes estimated from average or maximum uplift are in agreement (assuming the same fault model). The maximum estimated slip is derived from a measurement of

Table 2
Earthquake Magnitude Estimated from Regression Relationships between Fault Displacement and Magnitude

Uplift (m)*	Fault Model (Dip)	Fault Displacement (m)*	Magnitude†
1.6 avg	90°	1.6 avg	**M** 7.1
3.6 max	90°	3.6 max	**M** 7.1
1.6 avg	30°	3.2 avg	**M** 7.3
3.6 max	30°	7.2 max	**M** 7.3

*avg, average; max,maximum; **M**, moment magnitude.

†From regression relationship for all faults. Magnitudes are estimated from regression relationships in Wells and Coppersmith (1994).

maximum inferred uplift (3.6 m) along the coast. If the correlation between the emergent shoreline and marsh bench is not valid, neither is the estimated maximum slip. However, the average uplift (1.6 m) is derived from measurements of both the marsh bench and the open coast. This average is the same as Stevenson's (1954) reported average height of the marsh bench on the east side of Newport Bay. Therefore, if the correlation of marsh bench and emergent coastal shoreline is incorrect, it should not significantly affect the magnitude estimated from average uplift. The estimated magnitude is more sensitive to the fault model than to the use of average or maximum measurements. The results, summarized in Table 2, imply that the magnitude of the San Joaquin Hills earthquake was **M** >7.

Discussion

The southern Los Angeles basin has been assumed to have low seismic hazard relative to the northern basin due to low rates of instrumentally recorded seismicity and fewer mapped active faults (WGCEP, 1995). Based on our interpretation of the data, this region was more seismically active in the preinstrumental period. The most significant earthquake during the historic period was the 1933 **M** 6.3 Long Beach earthquake on the Newport–Inglewood fault zone (NIFZ) near the Santa Ana River in Orange County (Hauksson and Gross, 1991) (Fig. 1). The epicenter of the 1933 rupture propagated northwest toward the city of Long Beach, which sustained more damage (Barrows, 1974) and was more densely populated than the epicentral area in agricultural coastal Orange County. Aftershocks occurred around the rupture zone to the northwest and north, including the central Los Angeles basin (Hauksson and Gross, 1991). Very few aftershocks occurred southeast of the epicenter in the adjacent San Joaquin Hills. Low aftershock activity in the San Joaquin Hills might be explained by prior strain release in a large San Joaquin Hills earthquake or by a major displacement of the NIFZ on its southern, offshore segment. The southern, onshore NIFZ has ruptured several times in the last 12,000 yr, although the date of the most recent surface rupture is not known (Grant *et al.,* 1997).

The late Quaternary uplift rate of the San Joaquin Hills is approximately twice as high as uplift rates parallel to the NIFZ along the coast to the south (Shlemon, 1978; Lajoie *et al.,* 1979, 1991). Several observations suggest that the San Joaquin Hills are underlain by a fault that is distinct from the NIFZ, although they may be linked kinematically. There are several Quaternary anticlines along the NIFZ north of the San Joaquin Hills (Barrows, 1974; Wright, 1991). However, the San Joaquin Hills anticline is longer and has the greatest topographic expression. Other topographically prominent anticlines, such as Signal Hill, are located within the structurally complex NIFZ and are associated with step-overs (Barrows, 1974). In contrast, the San Joaquin Hills anticline is east of the main NIFZ, and there is a releasing bend at the mouth of the Santa Ana River where the fault goes offshore (Morton and Miller, 1981) near the northern San Joaquin Hills.

Changes in pollen types, as well as sedimentation, reported from a core of San Joaquin Marsh (Davis, 1992) are consistent with an interpretation of latest Holocene tectonic uplift of the San Joaquin Hills. San Joaquin Marsh is currently a freshwater marsh located between the city of Irvine and upper Newport Bay (Fig. 2a). Radiocarbon dates and analysis of pollen from core sediments show that San Joaquin marsh responded to changes in relative sea level during the Holocene (Davis, 1992). After approximately 4500 yr B.P., freshwater pollen types were replaced with salt marsh types as marsh flora responded to the Holocene sea level highstand (Davis, 1992). Freshwater conditions returned briefly circa 3800, 2800, 2300, and after 560 yr. B.P. (Davis, 1992). Davis correlated these freshwater intervals with periods of global cooling but noted that the post–560 yr B.P. episode is not an exact match with Little Ice Age ice cooling events or glacial advances in the White and Sierra Nevada Mountains, California.

Another possible explanation is that tectonic uplift of the San Joaquin Hills elevated San Joaquin Marsh above sea level, causing a return to freshwater conditions. From observations reported by Davis (1992), it appears that the change in salinity coincided with deposition of peat at depth of 131–122 cm (reported age 390 ± 80 yr B.P.), followed by silt and sand deposition during the historic period. Davis (1992) estimated an age of A.D. 1776–1797 for exotic taxa attributed to European contact, found in silt at 117-cm depth. The exotic pollen are only a few centimeters above the freshwater peat deposit, suggesting that the salinity change occurred shortly before the introduction of European pollens. If the salinity change was caused by tectonic uplift, the date of uplift is bracketed by the earliest plausible emergence of the marsh bench in A.D. 1635, and the introduction of European pollens circa A.D. 1776–1797. Of the known historic earthquakes, the A.D. 1769 earthquake is the best candidate because it occurred after the earliest plausible date of marsh bench emergence and just before the introduction of European pollen to San Joaquin marsh.

Several moderate magnitude earthquakes have occurred within the greater Los Angeles basin during the historic period: 1971 **M** 6.7 San Fernando, 1994 **M** 6.7 Northridge, and 1933 **M** 6.3 Long Beach earthquakes (WGCEP, 1995). The San Joaquin Hills earthquake was significantly larger (**M** >7) and may be the largest known earthquake that originated within the Los Angeles structural basin (as defined by Wright, 1991), and possibly within the greater Los Angeles region (as defined by Dolan *et al.,* 1995), in the last few centuries.

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