Bulletin of the Seismological Society of America, Vol. 88, No. 1, pp. 140–159, February 1998

Re-evaluation of the 1836 "Hayward Fault" and the 1838 San Andreas Fault Earthquakes

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Abstract Current seismic hazard models include two major earthquakes ($M \sim 7$) in the San Francisco Bay area that are close in space and time: an 1836 event on the northern Hayward fault and an 1838 event on the peninsula section of the San Andreas fault. Analysis and interpretation of the available historical accounts indicate that the 1836 event occurred east of Monterey Bay, far from the Hayward fault, and was of $M \sim 6¼$. Also, the 1838 event was not confined to the 60-km peninsula San Andreas as current models indicate. Instead, faulting probably extended from San Francisco to San Juan Bautista (~140 km), indicating a significantly larger earthquake ($M \sim 7½$) than previously thought.

Damaging effects of the 1836 earthquake were reported only from Santa Clara to Carmel, and no contemporary effects were reported to the north of Santa Clara or near the Hayward fault. The illusion of an "1836 Hayward earthquake" evolved from a newspaper reminiscence published following the 1868 Hayward earthquake, stating that the 1868 effects in the East Bay were similar to those of an 1836 event. The article describes various strong effects in the East Bay that differ completely from the effects recorded for the 1836 earthquake but are very similar to those documented for the major 1838 San Andreas earthquake that caused extensive damage on both sides of San Francisco Bay. Based on this and other evidence, we conclude that the reminiscence describes the destructive June 1838 effects, but it erroneously indicates the date as June 1836. There is no evidence for any major historical earthquakes in the San Francisco Bay area before the 1838 earthquake, back to the founding of Mission San Francisco Dolores in 1776.

During the 1838 San Andreas fault earthquake, the shaking intensity in Monterey was as strong as or stronger than during the great 1906 San Andreas fault earthquake. This suggests that the 1838 San Andreas fault rupture may have extended to San Juan Bautista as it did in 1906. Numerous probable aftershocks were felt in the area south of San Juan Bautista. These damaged Carmel and Santa Cruz in 1840, and Alisal, 16 km west of the San Andreas fault, in 1841. The northern end of the 1838 faulting was previously assumed to be 25 km south of San Francisco. However, Mission San Francisco Dolores was damaged in 1838 but not in 1906, suggesting that the 1838 faulting extended to San Francisco. Also, the 1838 aftershocks were felt in Oakland as frequently and violently as those following the major 1868 Hayward earthquake, suggesting that the 1838 faulting on the San Andreas extended to the latitude of Oakland.

The 1838 fault segment ruptured again 68 years later as part of the overlapping 1906 San Andreas fault rupture. This, and similar evidence from southern California, indicates that $M \sim 7½$ San Andreas fault earthquakes can recur at intervals of 68 years or less when they are followed by $M \sim 8$ earthquakes on overlapping segments of the fault.

Introduction

The urban San Francisco Bay area is one of the most seismically active regions in California. In the East Bay, the Hayward, Calaveras, and Concord faults traverse numerous cities. In the Peninsula and South Bay areas, the San Andreas

fault is within 20 km of all cities from San Francisco to Santa Cruz. Written records in the Bay area became available with the founding of Mission San Francisco Dolores in 1776. Since then, destructive earthquakes of $M \gtrsim 7$ were thought to have occurred on the Hayward fault in 1836 and 1868, and on or near the San Andreas fault in 1838, 1906, and 1989.

The 1836 and 1838 events are the least well documented, because they occurred after the Missions were secularized in 1834, which ended the regular Mission reports, and before the 1849 Gold Rush and regional newspaper coverage. From 1834 to 1849, the sources of information were limited to the writings of the few literate residents of the sparsely populated area and the notes of travelers. In 1837 Abel du Petit-Thouars, captain of the frigate *La Venus,* observed that California's capital, Monterey, had fewer than 40 to 50 houses and no more than 200 souls (Louderback, 1947).

It is important to improve our understanding of the 1836 and 1838 events, because their recurrence and effects, and those of the 1868 and 1906 events, form the basis for many of the earthquake hazard assessments in the Bay area. Hazard assessments of the northern Hayward fault have been strongly influenced by a major earthquake that supposedly occurred there in 1836, 32 years before the major 1868 Hayward earthquake. We researched and analyzed the primary historical accounts and found that the 1836 earthquake probably occurred in the Monterey–Santa Clara area and was of $M \sim 6¼$.

We show that the myth of the "1836 Hayward fault earthquake" evolved from a reminiscence published following the 1868 Hayward earthquake, that apparently described the effects in East San Francisco Bay of the June 1838 San Andreas fault earthquake, but erroneously indicated the date as June 1836. This mistake was compounded successively by Wood (1916), Louderback (1947), and Byerly (1951). Fissures near the Oakland waterfront, probably due to lateral spreading induced by the major 1838 San Andreas fault earthquake, became fissures that "opened along the Hayward fault from San Pablo to Mission San Jose" (Byerly, 1951). Eventually, the 1836 earthquake was used for calculations of earthquake probability on the northern half of the Hayward fault (Lindh, 1983; WGCEP, 1988, 1990).

For the evaluation of earthquake recurrence and probabilities on the Hayward and other Bay area faults, it is important to determine the date of the earliest major historical earthquake in the Bay area. We found no historical evidence for any major earthquakes in the San Francisco Bay area before the 1838 earthquake, back to the founding of Mission San Francisco Dolores in 1776.

Research and interpretation of the historical accounts of the major 1838 earthquake suggest that it resulted from rupture of the San Andreas fault from near San Juan Bautista to near San Francisco. We base this on the damage from San Francisco to Monterey that indicates ground shaking as strong as or stronger than that during the 1906 San Francisco earthquake and on numerous probable aftershocks that were strongly felt near both ends of the rupture. The proposed 1838 rupture is more than twice as long as previously thought, and indicates $M \sim 7½$. Studies of seismically triggered rockfalls in the Sierra Nevada (Bull, 1996) provide independent support for this large magnitude.

The rerupture of the 1838 segment during the more extensive 1906 earthquake faulting is similar to the rerupture of the major 1812 segment in the more extensive 1857 earthquake faulting (Jacoby *et al.,* 1988). We discuss the San Andreas fault behavior of irregular recurrence or clustering of M 7½ to 8 earthquakes, and triggering of overlapping segments, in light of these observations.

The 1836 Earthquake

Sources of Information

Five of the six available 19th-century references for the 1836 earthquake describe effects only in the region from Carmel to Santa Clara;

1. The Original 1836 Diary of Rafael Gomez

The only available first-hand account of the 1836 earthquakes was written by Rafael Gomez at Monterey. In his diary, which is from 6 January 1836 to 18 April 1837, he records three earthquakes. He reported feeling strong earthquakes in Monterey on 25 April and 9 and 10 June 1836 (Table 1). The 10 June earthquake was the most violent and the longest in duration. He died in 1837 in a horse riding accident at his Rancho de Tularcitos near Monterey. Juan Gomez, his son, apparently turned his father's diary (Gomez, 1836) over to H. H. Bancroft. We confirmed the authenticity of this unsigned, loose-leaf manuscript by comparing it with a genuine sample of Rafael's handwriting (Gomez, 1837). Table 1 shows that in 1874 General M. G. Vallejo copied information on the occurrences in Monterey from Gomez (1836), in compiling notes for his 1875 California memoirs.

2. Abel Du Petit-Thouars' 1837 Account

Louderback (1947, p. 48) provides information from Captain Abel du Petit-Thouars' *Voyage Autour du Monde sur la Fregate La Venus pendant les annees 1836–1839, Paris, Gide, Editeur, 1841, 5 volumes.* On 30 October 1837, Abel du Petit-Thouars observed at Mission San Carlos in Carmel that "the roofs [of the living quarters] were broken through in several places having already given way under their own weight." In the chapel, he saw a large painting of San Isidro "which was suspended quite obliquely by one of the upper corners of the frame. In this position the saint and his plow appeared inverted." The local priest lamented that "during an earthquake this painting had been inverted in this way, and surely this catastrophe had been a manifestation of the will of God, and a sure prediction of ruin of the missions." No annual report is available from the Mission, which was secularized in 1834. Although the date of the

Table 1
1836 Earthquake and Related Entries in the Monterey Diary of Gomez and the 1874 Notes of Vallejo

1836 Earthquake Date and Time	R. Gomez (Monterey, 1836)	M. G. Vallejo (1874)
April 25, ~5. a.m.	"Mzo 20—Salio la Fragata California para San Diego . . ." "Abril 25—Hubo un fuerte Temblor, como a las cinco de la manana . . ."	"Marzo 20—Salio la Fragata California para San Diego" "25—Fuerte temblores de tierra a las cinco de la mana-ana."
	Translation: "March 20—The frigate California departed for San Diego . . ." "April 25—There was a strong earthquake about five o'clock in the morning . . ."	Translation: "March 20—The frigate California departed for San Diego" "25—Strong earthquakes at five o'clock in the morning."
June 9, ~4 p.m.	"Junio 9, Como a las quartro de las tarde hubo un pasajero y fuerte temblor de tierra"	"Jun 9 Fuerte temblor de tierra, aunque no duro mas que medio minuto"
	Translation: "June 9. About four in the afternoon there was a transitory (or short) and strong earthquake"	Translation: "June 9 A strong earthquake, although it lasted for no more than a half minute"
Mainshock June 10, 7:30 a.m.	"Junio 10. A la media por los ocho de la manana repitio el temblor con mas fuersa{sic} y duracion . . ." "Junio 14. Dias 4h de la tarde fondeo entre puerto la Barca Quijote procedente de la Islas de Sandwich . . ."	"10 4th de la tarde repitio el temblor con mas fuerza y duracion" "14 Fondeo, procedente de Sandwich Yisland la Barca "Quijote" "
	Translation: June 10. At seven thirty in the morning the shaking recurred with more violence and duration . . . June 14. At four in the afternoon, the bark Quijote arrived from the Sandwich Islands . . .	Translation: 10 At 4 o'clock in the afternoon, the shaking recurred with more violence and duration. 14 The bark "Quijote" arrived from the Sandwich Islands.

event was not specified, we agree with Louderback's reasoning that it was most probably the June 1836 event, because there is no record of any other earthquakes in California between June 1836 and October 1837. Louderback (1947, p. 49) indicated that "an earthquake that was strong enough to swing and partly tear loose from its fastenings a large painting was probably at least of intensity VII Rossi Forel." This corresponds approximately to Modified Mercalli Intensity (MMI) VI to VII and is consistent with Gomez' description at Monterey, 5 km away, of the 10 June earthquake as more violent and lasting longer than the strong earthquake of 9 June (Table 1).

3. General M. G. Vallejo's 1874 Notes

With the help of Bancroft's assistant Cerrutti, General Vallejo in 1874 prepared a set of notes to use in writing his 1875 memoirs. The latter were prepared for H. H. Bancroft to use in his *History of California* (1886). The notes contain an almost verbatim copy of the Gomez diary (source 1). Both mention the 25 April earthquake, although Vallejo (1874) omits the word "Abril" (Table 1). Both mention the ship Quixote arrived from the Sandwich Islands on 14 June. Vallejo omits the time of the 9 June foreshock. He erroneously assigns the 4 p.m. time of the foreshock to the 10 June mainshock. Although the 1836 earthquake information is dependent on the Gomez diary, we present Vallejo's 1874 notes to show how the original information filtered into subsequent references such as Vallejo (1875) and Bancroft (1886).

Duration of 1836 Earthquakes

In the 1874 notes, 38 years after the event, Vallejo added the duration—no more than a half minute—to Gomez's statement about the 9 June 1836 foreshock (Table 1). Taken literally, this indicates a very long earthquake and conflicts with Gomez' eyewitness account "transitory (or short) and strong" for the event of the 9th, and thus is suspect. Vallejo's statement could be a misleading way of saying: strong earthquake, although it did not last long. Vallejo's 1874 notes give no details about the duration of the 10 June 1836 mainshock, only that it was longer than the 9 June 1836 event, as Gomez indicated. The mainshock duration is discussed further below, at the end of source 4: Vallejo's memoirs.

4. General M. G. Vallejo's 1875 Memoirs

Vallejo (1875, p. 84) lists the 1836 events among the contents of his chapter XLIV: "Earthquakes at Monterey and the effects they produced upon the minds of the inhabitants." The title states that the earthquake effects occurred at Monterey. There is no indication that his home in Sonoma was strongly affected, as it probably would have been had the earthquakes occurred on the northern Hayward fault 35 km from Sonoma (Fig. 1). The memoirs provide the added information that the earthquake created damaging havoc at Monterey and Santa Clara. They repeat the error in the 1874 notes of assigning the foreshock time to the mainshock (Table 1). In the following passage, Vallejo (1875, p. 97) gives

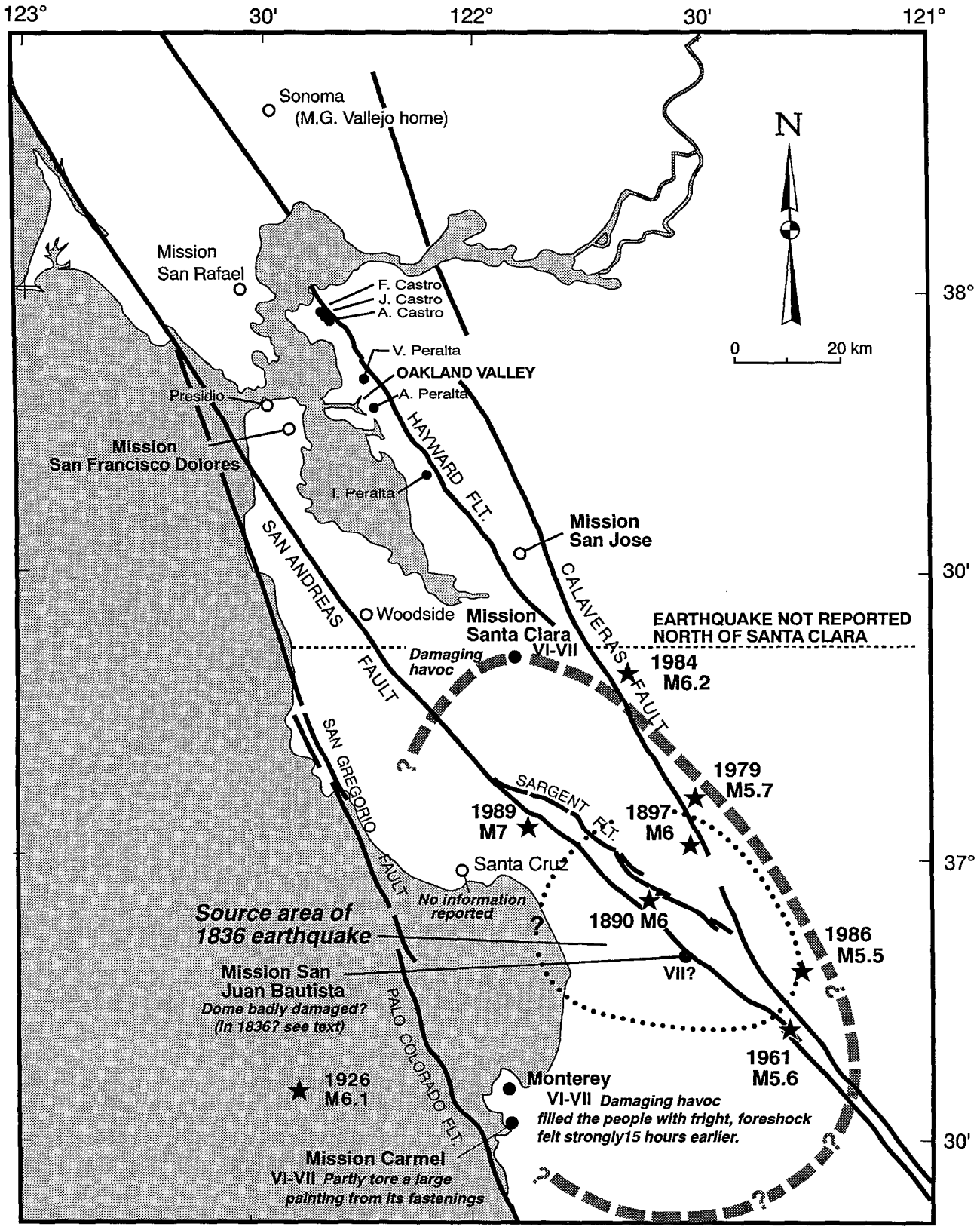

Figure 1. Area damaged at MMI VI–VII by the 10 June 1836 earthquake is outlined by the dashed contour. Dots near the Hayward fault indicate possible 1836 adobes (Table 3). The 1836 effects are compared in Table 4 to those of the eight starred earthquakes. An estimate of the approximate epicentral area of the 1836 event is outlined by the dotted contour.

details that, except for the phrase "shook us up," do not seem to concern his personal experience.

> In the month of June heavy earthquake shocks were felt. The first ones, which took place on the ninth, only lasted half a minute, but those which shook us up on the tenth of the same month at half past four in the afternoon lasted very nearly a minute and created damaging havoc [estragos] at Monterey and Santa Clara. Due to this cause, which filled many people with fright, Colonel Chico [in Monterey] was free to rule as he pleased for a few days, since, as I have stated in one of the previous chapters, these inexplicable phenomena of nature monopolized the thoughts of timid people and especially of the women, who considered the shocks as forerunners of the displeasure and wrath of the Supreme Creator.

This translation by E. R. Hewitt (Bancroft, 1886) differs slightly from that given by Louderback (1947, p. 41), and translates "estragos" as "damaging havoc" instead of "havoc." A third translation of this passage by Lothrop (1926) translates "estragos" simply as "damage." We estimate that the "damaging havoc at Monterey and Santa Clara . . . which filled many people with fright" may indicate MMI VI to VII. It is unlikely that the intensity at Santa Clara was greater than MMI VII, because there are no contemporary accounts of any effects to the north thereof (Fig. 1).

General Vallejo's Location on 9 and 10 June

Vallejo never states his whereabouts at the time of the earthquakes. Louderback (1947, p. 42) wrote: "At the time of the earthquakes Vallejo was away from home [Sonoma], marking time in Monterey." We have discovered that General Vallejo was in Monterey on 26 to 28 May and was back at Sonoma at the time of the earthquakes.

Vallejo's memoirs include his recollection:

> that on ". . . May the fifth Comandante general Chico sent me a peremptory order to turn over to my second, command of the garrison and of the Sonoma frontier, and to report at Monterey without loss of time . . . This note reached my hands eight days after it had been written. No sooner had I received it than I set out [May 15?], accompanied by two aids . . . [He met some merchants at San Jose who warned him about the treacherous ways of Chico] and then returned to Sonoma to get 22 soldiers, 10 civilians, and 16 Indians, all armed from head to foot (p. 69). [then he departed again for Monterey] . . . rested one day at Pajaro [3 km east of Watsonville] and then set out for Monterey on May 26th" (p. 70). At Monterey he met General Chico and spent the night (p. 75–76). He arranged meetings the next day with the alcalde (mayor or judge), and "ordered my soldiers to prepare to set out on the trip back to Sonoma on the following day" (p. 82–83).

That would have been May 28, giving him plenty of time to get back to Sonoma before the 9 and 10 June earthquakes.

Vallejo kept a detailed, bound letterbook containing chronologically ordered copies of outgoing correspondence written from Sonoma between 1 January and 1 November 1836 (Wright, 1953). He wrote no letters from Sonoma between 15 May (Bancroft Library No. C-B 3:204) and 7 June. Letters 117 to 120 were written on 7 and 8 June just before the 9 and 10 June foreshock and mainshock. Apparently, his trip to Monterey and back to Sonoma took place entirely between 15 May and 7 June.

Vallejo copied the earthquake date and time from Gomez' diary (Table 1). He provided no more detail of the nature of the damage effects at Monterey than at Santa Clara. He described both as "damaging havoc." This is consistent with his not being in Monterey during the earthquakes. His memoirs only indicate damage in the Monterey–Santa Clara area and give no indication of any damage to the north near the Hayward fault (Fig. 1).

Vallejo did not describe any earthquake effects at his Sonoma home, which suggests that the effects there were much less than at Monterey. This also is inconsistent with a source on the Hayward fault. During the 1868 earthquake on the *southern* Hayward fault, Sonoma was in the MMI VII zone, whereas Monterey was near the boundary separating the MMI V and VI zones (Toppozada *et al.*, 1981). The north end of the 1868 rupture near Berkeley was only 50 km south of Sonoma, but 140 km north of Monterey (Fig. 1).

The 1836 earthquake probably was felt at Vallejo's Sonoma home, because similar events in 1890, 1897, and 1984 (epicenters shown in Fig. 1) produced MMI II to V at Sonoma (Toppozada *et al.*, 1981; U.S. Earthquakes, 1984). Sonoma's location in an alluviated valley may account for a longer than usual duration of shaking, but Vallejo's (1875) duration of "nearly a minute" still appears exaggerated. It probably was Vallejo's simple way of noting that the second event was perhaps twice as long as the first, which he described in his 1874 notes as "no more than half a minute." Durations reported by lay persons are often inaccurate and exaggerated. For example, some people in the Bay area described an M 4.8 earthquake near San Jose on 21 May 1996 as "a 45-second shake" (*The Sacramento Bee,* May 22), although its magnitude indicates it could not have been felt for more than 5 or 10 sec.

5. Carter's Account

In a review of the California missions, Carter (1900, pp. 175 to 176) included his observations on the condition of Mission San Juan Bautista in 1895: "The walls of the church are the original ones, but the roof has been shingled, and a tall wood spire like that at San Luis Obispo, but uglier, because more obtrusive, has replaced the dome [or tower?], which was badly injured by an earthquake in 1836." The wooden tower actually was constructed in 1867 according to Berger (1941). In 1949, the tower "was torn down and

the building returned to its original form" (Lane Publishing, 1986, p. 246).

Damage at San Juan Bautista would be consistent with the "damaging havoc" at Monterey (42 km to the southwest) and Santa Clara (62 km to the northwest), and with the damage observed at Carmel by Du Petit-Thouars. However, we have been unable to find any original documentation for Carter's reported damage, which might have been from the 1836 earthquake, the 1838 earthquake, or both. The missions were secularized after 1834, thus ending the regular annual reports that sometimes contained earthquake information.

The first five references all indicate an origin for the 1836 earthquake in the area bounded by Monterey, Carmel, San Juan Bautista, and Santa Clara. We found no reports of any effects for the area north of Santa Clara (Fig. 1), except as alluded to in the next reference.

6. The 1868 Reminiscence

Twenty days after the major Hayward earthquake of 1868, the *Oakland Daily News* of 10 November, printed a reminiscence indicating that the 1868 effects in East San Francisco Bay "appear to have been a repetition of those observed in the 1836 earthquake" (Table 2). Damage along the Hayward fault is not supported by any of the above five accounts of the 1836 event, which mention no effects north of Santa Clara. In particular, Vallejo's memoirs state only that the 1836 earthquake created damaging havoc at Monterey and Santa Clara, which implies a source between the two, and mention no effects near the Hayward fault. The reminiscence was reprinted by two weekly newspapers: the *Alameda County Gazette* (San Leandro) of 14 November 1868 and the *Suisun Solano Herald* of 21 November 1868. A search of these and other Bay area newspapers printed through the remainder of 1868 produced no more information about the reminiscence.

Implication of a Hayward fault source for the 1836 earthquake rests exclusively upon this 1868 reminiscence of events more than 30 years past. We will argue that the reminiscence describes the major June 1838 San Andreas fault earthquake, but erroneously indicates the date as June 1836. We base this on the location of "Oakland Valley," 1838 damage in the East Bay, and foreshocks and aftershocks. It is more common for witnesses to confuse the year of long past events than the month or season. For example Holden's (1898) earthquake catalog lists a major earthquake in January 1856, which appears to be a misdated reference to the January 1857 Fort Tejon earthquake (Toppozada *et al.,* 1981). Also, the 1838 earthquake was misdated as occurring in 1839 in the Annals of San Francisco (Soule *et al.,* 1855). In the East Bay, the 1838 earthquake generated landslides, damaged and destroyed buildings at San Leandro and Mission San Jose, and was the most destructive event before 1868. We believe that the 1868 reminiscence describes the effects in the East Bay of the 1838 San Andreas fault earthquake, described later in this article.

Table 2 shows how the myth of the "1836 Hayward earthquake" evolved from the 1868 reminiscence. The erroneous inferences are in italics. We believe that the only error in the reminiscence is the 1836 date, which should have been 1838. It was not until 1916 that the seriously erroneous inferences were made. These culminated in Byerly's (1951) presumption that "Fissures opened along this [Hayward] fault from San Pablo to Mission San Jose." This clearly misrepresents the reminiscence that states that the *effects* "were felt along the foothills from San Pablo to Mission San Jose."

Oakland Valley

The reminiscence apparently originated in the Oakland Valley area, according to the first sentence in Table 2. Louderback, Wood, and Byerly assumed that "Oakland Valley" lay along the trace of the Hayward fault and that "the fissures were probably, at least in part, fault-trace phenomena." We have discovered that the place known as "Oakland Valley" surrounded a tidal slough at the bay shore, 6 km southwest of the Hayward fault (Merritt, 1928; Mosier and Mosier, 1986). The slough (Fig. 1) was dammed in 1869 to form Lake Merritt. The Oakland Valley name was not used after it was annexed by Oakland in 1872 as two large parcels northwest of the Fruitvale District (near A. Peralta's adobe, Fig. 1).

The "large fissures in the earth" described in the reminiscence were probably due to lateral spreading during the major 1838 San Andreas fault earthquake. Similar features formed during the 1906 San Andreas fault earthquake: "along the west shore of Lake Merritt the bank has been cracked and broken and caved off into the lake" (Youd and Hoose, 1978, p. 120). After the 1989 Loma Prieta earthquake, similar effects were observed near Lake Merritt (R. Eisner, oral comm.) and along the Oakland waterfront (Seed *et al.,* 1990; Borchardt, 1991). The major 1838 earthquake almost certainly generated shaking-related fissures in Oakland Valley, where its effects would have been comparable to those of the 1906 event.

Adobe Structures

In searching for reports of 1836 damage to the north of Santa Clara, we reviewed studies of the 832 adobes built in the Bay area from 1776 to 1850 (Hendry and Bowman, 1942; Bowman, 1951a, 1951b, 1967). Figure 1 shows the locations of the six adobes that were near the northern Hayward fault possibly in 1836. The dates of construction, listed in Table 3, for three of these indicate that they were present at the time of the 1836 earthquake. There is no indication that any were damaged in 1836.

Mission San Jose

Mission San Jose, built in 1797, stood at the southern end of the rupture that Byerly (1951) inferred for the 1836

Table 2
Evolution of the Myth Concerning the "1836 Hayward Fault Earthquake"

(Erroneous inferences are in italics)

Oakland Daily News, 10 November 1868 (following the 21 October 1868 Hayward fault earthquake)	"An Earthquake Reminiscence.—We are informed that in June, *1836,* there was an earthquake in what is now the Oakland Valley, the effects of which were felt along the foothills from San Pablo to Mission San Jose. There were large fissures in the earth, and the shocks must have been much heavier than those we have lately experienced. After the first and most violent shock, there were innumerable lesser ones, and for a month afterward there were continuous tremors of the earth, uniformly decreasing in violence. Since the earthquake of the 21st ult., there have been numerous shocks, diminishing in violence, and the [1868] phenomena appear to have been a repetition of those observed in *1836,* and noted by persons then residing in the valley."
Bancroft, (1886, v. IV, p. 77–78)	"An earthquake was felt at Monterey April 25, 1836; and more severe temblores occurred *from Monterey northward* on June 9th and 10th of the same year." [His footnoted sources were Gomez (1836); Vallejo (1875, v. III, p. 118); Suisun Solano Herald, Nov. 21, 1868. The Herald had reprinted the 1868 reminiscence, and this may have influenced Bancroft to write "from Monterey northward."]
Wood (1916)	"Region affected *[in 1836]* was approximately the same as that shaken in 1868. Great Fissures in the earth, and the shocks continued for a month. *May it be that the word fissure in this record refers to phenomena now known to characterize the surface outcrop of a fresh fault-slip,—the system of fractures we designate as a fault trace? . . .In this case it is very slightly more probable that the place of genesis was on the Haywards fault.*"
Louderback (1947, p. 73)	"*The fissures were probably, at least in part, fault-trace phenomena.*"
Byerly (1951)	"*On June 10, 1836 at 7:30 in the morning a great earthquake took place which centered on the Hayward fault at the base of the hills on the eastern side of San Francisco Bay. Fissures opened along this fault from San Pablo to Mission San Jose.* The quake "caused havoc" in Monterey and Santa Clara."

Table 3
Adobe Buildings near the Northern Hayward Fault Possibly in 1836 (from north to south in Fig. 1)

Quotations from Hendry and Bowman (1942)

1. The Francisco Castro Adobe Rancho Houses. Constructed in 1827.

   These were about 250 feet west of the highway and 1250 feet south of the road on what is now Church Street in San Pablo. Beechey's map (1941) of San Francisco Bay (1827–1828) shows two houses marked Rancho de Don Castro just west of the Hayward fault. "The inventory of 1852 states that on the death of the father [1831] there was only one old adobe house . . . shown on the Beechey maps and on the diseno of 1830 made by Forbes. In the early '40's the house was vacated and early fell into ruins . . ." (p. 489).

2. The Joaquin Castro Adobe. Possibly constructed in 1836.
   This house stood in San Pablo 50 feet west on the highway. "Maps of 1856 and 1857 show two houses at this site; evidently this house is the east one (p. 499). Joaquin testified that he was the second son to leave the homestead [Francisco's adobe] about 1836 or 1837 . . ." (p. 500).

3. The Antonio Castro Adobe. Possibly constructed in 1836.

   "This house stood about 330 feet east of San Pablo Avenue and about (p. 495) 300 feet south of Wildcat Creek, at the northern boundary of the city of Richmond. . . . In the inventory of 1852 Antonio's adobe house is given as 25 × 6 varas, or 68.5 × 16.5 feet, 7 feet high, shingled, with 4 rooms. It was badly damaged by the earthquake of 1906 and was finally razed about 1910. The date of its erection has not been learned. Joaquin testified that about 1836 Antonio was the first of the sons to receive his portion of the land, and this implies that a house was soon built" (p. 496).

4. The Vicente Peralta Adobe. Constructed in 1836.

   This house was at what is now 527 Vicente Street, Oakland, near Temescal Creek. It was not razed until the middle of the 1880s.

5. The Antonio Peralta Adobe. Constructed in 1821.

   This house was near Peralta Creek at what is now 2511 34th Avenue in the Fruitvale District of Oakland. The building was not razed until 1897. In 1840, it was abandoned as the main residence. It was reoccupied in 1868 after the Hayward earthquake wrecked a newer, larger adobe.

6. The Ignacio Peralta Adobe. Constructed in 1835.

   This adobe "stood about 100 feet north of San Leandro Creek and about 345 feet east of S. Bartlett Avenue. . . . It was built by Ignacio Peralta in 1835 . . . about 42 × 18 feet one story with tile roof and dirt floors; its long side with the porch, faced south and the creek. . . . The house was injured somewhat by the earthquake of 1868, but was not razed, so far as can be learned, until between 1874 and 1878" (p. 593).

earthquake (Table 2). Such an event would have seriously damaged the Mission. We found no such reports for the 1836 earthquake. However, the June 1838 San Andreas fault earthquake *did* damage Mission San Jose. According to Captain John Paty's interview in the *Sandwich Island Gazette* of 17 November 1838, "the walls of the Missions of St. Francisco, St. Jose and Santa Clara were badly injured." Also, Mission San Jose was seriously damaged in the Hayward earthquake of 1868: "At . . . the Old [San Jose] Mission the church and other adobe structures were nearly all destroyed" (*Contra Costa Gazette,* 31 October 1868).

Location of the 1836 Earthquake

We estimated the approximate location of the 1836 earthquake by comparing its effects at the four reporting sites with those of eight relatively well-defined nearby earthquakes (Fig. 1 and Table 4). The epicentral uncertainty of the pre-1961 events is at least 10 km. The 1836 epicenter is the most uncertain and is constrained only by MMI VI to VII effects at Carmel, Monterey, Santa Clara, and the unsubstantiated damage information from San Juan Bautista.

The 1926 event was strongest at Monterey and Carmel, indicating it was much closer to them than to San Juan Bautista and Santa Clara (Table 4). The 1961 event was slightly stronger at Monterey and Carmel than at Santa Clara, indicating it might be slightly south of the 1836 event. The 1979, 1984, and 1989 events were each stronger at Santa Clara than at Monterey and Carmel, indicating that they were north of the 1836 event. The 1890, 1897, and 1986 events were felt about equally at Monterey and Santa Clara and are within the probable source area of the 1836 event (Fig. 1). Sources on the San Andreas, Sargent, or Calaveras faults are possible.

It is also possible that the San Gregorio–Palo Colorado fault could have generated the intensities indicated in Figure 1. However, such a source is not supported by any damage or aftershock reports from Santa Cruz, only 15 km away. The historical occurrence of $M \sim 6$ events has been much more common in the area outlined by the dotted line in Figure 1 than on the San Gregorio–Palo Colorado fault.

Magnitude of the 1836 Earthquake

We estimated the earthquake's magnitude from the area shaken using Toppozada's (1975) relations between Richter local magnitude and isoseismal areas. The contoured area shaken at MMI VI to VII or greater is approximately 5500 km^2 (Fig. 1). If it represents the area shaken at MMI VII or higher, the estimate is M 6¾; if it represents the area shaken at MMI VI or greater, the estimate is M 5¾. We assume that the 5500 km^2 area was shaken at MMI between VI and VII, which indicates $M \sim 6¼$. Also, we estimated moment magnitude M_w 6.1 by using 5500 km^2 in Tuttle and Sykes' (1992) relation for MMI VI. They do not have a relation for MMI VII areas, which would have resulted in $M_w > 6.1$. We conclude that the 1836 earthquake was of $M \sim 6¼ \pm ½$. This is consistent with Table 4, in that at Santa Clara and Monterey, the effects of the 1836 earthquake were somewhat higher than those of the nearby 1890 and 1897 events of $M \sim 6$.

Possible Foreshocks

In Monterey, Gomez reported feeling two strong earthquakes before the 10 June 1836 mainshock (Table 1). The "strong earthquake" on 9 June (Table 1) was likely a foreshock, 15½ h before the mainshock. If it was ~45 km away near San Juan Bautista, and was felt at intensity MMI ~ IV to V in Monterey, it would have been of $M \sim 5$ to 5½ (Barosh, 1969; Toppozada, 1975).

The location for the 25 April "strong earthquake" cannot be determined from the single felt report at Monterey (Table 1). If it was an early foreshock 6½ weeks before the 10 June event, it would be of comparable lead time and magnitude to the M 5.3 and 5.4 Lake Ellsman earthquakes that occurred on 27 June and 8 August 1989, 16 and 10 weeks before the 17 October Loma Prieta earthquake.

Lack of Reported Aftershocks

In Monterey, Gomez noted the possible foreshocks but did not note any aftershocks following the 10 June 1836 earthquake, even though his diary continued to April 1837. This is consistent with the source area shown in Figure 1, about 20 to 60 km away. At a mean distance of 40 km, aftershocks of $M < 5$ would be felt at about MMI $\leqq$ IV. These would not have been noteworthy to Gomez. His diary entry for the 10 June mainshock was brief (Table 1), even though it created "damaging havoc" in Monterey (Vallejo, 1875). Earthquakes of $M \sim 6¼$ have few aftershocks of $M > 5$, and Gomez may not have felt any.

Gomez' lack of aftershock reports would not be consistent with sources closer to Monterey, such as the Palo Colorado fault, 10 to 20 km away. $M > 4$ aftershocks are frequent following $M \sim 6¼$ events, and would be felt 10 to 20 km away at MMI $\geqq$ IV making them noteworthy to Gomez. He reported none.

Last Major Earthquake on Northern Hayward Fault

Williams (1992) used paleoseismic techniques to demonstrate that there were six to eight earthquakes on the southern Hayward fault during the last 2100 years, indicating an average recurrence interval of 260 to 350 years. Yu and Segall (1996) used geodetic data to determine a rupture extending ~50 km from near Berkeley southeastward for the 1868 Hayward earthquake of $M \sim 7$, which would correspond to 1.9 ± 0.4 m of displacement and a recurrence interval of ~222 ± 66 years.

The paleoseismic record for the northern Hayward fault is meager. Borchardt and Mace (1992) discovered a clastic dike at Berkeley and considered it to be the result of groundwater injection due to a major earthquake on the nearby Hayward fault. Their trench also showed laminated sediments in a fault-parallel trough 10 and 40 m from the two traces of the Hayward fault. The sediments were underlain by a thin

Table 4
Comparison of the 1836 Earthquake Effects with Effects of Better-Defined Earthquakes* in the Carmel–Santa Clara Area Indicated in Figure 1

	1836 (M~6¼)	1890 (M 6)	1897 (M 6)	1926 (M 6.1)	1961 (M 5.6)	1979 (M 5.7)	1984 (M 6.2)	1986 (M 5.5)	1989 (M 7)
Santa Clara	VI–VII	(V–VI at San Jose, 5 km east of Santa Clara)	VI–VII	V	within IV–V region	V	VI	IV	VII
	damaging havoc	people rushed out (4 a.m.), furniture moved	a chimney thrown down	clocks were stopped		a few windows cracked, small objects moved	some walls cracked, shelving and equipment toppled		broke a few weak chimneys
San Juan Bautista	VII?	VII–VIII	VI–VII	in V zone	VI	VI	V–VI	IV	VI
	dome (or bell tower?) badly injured? (unsubstantiated)	chimneys fell, walls cracked	a chimney thrown down		a few pieces of crockery broke	walls cracked and plaster fell	hanging pictures fell, a few items shook off store shelves		items fell off shelves, a few pictures fell
Monterey	VI–VII	V	VI	VII	VI	IV	(V at Pacific Grove)	IV	VI
	damaging havoc . . . filled the people with fright	awoke many (4 a.m.)	plaster cracked, some fell	three chimneys were shaken down	ground cracked		a few glassware items broke		items fell off shelves, stucco cracked
Carmel	VI–VII		VII	VII	V	IV	V		VI
	a large painting torn loose from its fastenings		part of an adobe wall fell	a few chimneys were knocked down			a few items fell off store shelves		a few items fell off shelves, a few windows broke

*Intensities of the 1890 and 1897 events are from Toppozada *et al.* (1981); the 1926 event from Toppozada and Parke (1982); the 1961, 1979, and 1984 events from United States Earthquakes; and the 1986 and 1989 events from information provided by Carl Stover and Jim Dewey (USGS).

paleosol that formed after 1540 ± 90 A.D. If we assume that the trough was formed by earthquake displacement, then the last earthquake would be considerably more recent than 1450 A.D.

Lienkaemper *et al.* (1995) found evidence of a large rupture in their trench along the Hayward fault at Montclair in Oakland. They indicated "... that the 1836 earthquake is the most reasonable candidate in the early prehistoric period" for the rupture. Subsequently, they have agreed with our present findings that the last rupture on the northern Hayward fault probably occurred before 1776 (Lienkaemper, 1996, written comm.).

Budding *et al.* (1991) indicated that "An earthquake in 1808 caused damage at the Presidio in San Francisco. This is the oldest event in the (historical) catalogue that could have occurred on the Rodgers Creek fault zone although its actual source is unknown." On this basis, the WGCEP (1990) assumed that the most recent $M \sim 7$ event on the Rodgers Creek fault occurred in 1808 or earlier. However, we have found that the 1808 event was likely not a major earthquake.

In June and July 1808, 18 earthquakes damaged some poorly built structures at San Francisco Presidio (Arguello, 1808) but were not reported as damaging at missions San Francisco Dolores, San Jose, or Santa Clara (Fig. 1). Missions San Rafael and Solano (at Sonoma) were not yet built in 1808. Arguello reported on 17 July that 18 earthquakes were felt at the Presidio since 21 June, some of which

> have been so severe that all the walls of my house have been cracked, owing to the bad construction of the same. . . . The barracks of the Fort have been threatened with entire ruin, and I fear if these shocks continue, some unfortunate accident will happen to the troops at the Presidio.

The account of 18 earthquakes and MMI ~ VI to VII effects suggests a nearby $M \sim 5$ to 5½ event and its aftershocks. A distant major event, having aftershocks strongly felt at San Francisco, would have damaged more than the poorly built structures at the Presidio and should have been reported at missions Dolores, San Jose, or Santa Clara.

In 1957, an M 5.3 event occurred near the San Andreas

fault about 13 km south of the Presidio (Tocher, 1959). The sequence included 26 events of $M \geqq 3$, of which 22 were felt in San Francisco (Bolt and Miller, 1975). The mainshock generated MMI VI in and around San Francisco (Cloud, 1959), which can damage poorly built structures. It is probable that the 1808 events were similar to the 1957 events. We find no evidence for any major earthquakes in the San Francisco Bay area before the 1838 earthquake, at least since the founding of Mission Dolores and the Presidio at San Francisco in 1776.

As a result of the present article, a group including scientists from the U.S. Geological Survey and the University of California at Berkeley trenched the northern Hayward fault at El Cerrito in June 1997 to determine its paleoseismic behavior. Preliminary results are consistent with our conclusion that the most recent surface-faulting event probably occurred before 1776 (Kelson *et al.,* 1997).

Probability of a Large Earthquake on the Northern Hayward Fault

The WGCEP (1990) calculated a 30-year probability of 28% for an M 7 earthquake on the northern Hayward fault, using a displacement of 1.5 ± 0.5 m and a segment length of 50 km. Their analysis assumed that the 1836 earthquake occurred on this fault. However, our analysis indicates that the last major earthquake on the northern Hayward fault did not occur in 1836, but before 1776, and after 1450 according to Borchardt and Mace's (1992) study. When we repeat the WGCEP (1990) analysis, but assume that an $M \sim 7$ event has not occurred on the Hayward fault north of Berkeley for about 300 years, the 30-year probability for an $M \sim 7$ event to initiate on this segment is ~35%.

The method employed by WGCEP (1990) was revised for southern California (WGCEP, 1995) to reflect increased uncertainties. In 1998 to 1999, the WGCEP will again review the method and the probability values for northern California faults, including the Hayward.

The 1838 San Andreas Fault Earthquake

General Characteristics

The "Earthquake Reminiscence" in Table 2 describes characteristics similar to those reported for the major 1838 San Andreas fault earthquake. For example, the observation that "after the first and most violent shock, there were innumerable lesser ones" is consistent with the felt aftershocks that continued till Captain Paty left the Monterey–San Francisco area about 3 months after the June 1838 event (Louderback, 1947, p. 50). By contrast, the 1836 Gomez account describes *two* strong events. 15½ h apart in June, the second being the most violent, not the first. Gomez mentioned no aftershocks even though his diary continued to April 1837. Clearly, the reminiscence does not describe the earthquakes that Gomez reported in June 1836, instead it appears to describe the major June 1838 earthquake, as discussed under the 1836 earthquake above.

The 1838 earthquake damage in the East Bay is partly described in the *Sonoma Democrat,* 14 October 1865 article, which addresses the 8 October 1865 Bay area earthquake:

> It was unquestionably the most severe that has been experienced since the advent of Americans here, but not comparable to the one which occurred about the year 1838, which shook down thick walled adobe houses, and caused mountain sides to slide down. At that time the adobe house of Estudillo, an old settler in Alameda county, was thrown down and a large portion of a mountain side, near San Leandro, gave way and slid down to its base. The place where the slide occurred is plainly visible from the town of San Leandro. But the shaking up we received, last Sunday [8th], was quite sufficient to satisfy the present inhabitants. The amount of damage must be very large, though it will probably never be known. Besides a number of buildings which were ruined [in San Francisco], there are a great many others badly cracked and otherwise injured.

Damage in the 1838 event was reported from San Francisco to Monterey, and in the East Bay at San Leandro and Mission San Jose, and is summarized in Figure 2. The 1838 earthquake was "very severe in the harbor of San Francisco," although the effects are not described (Louderback, 1947, p. 56). In the East Bay, the 1838 effects of course were felt along the foothills from San Pablo to Mission San Jose as indicated in the reminiscence (Table 2). The 1838 earthquake would have been the event remembered by the people on both sides of San Francisco Bay (Fig. 2).

At Santa Cruz, the condition of the buildings was very poor following the 1838 earthquake, and they "should be demolished," although the cause is not specified (Tuttle and Sykes, 1992; Soto, 1839). Days after the earthquake, the minister wrote of the need (Real, 1838)

> to rebuild and restore that which is in disrepair or fallen. The roof of the church requires several rafters and the steeple reinforcing with wood since it has been three years since it was repaired and it is falling down again. . . . And this will be a means of placating in part the divine wrath, for in 2 weeks I have buried 8 deceased individuals of which there are at the moment many indians, as well as non indians.

The letter does not specify the nature of the "divine wrath." However, it was dated 16 July, about 2½ weeks after the 1838 earthquake that caused damage from San Francisco to Monterey, which suggests that the death and destruction were due partly to the earthquake. Table 5 shows that the 1838 damage level from Monterey to San Francisco was comparable to or greater than that in the 1906 San Francisco and the 1989 Loma Prieta earthquakes. It should have been also comparable at Santa Cruz, which had buildings

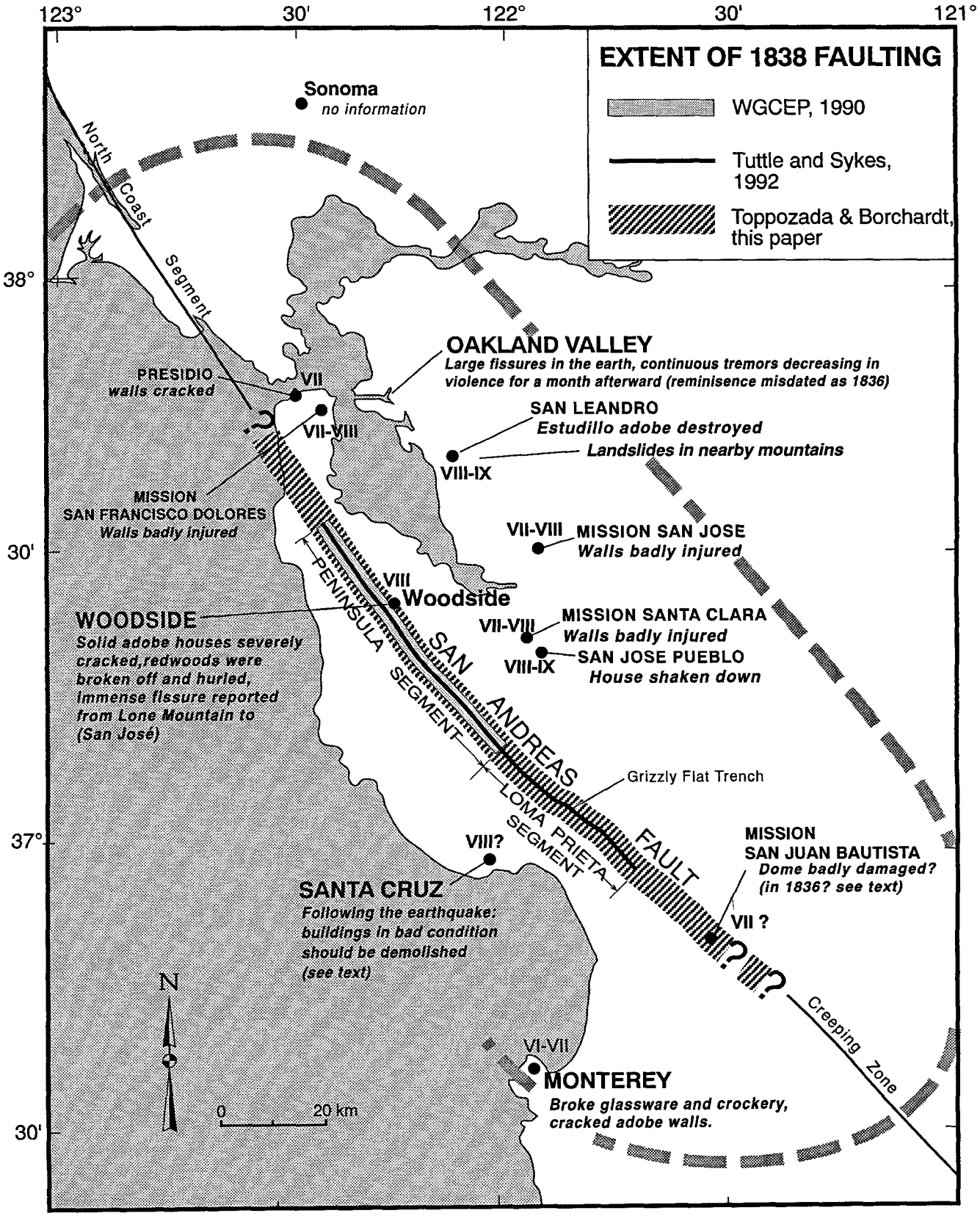

Figure 2. Intensities reported for the 1838 earthquake, approximate MMI VII isoseismal, and interpreted extent of faulting.

Table 5
Comparison of 1838, 1906 (M 7.8), and 1989 (M 7) Earthquake Damage

Site	1838*	1906†	1989‡
Mission San Francisco Dolores	Walls badly injured (MMI VII–VIII?)	No damage (MMI VI?)	No damage§ (MMI ~ VI)
Oakland Valley	Large fissures in the earth, continuous tremors for a month afterward decreasing in violence (misdated as 1836 in 1868 reminiscence).	Fissures near Lake Merritt (Youd and Hoose, 1978), tremors felt almost daily for 2 weeks (Lawson, 1908).	(MMI VII)
	Reminiscence suggests MMI ≧ 1868, i.e. MMI ≧ VIII (Toppozada *et al.*, 1981).	Severe damage to masonry buildings (MMI VIII).	
San Leandro	Estudillo adobe destroyed (MMI VIII–IX), and large landslide occurred in the nearby mountains	Nearly every chimney down, plastering greatly cracked (MMI VIII)	(MMI VII)
Woodside	Cracks in thick-walled adobes wide enough for a person to walk through (MMI VIII)	Partial collapse of buildings (MMI VIII–IX)	(MMI VII)
Mission San Jose	Walls badly injured (MMI VII–VIII?)	Nearly all chimneys thrown down, and plaster in houses cracked (MMI VIII)	(MMI VI–VII)
Santa Clara	Walls badly injured (MMI VII–VIII?)	Many brick buildings strongly damaged, nearly all chimneys thrown down (MMI VIII)	(MMI VI–VII)
San Jose	House shaken down (MMI VIII–IX)	Nearly all chimneys thrown down and 40 buildings thrown off their foundations (MMI VIII–IX)	(MMI VII)
Santa Cruz	Buildings in bad condition, should be demolished (MMI VIII?, reported after the event, cause not specified, see text)	Several brick buildings partly shaken down, many chimneys down (MMI VIII)	(MMI VIII)
Monterey	Caused alarm, broke crockery, glassware, and cracked some adobe walls (MMI VI–VII)	Some glassware broke, some furniture moved slightly and top-heavy pieces overturned (MMI V–VI)	(MMI VI)

*From Louderback (1947), and the present article.
†From Toppozada and Parke (1982).
‡From Stover *et al.* (1990).
§John Kariotis (oral comm., 1997).

and chimneys shaken down in 1906 and 1989, and up to five deaths and hundreds of injuries in 1989 (McNutt, 1990). This is also supported by the Sonoma Democrat statement quoted above, that the 1865 earthquake centered north of Loma Prieta (M ~ 6½, Toppozada *et al.*, 1996) was severe "but not comparable to the one which occurred about the year 1838, which shook down thick walled adobe houses, and caused mountain sides to slide down." The 1865 earthquake damaged many buildings in San Francisco and cracked brick walls and threw down chimneys in Santa Cruz (Toppozada *et al.*, 1981).

Extent of Faulting and Magnitude of the 1838 Earthquake

In June 1838, ground rupture probably occurred on the San Andreas fault at least from near Lone Mountain, south of San Francisco, toward Mission Santa Clara (Louderback, 1947). In the 1838 event, Charles Brown observed on the peninsula near Woodside (Fig. 2) thousands of redwoods being "broken off and hurled through the air for immense distances," suggesting major fault rupture (Louderback, 1947, p. 57). Similar faulting effects were observed in the Santa Cruz Mountains in the 1906 earthquake (Lawson, 1908, p. 110):

> Trees were uprooted. On the other side of Loma Prieta, along the line of the fault, the forest looked as though a swath had been cut through it two hundred feet in width.

The severe effects on trees in the 1838 and 1906 earthquakes suggest significant displacements on the San Andreas fault and on unstable slopes. Clahan *et al.* (1995) attributed fault displacements in the 1- to 3-m range on the peninsula near Woodside to each of the 1838 and 1906 earthquakes.

Previously, Lindh (1983) and WGCEP (1990) considered that the 1838 earthquake resulted from a ~60 km rupture of the San Andreas fault on the San Francisco peninsula corresponding to M ~ 7 (Fig. 2). We believe that faulting extended over a much greater length because the 1838 damage level from San Francisco to Monterey was as strong as or stronger than that in the great 1906 earthquake (Table 5) and because violent aftershocks were felt near Monterey and in Oakland.

Southern End of Faulting

For the 1838 earthquake, Tuttle and Sykes (1992) estimated M 7.2 or larger by using intensity information. They extended the rupture southeastward (Fig. 2) "through the

Loma Prieta segment, but . . . do not think that the evidence warrants extending the 1838 rupture any further south." We propose that the rupture not only included the Loma Prieta segment but also extended to the southeast as far as the 1906 rupture or further (Fig. 2), as indicated by Louderback (1947) and Sykes and Nishenko (1984). We base our proposal on

1. The intensity at Monterey being as strong or stronger in 1838 as it was in 1906 (Table 5) and 1989 (Table 4).
2. The frequent probable aftershocks described below that were strongly felt and damaging southward of San Juan Bautista.

Surface Faulting to San Juan Bautista

Prentice and Schwartz (1991) "believe there is a basis for concluding that 1906 surface faulting did occur as far southeast as San Juan Bautista." Observations from trenching the San Andreas fault in the Santa Cruz mountains (Fig. 2) apparently "preclude the occurrence of large surface displacements through Grizzly Flat in either 1838 or 1865" (Schwartz *et al.,* 1997). A lack of 1865 displacement is consistent with the 1865 event's probable location north of the San Andreas fault (Toppozada *et al.,* 1981, 1996; Tuttle and Sykes, 1992; Yu and Segall, 1996). But a lack of 1838 displacement is not consistent with the damaging effects in the Monterey area of the mainshock or the probable aftershocks affecting the area south of San Juan Bautista. At the Grizzly Flat site, it is quite possible that the 1838 and 1906 earthquakes ruptured the same stratigraphic horizon and are not distinguishable as separate events.

Probable Southern Aftershocks

Table 6 includes descriptions of the 1840 and 1841 earthquake effects reported in the area south of San Juan Bautista. We argue that these effects are due to probable aftershocks at the southern end of the 1838 earthquake rupture (Fig. 3).

The 1840 annual report for Mission Carmel (Suarez, 1840) states that

> the dome of the church which is in the presbytery is cracked open due to the strong earthquakes that occurred this year and the support beams for the rest of the roof are threatening to cave in because they are very rotten. The interior adornments are well preserved, with the exception of two mirrors and a statue of St. Miguel which were broken during the earthquake.

We estimate MMI VI to VII for the strongest event affecting the deteriorating church, but the date in 1840 is not defined.

Louderback (1944) disputes Holden's (1898) assertion of an 1840 earthquake at Santa Cruz, and states that

> no report emanating from any of the surrounding region . . . asserts that an earthquake occurred during that year, although one might expect that a severe earthquake effective at Santa Cruz would be strongly felt and might cause damage at Monterey.

Louderback obviously was not aware of the 1840 damage at Carmel, only 5 km from Monterey. At Santa Cruz, an 1840 earthquake is not specified in the two available 1840 references, but we think it is implied. The first is a letter from Jose Bolcoff at Santa Cruz to prefect Castro at Monterey dated 24 January 1840 (Louderback, 1944):

> On 16th & 17th of this month, great sea waves came in more than 200 yards from the shore and carried off all the roofing material intended for the community. On the 18th of the same month the tower of the church of Santa Cruz fell [2,000 yards from the shore]. It appears that some of the houses will also fall.

Earthquake damage to the tower and houses on 18 January is possibly implied.

A second reference to the fallen tower is from the Mission Santa Cruz annual report of 31 December 1840, signed by Fray Antonio Real (Louderback, 1944):

> The church . . . tower fell to the ground owing to the abundance of water as well as the weakness of the ground on which it was built, and in ringing [clanging] the bells, two broke.

This does not specify earthquake damage, but it states that the tower collapsed due partly to poor site conditions. The indication that the bells broke by ringing or clanging not just by falling with the tower suggests that the tower shook before it collapsed. We interpret the poor site conditions, the ringing of the bells, the tower collapse, and Bolcoff's statement that some of the houses will also fall as indicating possible earthquake shaking of MMI VI to VII. Such an earthquake could have been felt strongly also at Carmel. It is quite possible that the damage described in the 1840 Carmel annual report occurred on 18 January when the Santa Cruz tower fell and the houses were damaged. That could be due to an $M \sim 6¼$ aftershock near San Juan Bautista, ~45 km from both Santa Cruz and Carmel, 1½ years after the June 1838 earthquake (Fig. 3). The alternate explanation of two damaging 1840 earthquakes of $M \sim 5½$, one near each Mission, is less likely. Aftershocks of 1½ magnitude units smaller than the mainshock have a significant probability of occurring 1½ to 3 years after the mainshock (Reasenberg and Jones, 1989). For example, the 1952 Kern County earthquake of M 7.5 was followed 1½ years later by an M 5.9 aftershock at the same location (Real *et al.,* 1978). Also, the June 1992 Landers earthquake of M 7.3 had an M 5.4 aftershock in March 1997 near the northern end of the aftershock zone.

Sir George Simpson (1930) visited Monterey in 1841 and reported that 120 events were felt in Monterey during

Table 6

Strong Earthquakes between San Juan Bautista and Parkfield after the Major 1838 and before the Great 1857 Earthquake

Local magnitudes estimated from felt effects (Toppozada, 1975)

1840.1.18

Carmel Annual Report dated 31 December 1840 details damage to Mission San Carlos (Carmel): "The dome of the church which is in the presbytery is cracked open due to the strong earthquakes that occurred this year, and the support beams for the rest of the roof are threatening to cave in because they are very rotten . . . two mirrors, a statue of St. Miguel . . . were broken during the earthquake." This indicates MMI VI–VII.

Similar damage on 18 January at Santa Cruz (MMI VI–VII) is implied in letters from Bolcoff and Real (Louderback, 1944). This suggests an earthquake probably centered near San Juan Bautista, which is equidistant (~45 km) from Carmel and Santa Cruz. MMI VI–VII at Carmel and Santa Cruz, at distances of ~45 km, indicates $M \sim 6¼$ (Barosh, 1969; Toppozada, 1975).

1841.7.3

In Monterey, Duflot de Mofras (1844) reported hearing a terrible noise like rumbling thunder, and then felt an earthquake strong enough that he had to support himself against a tree, but no damage was done to the houses, indicating MMI VI. The shock was felt at the same time in the buildings and farms of the interior. The shore was covered with beached fish. This suggests a wave probably resulting from a quake-induced submarine slump. The earthquake was likely centered near the southern end of the 1838 rupture near San Juan Bautista. MMI VI at Monterey 42 km away would indicate $M \sim 6$ (Barosh, 1969; Toppozada, 1975).

1841.7.29

Alisal, 8 km east of Salinas and 20 km south of San Juan Bautista, MMI VI–VII. The walls of Hartnell's house "were badly rent." This was the 25th shock felt at Alisal within the last 2 months. "One day they had five successive shocks, which made the whole building tremble violently. Frequent as these occurrences are, they are confined to this spot [Alisal] alone" (Robinson, 1969). The earthquake likely was centered near the southern end of the 1838 rupture. MMI VI–VII at Alisal 16 km from the San Andreas fault, would indicate $M \sim 5¾$ (Barosh, 1969; Toppozada, 1975).

In his January 1842 visit to Mission Carmel, G. Simpson observed "Near the mission there is a very distinct rent in the earth, of a mile or so in length, and of 30 or 40 feet in depth, the result of one of the recent earthquakes . . . the beautiful church . . . has had one side pretty severely shattered by a recent shock" (Louderback, 1947). Simpson (1930) also related that in Monterey "earthquakes . . . are so frequent that a hundred and twenty of them were felt during two successive months of the last summer [1841] . . . the shocks being seldom severe, and often so light . . . as to escape the notice of the uninitiated stranger." The severely shattered side of the church may include some of the effects described in the 1840 annual report. The 3 July 1841 earthquake of $M \sim 6$ that generated MMI VI at Monterey, 5 km from Carmel, probably also contributed to the "severely shattered side." The open rent in the earth was probably due to a lateral spread along the banks of the Carmel River, which is only 70 m from the mission. This rent was likely triggered by the 3 or 29 July 1841 earthquakes. Any earth fissures induced by the 1840 earthquake probably would have been eroded by the time of Simpson's visit in January 1842.

1853.2.1

San Simeon (MMI VI). Pico adobe cracked, causing the alarmed family to run out fearing a wall could fall. (A shock was felt 2 weeks earlier at Captain Dana's rancho 25 miles south of San Luis Obispo, about 17 January). San Simeon had comparable MMI VI shaking in the 1952 Bryson earthquake of M 6. The 1853 event could be $M \sim 5$ if near San Simeon, or $M \sim 6$ if near Bryson. We assume it was a $M \sim 5½ \pm ½$ in the San Simeon–Bryson area.

1853.9.2

San Joaquin to the Salinas.

"Sufficiently violent to frighten cattle and people on the evening of Sep 2nd, from the San Joaquin to the Salinas through the Gavilan range, and between the 36th and 37th latitudes." From a possible source on or near the San Andreas fault (near 36½° N, 121° W, with a large uncertainty) a radius of about 100 km would encompass the San Joaquin and Salinas valleys. We assume that this 32,000-km^2 area was shaken at MMI V or greater to cause the fright described. This suggests an earthquake of $M \sim 6$. Earthquakes of this magnitude are rare in the creeping zone of the San Andreas fault. For comparison, an event of $M \sim 6$ in this zone occurred on 6 March 1882, generating MMI V or greater shaking from Santa Cruz to Merced, 160 km inland, and to near Parkfield, 200 km to the southeast (Toppozada *et al.,* 1981, 1996).

1855.1.13

6:30 pm, MMI V, San Benito and San Miguel. Also felt at San Luis Obispo. MMI V area of ~8000 km^2 indicates $M \sim 5¼$. In the 1966 Parkfield earthquake of M 6, San Miguel was in the MMI VI zone, San Luis Obispo was in the V zone, and San Benito was in the IV zone. This suggests that the 1855 event was northwest of Parkfield, in or near the creeping zone, near 36¼° N, 120¾° W, with a large uncertainty.

1855.2.19

5:45 a.m. near San Juan Bautista "very severe earthquake" (Bixby, 1855 diary), $M \sim 5$?

1857.1.9

At about dawn (~6 a.m.) and sunrise (~7 a.m.), foreshocks of $M \sim 5$ to 6 preceded the great Fort Tejon earthquake by about 2 and 1 h, respectively. These were near the northwestern end of the 1857 fault rupture, suggesting that the extensive 1857 faulting initiated near the Parkfield–Cholame area, and propagated ~330 km southeastward to Cajon Pass (Sieh, 1978).

two successive months of the summer of 1841 "being seldom severe, and often so light . . . as to escape the notice of the uninitiated stranger" (Table 6). It is conceivable that some of these earthquakes may have occurred on faults closer to Monterey than the San Andreas, which is ~45 km away. It is much more likely that they were the same numerous shocks that were violently felt in June and July 1841 at Alisal, 16 km from the San Andreas fault (Fig. 3). Table 6 indicates that the earthquake damage and extensive ground fissure that Simpson observed in his January 1842 visit to Carmel were probably due to the 3 or 29 July earthquakes, subsequently described.

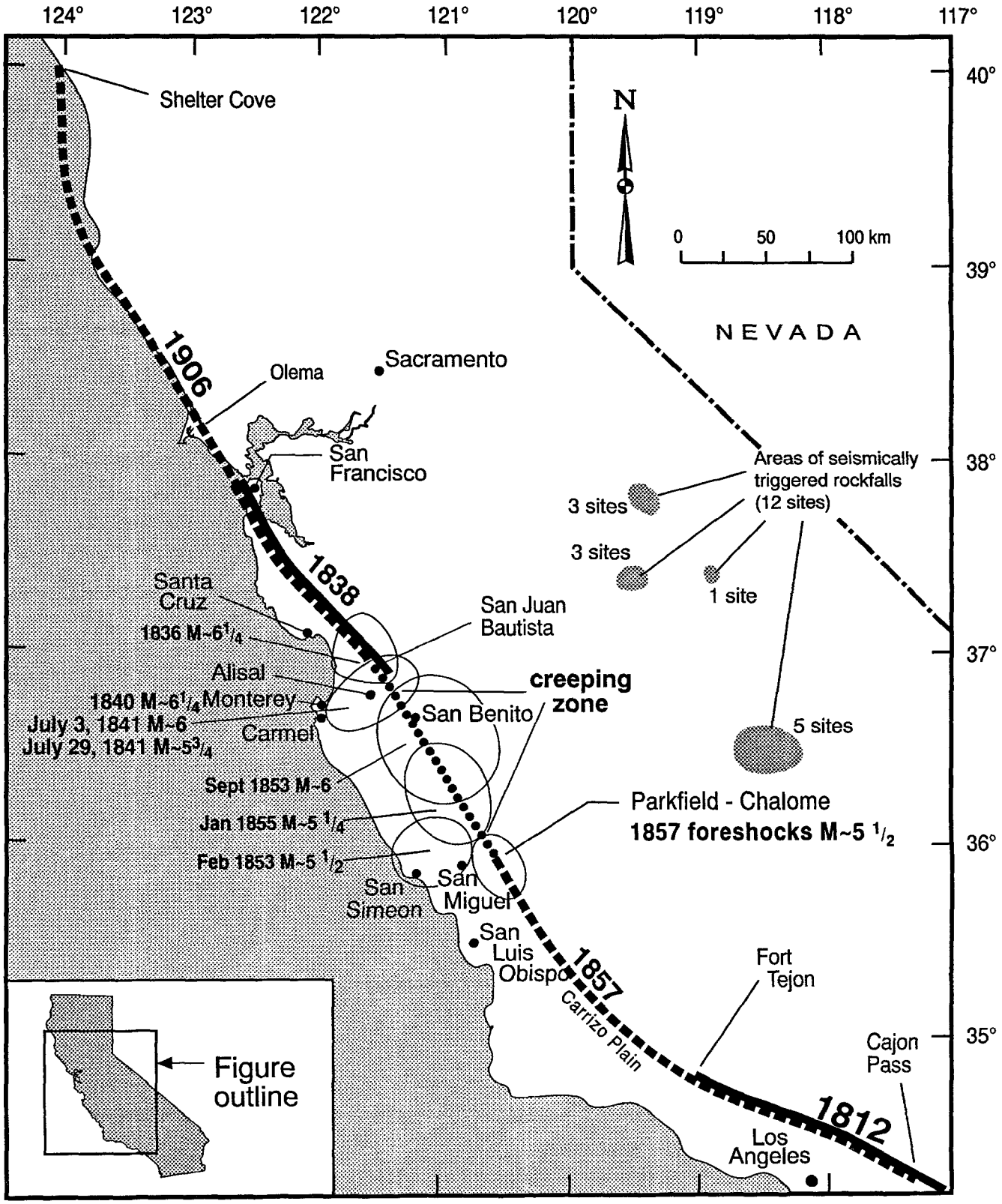

Figure 3. San Andreas fault ruptures in June 1838 and January 1857. The intervening creeping zone and adjacent area were affected by strong ($M \sim 5$ to 6) earthquakes from 1840 to 1857. The approximate 1840 to 1857 epicentral areas are outlined to indicate uncertainty in location. The 1906 and 1812 ruptures are also shown. The shaded areas are where seismically triggered rockfalls were dated by lichenometry as 1815, 1837, 1857, and 1909, all ± 10 years (Bull, 1996).

On 3 July 1841, Duflot de Mofras (1844) described feeling strong shaking in Monterey indicative of MMI VI. The shock was also felt in the buildings and farms in the interior (Table 6).

On 29 July 1841, Robinson (1858, 1969) described experiencing frightening damage indicative of MMI VI to VII at Hartnell's rancho at Alisal east of Salinas, 20 km south of San Juan Bautista (Table 6). He was informed by Hartnell that this was the 25th shock felt at Alisal within the last 2 months and that one day they had five shocks "which made the whole building tremble violently. Frequent as these occurrences are, they are confined to this spot alone [Alisal]." This strongly suggests a source on the San Andreas fault, just 16 km from Alisal (Fig. 3), rather than faults closer to Monterey, such as the Tularcitos or Palo Colorado. An $M \sim 6¼$ event would be required on faults near Monterey to generate MMI VI to VII at Alisal 30 to 40 km away. Such an event would generate MMI VII to VIII within 10 km at Monterey, whereas the highest intensity reported for Monterey in 1841 was MMI VI on 3 July. The numerous other events were generally felt lightly in Monterey as Sir George Simpson indicated, and they probably included the 25 shocks felt violently at Alisal.

Three out of four earthquakes of $M \geqq 5$ within 50 km of Monterey have occurred on the San Andreas fault from 1900 through 1974 (Real *et al.,* 1978). We would expect an even higher ratio of events on the San Andreas fault in the 3 years following rupturing of that fault to within 50 km of Monterey in an $M > 7$ earthquake (Reasenberg and Jones, 1989). For example, the 1989 Loma Prieta earthquake was followed 6 months later by M 5.3 and 5.4 aftershocks at the southeastern end of the aftershock zone. We conclude that the 1840 and 1841 earthquakes described earlier were most probably aftershocks near the southern end of the extensive 1838 rupture. The 1841 events were reported at Monterey by Duflot de Mofras and at Alisal by Robinson. We found no other travelers' notes to shed light on aftershocks of the 1838 earthquake.

Northern End of Faulting Opposite San Francisco

The northern end of the 1838 faulting was previously assumed to be 25 km south of San Francisco (Fig. 2). Evidence of stronger damage at San Francisco in 1838 than in 1906 and of frequent violent aftershocks at Oakland suggests that the 1838 faulting extended to San Francisco.

The walls of Mission San Francisco Dolores were "badly injured" in 1838 according to Captain Paty (Louderback 1947, p. 49). There is no evidence that Mission Dolores was significantly damaged in the 1906 earthquake (Lawson, 1908). A photograph shows the well-built Mission undamaged and the nearby new church badly damaged in the 1906 earthquake (Hansen and Condon, 1989, p. 91). It is possible that the Mission was strengthened after the 1838 earthquake, although that is unlikely after secularization. We speculate that the stronger damage in 1838 than in 1906 may be related to the location of the two epicenters. In the 1906 earthquake, Mission Dolores was near the epicenter (Bolt, 1968; Boore, 1977; Wald *et al.,* 1993), and in 1838 it was near one end of the rupture. If the 1838 epicenter was not near Mission Dolores but nearer the other end of the rupture, the greater 1838 damage at Mission Dolores might be attributable to rupture directivity.

The 1868 aftershocks were felt frequently and violently in Oakland, only 6 km from the Hayward fault rupture. The 1838 aftershocks were felt equally frequently and violently in Oakland, 25 km from the San Andreas fault, acknowledging that the reminiscence refers to the 1838, not the 1836, event (Table 2). This indicates that the 1838 aftershocks were of larger magnitudes than the 1868 aftershocks, and it also suggests that the 1838 faulting on the San Andreas extended to the latitude of Oakland. This would place the entire 25-km northern end of the rupture within 25 km of Oakland and would increase the probability of violent aftershock effects being felt there (Fig. 2).

The 1906 epicenter near San Francisco was near the area where the 1906 surface slip changed from <3 m to the southeast to ≧4 m to the northwest (WGCEP, 1990; Thatcher *et al.,* 1997) and where current seismicity abruptly diminishes to the northwest near the juncture with the San Gregorio fault (Jennings, 1994). All suggest a segment boundary in this vicinity, which is consistent with our proposed northwestern end of the 1838 faulting. If the 1838 rupture had extended northwestward of San Francisco, Sonoma would have likely been damaged, but there is no record of that. The approximate MMI VII contour in Figure 2 is based on the 55-km average extent of MMI VII shaking observed in the 1868 $M \sim 7$ Hayward and 1906 M 7.8 San Andreas fault earthquakes (Toppozada *et al.,* 1981; Toppozada and Parke, 1982).

A rupture length of ~140 km from San Juan Bautista to San Francisco corresponds to a mean displacement of 3 m, and $M_w \sim 7½$ (Wells and Coppersmith, 1994). This would account for the severe effect of the fault rupture on trees near Woodside, the widespread mainshock damage from Monterey to San Francisco, and the probable aftershocks that were violently felt in Oakland and Alisal (Figs. 2 and 3).

Independent Evidence of an $M \sim 7½$ for the 1838 Event

Bull (1996) used lichenometry to date seismically induced rockfalls at 12 sites in the south central Sierra Nevada (Fig. 3). He found prominent synchronous rockfall pulses that occurred at the time of the great ($M \sim 8$) San Andreas fault earthquakes of 1857 (dated 1857 ± 10) and 1906 (dated 1909 ± 10). He also found an equally prominent pulse dated 1837 ± 10 that he labeled "of unknown cause," because he was not aware of any $M \geqq 7½$ earthquakes with that date. We suggest that this pulse was due to the 1838 earthquake, which was as damaging from San Francisco to Monterey as the great 1906 earthquake (Table 5). The 1838 rockfalls were at least as widespread and abundant as those resulting from the great 1857 and 1906 earthquakes (Bull,

1996). This suggests that the 1838 intensity of shaking was roughly comparable in the Sierra Nevada from these three earthquakes and supports the large $M \sim 7\frac{1}{2}$ derived for the 1838 event in the present article.

A Possible Link to the 1857 Earthquake

The great 1857 southern California earthquake resulted from a 345-km rupture of the San Andreas fault from the southern end of the creeping segment near Parkfield to Cajon Pass (Fig. 3). Thus, in the 18½ years from the 1838 to the 1857 earthquakes, the San Andreas fault ruptured from San Francisco to Cajon Pass in two earthquakes of M 7½ to 8. This ~600-km extent of faulting was interrupted only by the ~110-km creeping zone, between San Juan Bautista and Parkfield (Fig. 3).

Near the southeast end of the 1838 rupture, probable aftershocks occurred frequently and caused damage at Carmel and Santa Cruz in 1840, and at Alisal, 20 km south of San Juan Bautista, in 1841. In or near the creeping zone farther to the southeast, where earthquakes of $M \geqq 5$ are historically rare (Real *et al.*, 1978), strong earthquakes of M 5 to 6 occurred in 1853 and 1855 (Table 6). These events may have been manifestations of stress transfer across the ~110-km creeping zone of the San Andreas fault, between San Juan Bautista and Parkfield. On 9 January 1857, the San Andreas fault ruptured in the great M 7.9 Fort Tejon earthquake (Table 6, Fig. 3), starting with foreshocks in the preceding hours in or near the Parkfield–Cholame region (Sieh, 1978).

The evidence from seismicity in this sparsely populated area for a link between the 1838 and 1857 earthquakes is tenuous. But the proximity in space and time (~110 km and 18½ years) of these $M \geqq 7\frac{1}{2}$ earthquakes on the San Andreas fault and the initiation of the 1857 rupture at the end nearest to the 1838 rupture, as indicated by the foreshocks in the preceding hours, suggest a possible link.

Observations Regarding Major Ruptures of the San Andreas Fault

The ~140-km segment that generated the 1838 earthquake ruptured again only 68 years later during the great M 7.8 San Francisco earthquake of 1906. A similar paired sequence also occurred on the San Andreas fault in southern California. The 1812 earthquake segment through Wrightwood, arguably of ~170-km length corresponding to $M \sim 7\frac{1}{2}$ (Jacoby *et al.*, 1988), ruptured again only 44 years later in the great M 7.9 Fort Tejon earthquake of 1857 (Fig. 3). Studies of seismically induced rockfalls in the Sierra Nevada suggest that the shaking intensity in the 1812 event was roughly comparable to that in the great 1857 and 1906 earthquakes (Bull, 1996), which would support an $M \sim 7\frac{1}{2}$ for the 1812 event.

In both 1812 and 1857, a segment of ~140 to 170 km ruptured in an $M \sim 7\frac{1}{2}$ earthquake, and ruptured again with little additional strain accumulated (~1½ m) after 44 to 68 years, as part of a ~345- to 470-km-long faulting event ($M \sim 8$). In each pair, the first rupture occurred in, or included, restraining bends. The 1812 event occurred in the Transverse Ranges, and the 1838 event included the Santa Cruz Mountains to San Juan Bautista bend. The final great ruptures included long straight segments where the greatest displacements occurred (Fig. 3). The maximum surface displacement in 1857 was ~9 m in the Carrizo Plain (Sieh, 1978), and in 1906 was ~6 m near Olema (Lawson, 1908; WGCEP, 1988).

The 1812 faulting did not immediately trigger rupture of the adjoining segment to the northwest, even though >7 m of strain was already stored there as evidenced in the 1857 displacement in the Carrizo Plain. The 1838 faulting did not immediately trigger rupture of the adjoining segment to the northwest, even though >4 m of strain was already stored there as evidenced in the 1906 displacement at Olema. The delays between the major earthquakes of 1812 and 1838 and the overlapping great earthquakes that followed 44 and 68 years later might have been related to strong zones or discontinuities at the fault segment boundaries near Fort Tejon and San Francisco, and/or to the strength of the maximum fault slip zones in the Carrizo Plain and the Marin–Sonoma County coast (Fig. 3).

Earthquakes that are separated by only 44 or 68 years generally cannot be recognized as separate events by paleoseismologic trenching of faults, because of limitations in stratigraphic resolution and radiocarbon dating. For example, paleoseismologic trenching alone did not recognize the 1812 San Andreas fault earthquake (Sieh *et al.*, 1989). It was recognized only from dendrochronologic studies of old trees on the fault near Wrightwood (Jacoby *et al.*, 1988).

The 1812 to 1857 earthquake pair on the southern and the 1838 to 1906 earthquake pair on the northern San Andreas fault are the only known $M \geqq 7\frac{1}{2}$ earthquakes on that fault in the 200-year historical record. These four events suggest that other paired $M \geqq 7\frac{1}{2}$ earthquakes separated only by a few decades also occurred on the San Andreas fault more than 200 years ago but may not have been recognized as pairs of events in the paleoseismologic record. Accounting for the unrecognized members of such pairs would alter the nature of the earthquake distribution on the San Andreas fault and affect the estimates of seismic hazard and loss.

Major $M \geqq 7\frac{1}{2}$ earthquakes on the 1812 fault segment occur at highly variable intervals from 44 to 330 years (Jacoby *et al.*, 1988; Sieh *et al.*, 1989). The recurrence on the 1838 fault segment also appears to be highly variable. This, and the variability in rupture lengths from ~140 to ~470 km for the 1838 and 1906 earthquakes, raises the question of uncharacteristic earthquakes (Grant, 1996) and the interaction of *overlapping* fault segments. Current seismic hazard models consider segment interactions in cascades of simultaneous ruptures of *contiguous* segments (WGCEP, 1995; Petersen *et al.*, 1996).

Conclusions

Contemporary felt reports of the 1836 California earthquake are limited to Carmel, Monterey, San Juan Bautista,

and Santa Clara, and they indicate an $M \sim 6\frac{1}{4}$ event east of Monterey Bay. The illusion of a Hayward fault earthquake stems from a reminiscence appearing in the Oakland newspaper following the 1868 Hayward earthquake. It indicated that the effects of the 1868 earthquake were similar to those of a June 1836 event that generated fissures in "Oakland Valley," had many violent aftershocks, and was damaging in the East Bay. The effects described are similar to those of the major June 1838 earthquake on the San Andreas fault, not the June 1836 event east of Monterey Bay. The 1838 earthquake was destructive in the East Bay at San Leandro and Mission San Jose. It also generated numerous widely felt aftershocks. In contrast, there are no contemporary reports indicating that the 1836 earthquake was felt north of Santa Clara or that it had any felt aftershocks. We discovered that "Oakland Valley" was near the Oakland waterfront, 6 km to the west of the Hayward fault. The fissures previously assumed to represent rupture along the Hayward fault were probably lateral spreading induced by the 1838 San Andreas fault earthquake. Such fissures were induced near the Oakland waterfront also by the San Andreas fault earthquakes of 1906 and 1989.

Before the 1838 event, no major earthquakes are known in the Bay area back to 1776, when San Francisco Mission and Presidio were founded. The last major earthquake on the northern Hayward fault occurred more than 220 years ago, not 160 years ago as previously thought, which increases the hazard somewhat on this segment of the fault.

The major 1838 San Andreas fault earthquake caused damage to the missions and their surroundings from San Francisco to Monterey that was as strong as or stronger than that of the great 1906 earthquake. The strong 1838 earthquake damage from Monterey to San Francisco and the frequent violent aftershocks at Oakland suggest faulting on the San Andreas from San Juan Bautista to San Francisco. In the following 3 years, probable aftershocks occurred frequently in the area south of San Juan Bautista and caused damage at Carmel and at Alisal, 16 km west of the San Andreas fault. The suggested 140-km rupture is much longer than the 60-km 1838 rupture previously assumed (Lindh, 1983; WGCEP, 1990) and indicates $M \sim 7\frac{1}{2}$ instead of 7. This large magnitude is consistent with studies of seismically induced rockfalls in the Sierra Nevada, which indicate that the shaking in 1838 was as strong and widespread as that in the great San Andreas fault earthquakes of 1906 and 1857 (Bull, 1996).

The 1838 earthquake segment ruptured again 68 years later as part of the great 1906 earthquake rupture that extended as far as 330 km northwest of San Francisco. This occurrence is similar to the rerupture of the 1812 earthquake segment as part of the great 1857 earthquake rupture that extended as far as 170 km northwest of Fort Tejon. These observations indicate that the recurrence times of major earthquakes on the 1812 and 1838 San Andreas fault segments can be as short as 44 to 68 years, when they are followed by large events on the adjoining segments.

Acknowledgments

Tianqing Cao calculated the revised probabilities for the Hayward fault. Martitia Tuttle kindly provided copies of the 1838 and 1839 letters from Mission Santa Cruz, translated by Star Gurcke. We appreciate the thoughtful reviews by William Bakun, William Bryant, William Bull, Chris Cramer, Robert Darragh Jr., Lind Gee, Jim Lienkaemper, Allan Lindh, Mark Petersen, Carol Prentice, Michael Reichle, David Schwartz, Paul Segall, Roger Sherburne, Kerry Sieh, and Lynn Sykes. Bob Sydnor referred us to W. B. Bull's article on dating earthquakes with lichenometry. Carl Stover provided an intensity map for the 1986 Quien Sabe earthquake. Jim Dewey provided intensity questionnaires for the Santa Clara to Carmel area of the Loma Prieta earthquake. We thank Claudia Hallstrom and Donna Ransom for their help in the library research, and Claudia for assembling the manuscript. Lisa Chisholm provided word processing support, and Ross Martin provided graphics support. Translation from the original Spanish was provided by Roger Burbach and Antonio Bombal. We thank the many helpful librarians at Bancroft Library, California Historical Society, California Society of Pioneers, and California State Library. We especially thank Kathleen Digiovanni of the Oakland Public Library for helping us determine the location of Oakland Valley.

Research supported in part by the U.S. Geological Survey, Department of the Interior, under Award Number 1434-93-G-2313. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the State of California or of the U.S. Government.

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Manuscript received 3 April 1997.