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San Andreas Fault Zone, California: $M \geq 5.5$ Earthquake History

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Abstract The San Andreas fault zone has been a very significant source of major California earthquakes. From 1812 to 1906 it generated four major earthquakes of $M \sim 7$ or larger in two pairs on two major portions of the fault. A pair of major earthquakes occurred on the central to southern region, where the 1857 faulting overlapped the 1812 earthquake faulting. A pair of major earthquakes occurred on the northern region, where the 1906 faulting overlapped the 1838 earthquake faulting. Also, earthquakes of $M \sim 7$ occurred in the San Francisco Bay area on the Hayward fault in 1868 and the Santa Cruz Mountains near Loma Prieta in 1989 and on the Imperial fault near the border with Mexico in 1940.

The 1838 earthquake's damage effects throughout the Bay area, from San Francisco to Santa Clara Valley and Monterey, were unequalled by any historical earthquake other than the 1906 event. This, and numerous strong possible aftershocks during the following 3 years in the San Juan Bautista vicinity, suggest 1838 faulting from San Francisco to San Juan Bautista.

Cycles of seismicity and quiescence were associated with the Bay area earthquakes of 1868, 1906, and 1989. The 1868 earthquake on the Hayward fault was preceded by 12 earthquakes of $M \geq 5.5$ from 1855 to 1866, within 60 km of the Hayward fault, and was followed by 13 quiet years. The 1906 San Andreas fault event was preceded from 1881 to 1903 by 18 earthquakes of $M \geq 5.5$ and was followed by quiescence, with only three earthquakes of $M \geq 5.5$ until 1954. The Bay area has been seismically quiet at the $M \geq 5.5$ level since the 1989 Loma Prieta earthquake and its 1990 aftershocks, which contrasts with the 10 years before 1989, when five M 5.5–6.2 events occurred. The Loma Prieta earthquake is of similar magnitude to the 1868 Hayward event and could be followed by a similarly short quiet period.

The 1857 earthquake had immediate foreshocks in the Lonoak–Bitterwater region ~50 km northwest of Parkfield. In the northern end zone of the 1857 rupture, extending southeast from Bitterwater ~70 km to Parkfield, the rate of seismic moment release has decreased with time since 1857. This may reflect the decay with time of the stress loading due to the ~9 m 1857 fault displacements ~80 km southeast of Parkfield and explain why the predicted earthquake, which was based on the assumption of regular recurrence of Parkfield earthquakes, has not yet occurred.

The extent of the 1812 earthquake fault rupture is not well defined. Jacoby *et al.* (1988) estimated that it extended ~170 km from Cajon Pass to Tejon Pass. Based on this estimate, we present the hypothesis that the rupture occurred in two segments in December 1812. The eastern segment generated the 8 December earthquake that damaged San Juan Capistrano, San Gabriel, San Fernando, and San Buenaventura. Thirteen days later the western segment ruptured generating the earthquake that damaged San Fernando and San Buenaventura again, as well as Santa Barbara, Santa Ynez, and Purisima Concepcion.

Introduction

This article summarizes the earthquake history of the San Andreas fault zone (area outlined in Fig. 1) and provides new information and interpretations in the San Francisco Bay area, Parkfield and its surroundings, and the Fort Tejon–Cajon Pass region. It builds and expands on previous works including those of Toppozada (1975, 1984, 2000), Toppozada and Parke (1982), Toppozada and Borchardt (1998), Toppozada *et al.* (1978, 1981, 1990, 1992, 2000, 2002).

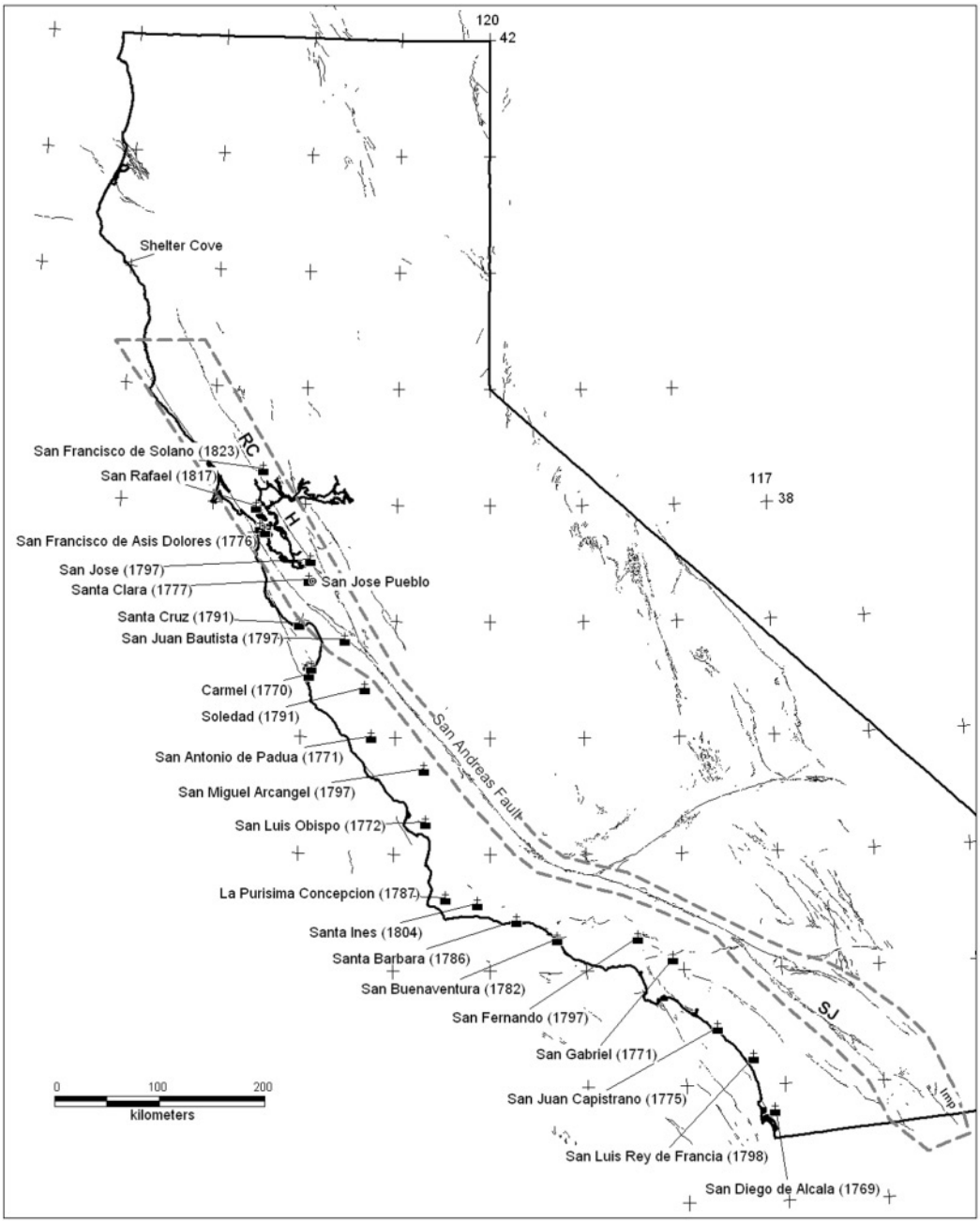

Figure 1. Index map showing the California missions. The dates the missions were established are indicated. All missions were secularized in 1834. Dashed region represents area of San Andreas fault zone considered in this article. Fault zones: H, Hayward; RC, Rogers Creek; SJ, San Jacinto; Imp, Imperial.

First we discuss the 1906 rupture zone seismicity and the changes in seismicity before and after M ~7 or larger San Francisco Bay area earthquakes. Then we discuss the seismicity near the southern end of the creeping zone where the great 1857 earthquake faulting initiated, including Parkfield and the zone ~70 km to the northwest. We describe numerous newly identified earthquakes in this Parkfield–Bitterwater zone and surrounding region to elucidate the earthquake history and its implications for the Parkfield earthquake prediction. We, finally, reinterpret the effects of the 1812 earthquakes that occurred and were destructive between Orange and Santa Barbara Counties, in light of 1812 faulting that possibly extended ~170 km in the Fort Tejon–Cajon Pass region, and briefly review the seismicity to the southeast of Cajon Pass.

Appendix A presents additional information regarding newly defined earthquakes in the Parkfield–Bitterwater area and surroundings. Appendix B provides parameters and de-

scriptions of the $M \geq 5.5$ San Andreas fault zone earthquakes, within the area outlined in Figure 1. The magnitude (M) listed is the preferred magnitude from Toppozada and Branum (2002), who list the different available magnitude types for each earthquake. Moment magnitude is used when available, otherwise the order of preference is surface wave, local, and magnitude derived from the areas shaken at various intensities. Appendix B specifies the type of magnitude for each earthquake.

The earthquake history of the San Andreas fault is of variable completeness. It is most complete in the San Francisco Bay region, where regular newspaper publishing started around 1849. With the extensive research of the Bay region newspapers by Townley and Allen (1939), Toppozada *et al.* (1981), and in the present article, the record of $M \geq 5.5$ events is probably complete back to about 1850 in the Bay region. Before 1850, missionary and related documents were available sporadically from about 1780 to when the missions were secularized in 1834. A few documents were available in 1840 during an attempt to resurrect the missions, including an important Carmel mission report. The earthquake record may be complete for $M \geq 6.5$ events from about 1800 to 1833, within about 70 km of the missions, which includes much of the San Andreas fault zone from near San Gabriel to San Francisco (Fig. 1). Elsewhere, the record is probably complete for $M \geq 6.5$ events from about 1880 and $M \geq 6.0$ events from about 1910, based on the increase in California population and published newspapers (Toppozada *et al.*, 1981; Agnew, 1991). We used occasional Weather Bureau records of earthquake effects, which started around 1890. We also used the University of California at Berkeley (UCB) seismographic bulletins, which started in 1910, to determine relative sizes of the Parkfield region earthquakes. During the modern instrumental period, the record is complete to $M \geq 5.5$ from 1932 in southern California (Hileman *et al.*, 1973) and from 1942 in northern California (Bolt and Miller, 1975).

We estimate preinstrumental epicenters to be in the centers of maximum Modified Mercalli intensity (MMI) shaking, generally from isoseismal maps. We estimate preinstrumental magnitudes from the size of the areas shaken, using relations developed by Toppozada and Branum (2002) between moment magnitude M_W of modern earthquakes and areas shaken at or above MMI V, VI, and VII. For smaller events where only the total felt area (MMI II) was known, we estimated M from the total area using the relation of Toppozada (1975), with a correction of $+1/4M$ as indicated by Ellsworth (1990). We have also applied the method of Bakun and Wentworth (1997), which determines epicenters and magnitudes from felt intensities, to some earthquakes in and near the creeping zone within ~70 km northwest of Parkfield.

The uncertainties in the estimates of epicenter and magnitude for preinstrumental (pre~1932–1942) earthquakes can be up to 50–100 km and 0.5M unit. Uncertainties may be smaller for post-1868 earthquakes in the densely populated San Francisco Bay area. We attempted to improve some estimates by comparing the shaking intensities of preinstrumental earthquakes to those of neighboring instrumented earthquakes. This was possible in regions such as San Francisco Bay and Parkfield that have preinstrumental and modern earthquake epicenters and have towns that can provide felt intensities.

The Northern San Andreas Fault Zone

The region surrounding the 1906 rupture zone includes the seismicity associated with the major 1838 and 1906 San Andreas, 1868 Hayward, and 1989 Loma Prieta earthquakes. The seismicity was high in the years before and remarkably low in the years after each of these four major earthquakes (Toppozada, [2002], his figure 3b), although the post-1838 seismicity may be incomplete before the 1849 Gold Rush.

Earthquakes before and after the Major 1838 Event

We identified earthquakes of about M ~5.5 or larger in 1781, 1800, 1808, 1825, 1827, and 1836 from the scant pre-1838 records. These events generally caused varying damage between San Francisco and San Juan Bautista. The 1800–1836 events are described in Appendix B. The 1781 event was felt from San Francisco (distinctly) to Carmel (slightly) and broke a bottle at Santa Clara (Serra, 1955).

Toppozada and Borchardt (1998) showed that a supposed major 1836 Hayward fault earthquake probably was a M ~6.25 event in the Gilroy–San Juan Bautista environs, away from the Hayward fault. The more recent magnitude–area relations of Toppozada and Branum (2002) indicate M ~6.5.

The 1838 San Andreas fault event was the first recognized major (M ~7 or larger) Bay area earthquake since the 1776 founding of Mission San Francisco Dolores. It occurred after the regular mission annual reports ceased in 1834 and before regular local newspaper publishing started in 1849. Most of what we know about the 1838 earthquake is from reminiscences decades after the event. This earthquake was studied by various investigators:

1. Louderback (1947, p. 74) summarized the 1838 account of damage to missions San Francisco, San Jose, and Santa Clara by Captain Paty, the 1879 retrospection of C. Brown of effects near the San Andreas fault, and other information. He concluded that "The evidence of greater intensity at Monterey than in 1906 may mean that the fault rupture extended further south in 1838 than in 1906." Sykes and Nishenko (1984) concurred and reemphasized this conclusion.
2. Lindh (1983) and the Working Group on California Earthquake Probability (WGCEP) (1990) suggested that the 1838 earthquake resulted from a ~60-km rupture (corresponding to M ~7) on the San Andreas fault extending northward from the Loma Prieta segment, which is a ~50 km segment centered on Loma Prieta (Fig. 2b).

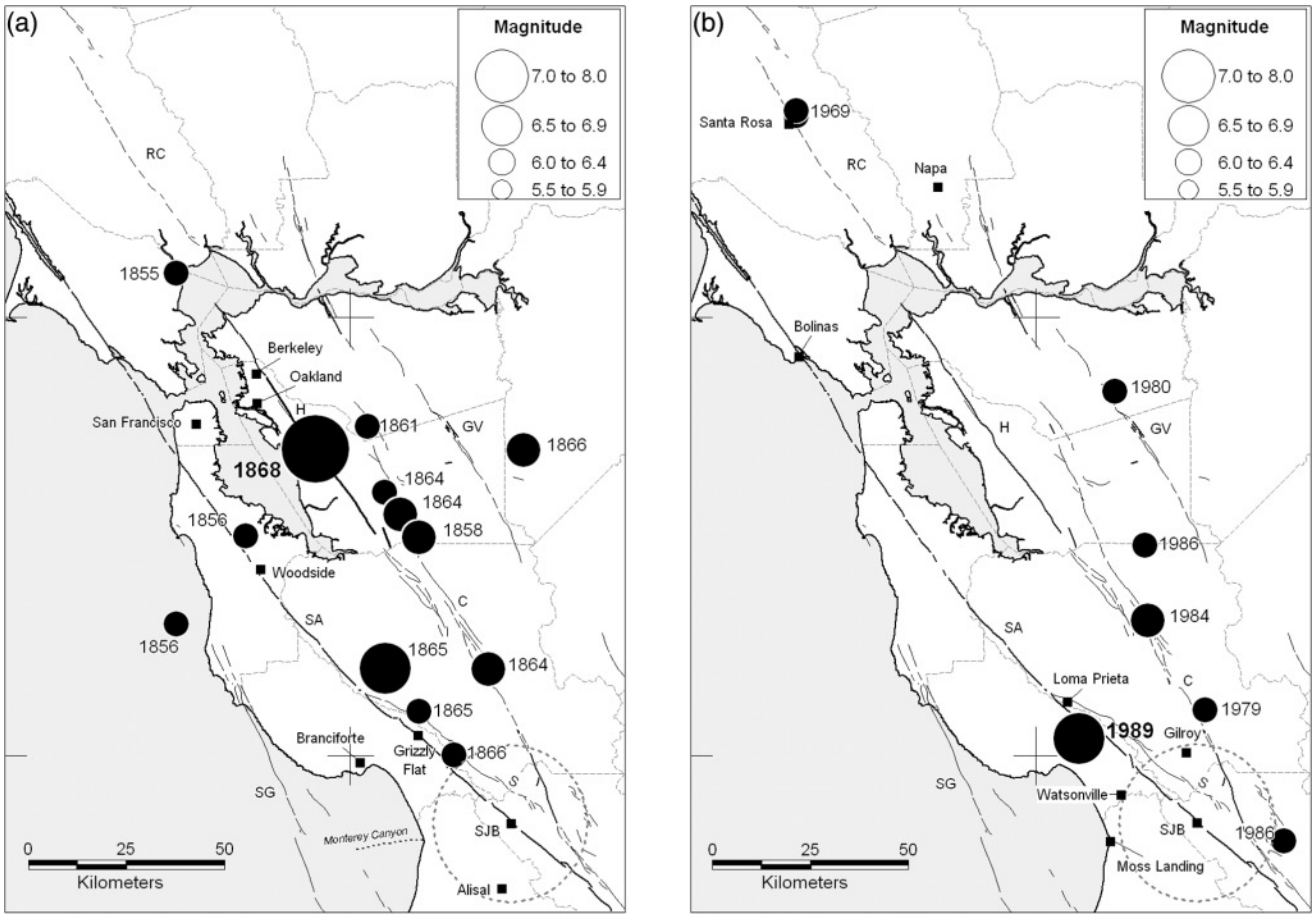

Figure 2. (a) $M \geq 5.5$ San Francisco Bay area seismicity from 1855 to 1868. Fault rupture of the 1868 Hayward Earthquake is the bold line through the epicenter. (b) $M \geq 5.5$ San Francisco Bay area seismicity from 1969 to 1989. Dashed circle represents 20 m radius from San Juan Bautista (SJB). Fault zones: H, Hayward; RC, Rogers Creek; SA, San Andreas; C, Calaveras; GV, Green Valley; SG, San Gregorio; S, Sargent.

3. Tuttle and Sykes (1992) further analyzed the 1838 intensity information and extended the rupture ~50 km southeastward through the Loma Prieta segment and estimated $M \geq 7.2$.
4. Toppozada and Borchardt (1998) analyzed new as well as previously available information and estimated a ~140 km rupture from San Francisco to San Juan Bautista and M ~7.5.
5. Schwartz *et al.* (1998) saw no direct evidence of large 1838 surface displacements (~2 m) in the Grizzly Flat trench in the Santa Cruz Mountains (Fig. 2a). However, they did not rule out 1838 faulting in the Santa Cruz Mountains, having "small lateral displacements with a limited vertical component."
6. Hall *et al.* (1999) interpreted San Andreas fault offset of young channel deposits at Filoli near Woodside (Fig. 2a) of about 4.1 m (± 0.5) as 2.5 m (± 0.2) in 1906 and 1.6 m (± 0.7) possibly in 1838. The plus or minus uncertainties allow equal 1838 and 1906 offsets of 2.3 m. This would be consistent with roughly similar San Andreas faulting between San Francisco and San Juan Bautista in 1838 and 1906.
7. Bakun (1999) estimated M ~6.8 ($+0.4$, -0.5) from intensity data but stated that this may be too small because of the inadequate distribution of reporting localities. He used the intensity information from Toppozada and Borchardt (1998) but assumed that mission churches were poorly built and significantly damaged at MMI VII.
8. Toppozada (2000) documented that in the 1906 San Francisco earthquake, "Mission Dolores, built in 1777, with its adobe walls and wooden frame, was not injured, while its more modern successor [built in 1876] was greatly damaged [tower and roof]" (Gilbert *et al.*, 1907, p. 27). This illustrates that mission Dolores was not poorly built or significantly damaged at MMI VII. Thus, the 1838 MMI was probably VII–VIII when the mission walls were badly injured at San Francisco, San Jose, and Santa Clara, according to Captain Paty (Louderback, 1947). The low 1906 San Francisco MMI of VII was probably due to the absence of directivity effects because the epicenter was

opposite San Francisco. The higher 1838 MMI was possibly due to directivity from an epicenter south of San Francisco.

9. Toppozada (2000, his figure 1) suggested that the 1838 intensities in Gilroy and Monterey (Figs. 2b, 3) were comparable to the 1906 intensities and greater than the 1989 Loma Prieta intensities. This suggests that the 1838 San Andreas faulting extended southeast of Loma Prieta to the San Juan Bautista region (Fig. 2), between Gilroy and Monterey, as in 1906.

The 1838 earthquake was followed by a 17- to 18-year period with few $M \geq 5.5$ earthquakes identified in the Bay area, although pre-1850 documentation was very poor. We have little knowledge of aftershocks in 1838–1839 because documentation is lacking. Unusually numerous and strong 1840–1841 earthquakes in the San Juan Bautista region are described next and were possibly aftershocks of the 1838 event.

1840–1841 Earthquakes near San Juan Bautista

The 1840 Mission Carmel annual report and fortuitous notes of travelers describe numerous 1840 and 1841 earthquakes in the Santa Cruz–San Juan Bautista–Carmel region. Several of these were of $M \sim 6$, making this one of the most seismically active historical periods in the San Juan Bautista vicinity (Toppozada [2000]; his figure 2). This unusually high seismicity near the rupture end indicated by the 1838 mainshock damage suggests aftershock activity.

18 January 1840, M ~*6.5.* The Santa Cruz church tower fell, and about 1 km (3000–4000 ft) to the southeast at Branciforte Pueblo (Fig. 2a) houses were damaged and threatened to fall (Louderback, 1944). Bancroft (1886) attributed this damage to an earthquake that also generated a sea wave. Louderback (1944) indicated that the wave preceded the damage by two days and was probably due to ocean storms and rain. He further interpreted the Santa Cruz annual report statement "the tower fell to the ground owing to the abundance of water as well as the weakness of the ground on which it was built" to mean that the damage to the church was probably also due to the rain storm. However, this does not explain the damaged houses about 1 km away at the pueblo. Louderback (1944) concluded there was no earthquake: "no report emanating from any of the surrounding region from Monterey to San Francisco has yet been cited by anyone which asserts that an earthquake occurred during that year". Clearly he was not aware of the annual report dated 31 December 1840 from Mission Carmel, 5 km from Monterey, which describes various earthquake damage, including: "The dome of the church which is in the presbytery is cracked open due to the strong earthquakes that occurred this year [exact date in 1840 not specified]" (Toppozada and Borchardt, 1998, p. 152).

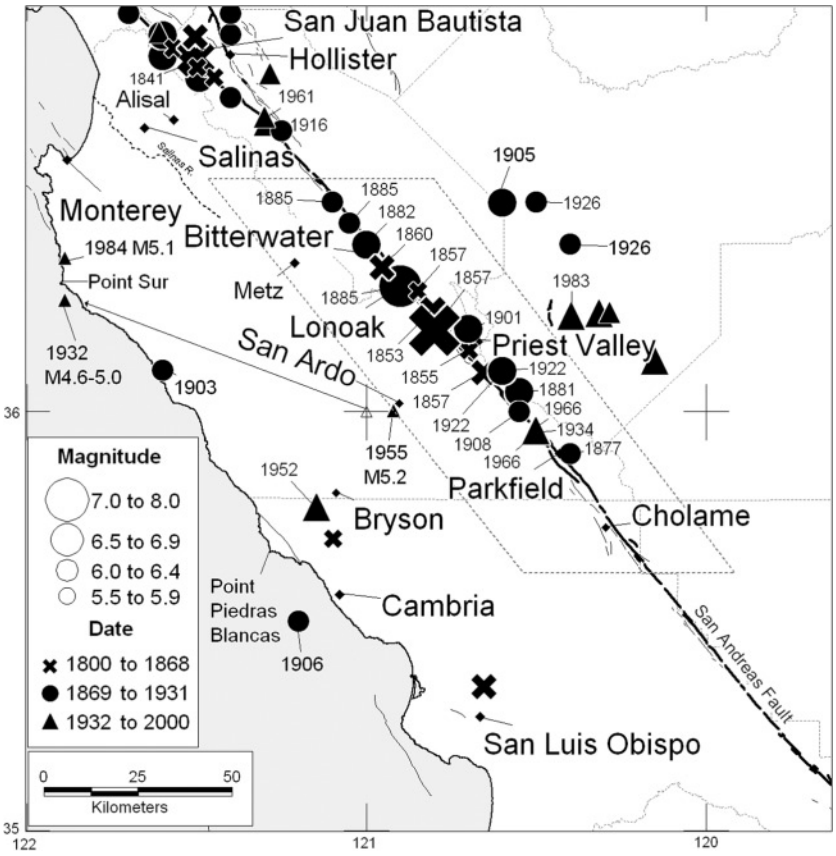

Figure 3. M ≥5.5 seismicity in the Parkfield–Bitterwater region and surrounding areas. The dashed region is that considered in Figures 7 and 10. Earthquakes to the east and west of the dashed region were not included in Appendix B.

We believe that the Santa Cruz tower collapse and the damage to houses 1 km away most probably resulted from the earthquake cataloged by Bancroft. It is possible that the mainshock of the "strong [1840] earthquakes" that damaged Carmel was the 18 January earthquake that caused MMI VI to VII damage 50 km north of Carmel, at Santa Cruz and Branciforte Pueblo (Toppozada and Borchardt, 1998). A probable source of such an earthquake is the San Andreas fault vicinity of San Juan Bautista, ~50 km from both Santa Cruz and Carmel. This is where the 1838 mainshock damage suggests the end of the 1838 rupture was. It is also the probable source of numerous 1841 earthquakes, described in the following sections. A M ~6.5 earthquake near San Juan Bautista would generate the MMI VI–VII damage observed ~50 km away at both Santa Cruz and Carmel in 1840 (Figs. 2a, 3), according to the magnitude–area shaken relations of Toppozada and Branum (2002). Alternate interpretations of two earthquakes of M 5.5–6, one near each mission, or that the only earthquake damage was near Carmel, and that the rain storm destroyed the Santa Cruz church tower and houses in Branciforte Pueblo 1 km away, are less likely.

3 July 1841, M ~6. Duflot de Mofras (1844, pp. 56–57) reported strong shaking (MMI ~V–VI) in Monterey and that the shock was also strongly felt on "the farms of the interior," probably in the Salinas Valley (Fig. 3), and that the shore became covered with beached fish. This was probably one of the 25 earthquakes in June and July 1841 noted, after the 29 July 1841 event described next, as felt most severely at Alisal, 16 km south of San Juan Bautista and 14 km from the San Andreas fault (Fig. 3).

Simpson (1930, p. 344) related in 1842 in Monterey that "earthquakes . . . are so frequent that a hundred and twenty of them were felt during two successive months of last summer [1841] . . . the shocks being seldom severe." The 3 July event was probably one of the events felt seldom severely at Monterey, 45 km from the San Andreas fault, and most severely at Alisal, 14 km from the San Andreas fault. From this we deduce a probable source in the San Andreas fault vicinity, ~8 km southeast of San Juan Bautista (Fig. 3). We employed the magnitude–area shaken equations of Toppozada and Branum (2002) to determine M ~5.9 from a MMI V to VI radius of ~45 km from the San Andreas fault to Monterey. A local tsunami resulting from a submarine landslide in Monterey Bay triggered by the earthquake would account for the beached fish. Numerous landslides are mapped in the submarine Monterey Canyon area (Greene and Kennedy, 1989; Greene *et al.*, 2001). Also, the 1989 Loma Prieta earthquake triggered minor submarine landslides in Monterey Canyon that generated minor sea waves at Moss Landing (Gardner-Taggart and Barminski, 1991).

29 July 1841, M *~5.8.* Robinson (1858, 1969) described alarming MMI VI–VII earthquake damage at Hartnell's Alisal ranch, 16 km south of San Juan Bautista. Hartnell told Robinson that it was the 25th earthquake that was felt most severely at Alisal within two 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 alone." This suggests that the shocks were more violent at Alisal than at neighboring settlements in Salinas River Valley to the southwest (Fig. 3).

This, and Simpson's statement that the shocks were seldom severe in Monterey, suggest a source on or near the San Andreas fault, which is 45 km northeast of Monterey (Fig. 3). The MMI VI–VII radius of ~14 km from the San Andreas fault to Alisal suggests M ~5.8, using the magnitude–area equations of Toppozada and Branum (2002).

We know about the 3 July 1840 and 29 July 1841 earthquakes from the 1840 Carmel Mission report, which resulted from an effort to revive the missions, and from travelers' notes. We do not know of other strong possible 1838 aftershocks, except those mentioned in the Oakland reminiscence published 20 days after the 1868 earthquake (Toppozada and Borchardt, 1998), because documentation was lacking in the year or two following the major 1838 earthquake.

Other $M \geq 5.5$ Earthquakes in the San Juan Bautista Vicinity

Historical earthquakes of M ≥5.5 have occurred within ~20 km of San Juan Bautista almost exclusively from 1836 to 1841 and from 1883 to 1910 (Toppozada, [2000], his figure 2a,b). These periods immediately preceded and followed the major 1838 and 1906 San Andreas fault earthquakes, respectively, that apparently had rupture ends near San Juan Bautista. Portions of the Sargent and Calaveras faults fall within ~20 km of San Juan Bautista, and some of the epicenters may have occurred on these or on the San Andreas fault.

Earthquakes of M 5.6 and 5.5 occurred in the Hollister–Paicines area of the creeping zone ~30 km southeast of San Juan Bautista in 1916 and 1961 (Fig. 3). After 1910, $M \geq 5$ events occurred within ~20 km of San Juan Bautista in April 1954 (M 5.6), September 1963 (M 5.0), April 1990 (M 5.3 Loma Prieta aftershock), all near Watsonville, and in August 1998 (M 5.1) (Uhrhammer *et al.*, 1999). The 1998 hypocenter at 9-km depth was located 13 km southeast of San Juan Bautista and 13 km northeast of Alisal, where the frequent 1841 earthquakes were most damaging.

Other major earthquakes that did not involve rupture of the San Andreas fault segment from San Juan Bautista to San Francisco or beyond were not associated with increased seismicity near San Juan Bautista. For example, the seismicity associated with the 1868 Hayward and 1989 Loma Prieta earthquakes of M ~7 described subsequently did not include any earthquakes of $M \geq 5.5$ within 20 km of San Juan Bautista (Fig. 2a,b). This is consistent with our theory that the 1840 and 1841 earthquakes were probably aftershocks of the 1838 event, which we believe had a rupture end near San Juan Bautista.

Earthquakes before the Major 1868 Hayward Fault Event

Newspapers began to be published regularly in the San Francisco Bay area during the 1849 Gold Rush, which improved the reporting of local earthquake effects. The first significant post-1849 Bay area earthquakes were the 1855 *M* 5.5 and 1856 January and February *M* 5.7 and *M* 5.9 events, respectively, in the general vicinity of the Rodgers Creek, San Gregorio, and San Andreas faults, respectively (Appendix B), (Toppozada *et al.*, 1981).

In 1858, an East Bay earthquake of *M* 6.2 caused some damage to buildings from San Jose to San Francisco. It was followed by eight earthquakes of *M* 5.8–6.5 from 1861 to 1865 in the east and south Bay areas (Fig. 2a, Appendix B). This was one of the most seismically active periods in the Bay area during the past 150 years and culminated in the destructive 1868 Hayward fault earthquake (Fig. 2a).

The shaking effects of the 1861 East Bay earthquake, interpreted from 30 regional newspaper and other reports, indicate *M* 5.8. This magnitude contrasts with the unreasonably high *M* 6.4–6.9 suggested by Rogers and Halliday (1992), who assumed that 10–13 km of poorly documented fissures indicated Calaveras fault rupture. The 1984 Morgan Hill earthquake of *M* 6.2, which had stronger and more widespread shaking effects than the 1861 earthquake, generated only minor surface cracks that were not clear Calaveras fault rupture (Hart, 1984; Harms *et al.*, 1984). Thus the ~10-km fissures in 1861 may have been more related to secondary ground failure than to faulting. The California fault map suggests ~4.5 km of 1861 rupture (Jennings, 1994).

In 1864, three strong and two moderate earthquakes occurred in the east and south Bay areas. In February, a *M* 6.1 earthquake, near the Calaveras fault southeast of San Jose (Fig. 2a), cracked walls slightly from Monterey to San Jose. In March and May, two East Bay earthquakes of *M* 6.0 and 5.8 centered in the Calaveras–Hayward fault region of Alameda county, damaged plastering slightly from San Francisco to San Jose. In June and July, two East Bay earthquakes of *M* 5.4 and 5.2, too small to be shown in Figure 2a, occurred near the March and May epicenters and were possibly aftershocks.

In March 1865, a *M* ~5.2 earthquake, too small to be shown in Figure 2a, occurred near Santa Rosa and the Rodgers Creek–Healdsburg fault zone. It was preceded 6.5 hr earlier by a *M* ~5.1 foreshock. This is generally comparable to the 1969 occurrence near Santa Rosa of *M* 5.6 and 5.7 earthquakes 83 minutes apart.

In May 1865 a *M* 5.9 earthquake occurred in the Santa Cruz Mountains area and was possibly a preshock of the destructive 8 October 1965 earthquake of *M* 6.5 that was centered ~10 km north of Loma Prieta. The October earthquake was most destructive in the Watsonville–Santa Cruz–San Jose area, but in 1865 Samuel Clemens (or Mark Twain) described it as "the great earthquake in San Francisco" because the losses were greatest there. Bakun (1999) derived a similar location and magnitude for this earthquake to those of Toppozada *et al.* (1981). McNutt and Toppozada (1990) and Tuttle and Sykes (1992) compared the 1865 earthquake to the 1989 Loma Prieta event and found that it was smaller and ~15 km to the north of the Loma Prieta event. Yu and Segall (1966) suggested thrusting on a fault dipping to the southwest, based on sparse triangulation data.

Five and a half months later, in March 1866, a *M* 5.9 possible aftershock of the October 1865 earthquake occurred in the Gilroy–Watsonville area. This is similar to the occurrence in the Gilroy–Watsonville area of a *M* 5.3 aftershock six months after the October 1989 Loma Prieta earthquake. This similarity in the location and timing of mainshocks and aftershocks is tempered by the uncertainty in location of the 1866 earthquake.

In July 1866, a *M* 6.0 earthquake occurred in the San Joaquin Valley (SJV) Border region about 20 km south-southwest of Stockton and was felt over a distance of 360 km from Visalia, Tulare County, to Nevada City, Nevada County (Toppozada *et al.*, 1981).

The major 1868 Hayward earthquake (Lawson, 1909; Toppozada *et al.*, 1981) was the strongest event in the Bay area since the major 1838 San Andreas fault earthquake. Yu and Segall (1996) calculated an 1868 rupture length of ~50 km on the Hayward fault extending southeastward from the Berkeley–Oakland area (Fig. 2a). That earthquake also was referred to as "the great San Francisco earthquake" because in 1868 that bustling city again suffered much of the damage. The vulnerability of San Francisco to earthquakes on the Hayward fault mirrors the vulnerability of Oakland to earthquakes on the San Andreas fault. The latter is illustrated in the 1868 *Oakland Daily News* reminiscence that equates the effects in Oakland of the 1868 Hayward earthquake to those of the 1838 San Andreas fault earthquake (Toppozada and Borchardt, 1998). The level of seismicity in the Bay area was low after the 1868 Hayward earthquake for about 13 years until 1881.

Pre- and Post-1906 *M* ≥6 Activity

Earthquakes of *M* ~6 or larger occurred within 20 km of San Juan Bautista in 1883, 1890, 1892, 1897, 1899, and 1910 (Toppozada, [2000]; his figure 2b). These were the largest events to occur near San Juan Bautista since the 1840 and 1841 probable aftershocks of the 1838 earthquake. Since 1910, the largest earthquake within 20 km of San Juan Bautista occurred in 1954 (*M* 5.6).

Other *M* ≥6 earthquakes occurred near the SJV border: in 1881 east of San Jose, in 1889 near Antioch in the Sacramento–San Joaquin River Delta, and in 1892 in the Vacaville–Winters area (Toppozada, [2000], his figure 3a). The 1889 and 1892 earthquakes were centered ~37 km apart. Interestingly, they were temporally and spatially related in a similar way that the *M* 6.4 and 6.2 Coalinga and North Kettleman Hills earthquakes of 1983 and 1985, which were 25 km apart, were related.

Other *M* ≥6 earthquakes occurred in 1898 near the

southern Rodgers Creek fault and Mare Island (Toppozada *et al.,* 1992) and two weeks later near Mendocino and the San Andreas fault (Appendix B). Two events occurred in 1903 near San Jose.

The seismicity of the Bay area culminated in the great San Francisco earthquake of 1906 (M 7.8), which was followed by a 63-year quiet period during which few $M \geq 5.5$ earthquakes occurred in the Bay area and surroundings (Toppozada, [2000], his figure 3b). This observation of an earthquake cycle of strain accumulation and release has been noted by various authors including Gutenberg and Richter (1954), Tocher (1959), and Ellsworth *et al.* (1981). The great 1906 earthquake represents the major strain release because strain energy increases by about 30-fold for unit increase in M. The high level of seismicity before 1906 is a manifestation of stored strain and represents only minor strain release.

The immediate post-1906 $M \geq 5.5$ seismicity was limited to a 1910 aftershock near Watsonville and a 1911 earthquake near San Jose. This was followed by a 58-year quiet period with $M \geq 5.5$ earthquakes occurring only in 1916 and 1961 south of Hollister and in 1954 near Watsonville.

Pre- and Post-Loma Prieta $M \geq 5.5$ Seismicity

$M \geq 5.5$ earthquakes occurred in the Bay area in 1969, 1979, 1980, 1984, and twice in 1986, leading to the 1989 Loma Prieta earthquake of M 6.9 (Appendix B). Jaume and Sykes (1996) attributed this increased seismicity to recovery from the stress shadow of the great 1906 earthquake. The Bay area seismicity from 1969 to 1989 was similar to, but less energetic than, that from 1855 to the 1868 Hayward earthquake (Toppozada, [2000], his figure 3b).

The M 6.9 Loma Prieta earthquake of 1989 has been followed by total quiescence in the Bay area at the $M \geq 5.5$ level for ~13 years so far. The largest events since the 1990 Loma Prieta aftershocks were of M 5.1 in 1998 near San Juan Bautista, M ~5 in 1999 near Bolinas, north of the Golden Gate, and M 5.2 in 2000 near Napa. If this quiescence lasts about 13 years, as did the quiescence following the 1868 Hayward earthquake, also M ~7, then potentially damaging $M \geq 5.5$ earthquakes in the Bay area could reappear after about 2002. However, the 1868 Hayward and 1989 earthquakes were on different faults on opposite sides of San Francisco Bay, and the seismicity preceding 1868 was more energetic, including 12 M 5.5 to 6.5 events from 1855 to 1866 (Toppozada [2000], his figure 3). Thus, the post-1989 quiet period may not have the same duration as the post-1868 quiet period, but it emphasizes the importance of earthquake preparedness activities in the Bay area.

Parkfield–Bitterwater Region

In this section we present the differences between the areas shaken by Parkfield and Bitterwater earthquakes of M 5–6 and distinguish among these and earthquakes located to the east and west of the San Andreas fault. We also briefly review the earthquakes located off the San Andreas fault that we helped to define. We review highlights of the Parkfield–Bitterwater seismicity and present additional data in Appendix A. Table 1 lists Parkfield–Bitterwater region earthquakes of $M \geq 5.0$, including those identified in Appendix A. No earthquakes of $M > 5$ have occurred in the Parkfield–Bitterwater zone after 1966.

Areas Shaken by M ~5 to 6 Parkfield and Vicinity Earthquakes

Instrumental magnitudes are available for Parkfield earthquakes that have occurred since 1934. The felt extents for these earthquakes are listed in Table 2, to assist in analyzing the poorly to noninstrumented pre-1934 events.

The felt area of the 1966 Parkfield M ~6.0 mainshock is longer in the northwesterly direction than in the northeasterly direction (United States Earthquakes, [USE]), due to the northwesterly alignment of the San Andreas fault and of the Coast Ranges (Fig. 4). The felt area of the 1966 event extended from Parkfield northwesterly to Felton (195 km), southeasterly to Ventura (207 km), and northeasterly to Reedley (116 km).

Instrumented M ~5 events occurred two days before the 1934 mainshock and in 1939, 1956, and 1975. Table 2 indicates that the M 4.5 and 4.7 events of 1958 and 1961 were felt over smaller areas than were the $M \geq 4.9$ events. The earthquakes of M 4.9–5.2 were felt from 150 to 185 km to the northwest and from 80 to 109 km to the northeast. This indicates that the felt limit alone may not distinguish between M ~5 and M ~5.5–6.0 events. Intensity IV–V and greater shaking helps to differentiate between M ~5 and M 5.5–6.0 events. The 1934 and 1966 mainshocks were felt at intensities IV–V or greater at San Luis Obispo, Paso Robles, and Coalinga. Every $M < 5.5$ earthquake was felt at intensities less than IV–V at either San Luis Obispo, Paso Robles, or Coalinga (Table 2).

Figure 5 compares the areas shaken at MMI VI or greater in the 1966 Parkfield, 1983 Coalinga, and 1952 Bryson earthquakes. The Parkfield event was felt equally on both sides of the San Andreas fault, whereas the Coalinga event was felt more strongly to the east, and the Bryson event was felt more strongly to the west of the fault. We used these patterns to distinguish between earthquakes on the San Andreas fault from those to the east and to the west. In analyzing the historical earthquakes, we sharpened the definition of events to the east and west of the San Andreas fault, which we briefly discuss next.

San Ardo Earthquakes. The Berkeley catalog (Bolt and Miller, 1975) locates two M 5 or larger events, in 1932 and 1955, near San Ardo. The 1955 earthquake of M 5.2 is a useful standard in this area of low seismicity, and its MMI V zone is outlined in Figure 5.

We found that Bolt and Miller's (1975) epicenter for the 1932 event on the 36° N, 121° W coordinate crossing near San Ardo was clearly inconsistent with the felt effects.

Table 1

Earthquakes of M^* ≥5 in the Parkfield–Bitterwater Region (dashed box in Figure 3) and pre-1927 M ≥5.5 Events in Surrounding Areas

Sequence	Date	Local Time	Magnitude	Region—Notes
	2 Sept 1853	?	~6.0	Priest Valley/Lonoak
	13 Jan 1855	6:30 p.m.	~5.5	Priest Valley
	9 Jan 1857	Dawn	6.1	1857 dawn foreshock
	9 Jan 1857	Sunrise	5.6	1857 sunrise foreshock
	9 Jan 1857	8:24 a.m.	7.9	Priest Valley
	16 Apr 1860	7:30 p.m.	6.0	Lonoak/Bitterwater
	30 May 1877	2:30 a.m.	~5.5	Parkfield
1881 sequence	1 Feb 1881	4:11 p.m.	6.0	Parkfield
	1 Feb 1881	9:00 p.m.	~5.5	Aftershock
	6 May 1881	5:45 a.m.	~5.3	Aftershock
	6 Mar 1882	1:45 p.m.	6.0	Bitterwater
	30 Mar 1885	11:56 p.m.	5.7	Bitterwater
	2 Apr 1885	7:25 a.m.	5.9	Bitterwater
	11 Apr 1885	8:05 p.m.	6.5	Lonoak
1901 sequence	2 Mar 1901	11:45 p.m.	6.4	Priest Valley
	2 Mar 1901	11:50 p.m.?	5.0–5.5?	Immediate aftershock?
	5 Mar 1901	10:45 p.m.	~5.5	Aftershock
	14 Aug 1901	3:11 a.m.	~5.5	Aftershock
	14 Aug 1901	3:22 a.m.?	~5.5?	Aftershock?
	24 Mar 1903†	11:45 p.m.	~5.9	South of Point Sur†
	25 May 1905‡	6:50 p.m.	6.1	North of San Benito Mountain‡
	6 Dec 1906†	10:40 p.m.	~5.7	Cambria†
	27 Apr 1908	2:50 a.m.	~5.8	Parkfield/Priest Valley
	8 Sept 1915	4:45 a.m.	~5.0	Parkfield region
1922 sequence	10 Mar 1922	2:40 a.m.	~5.0	Foreshock
	10 Mar 1922	3:21 a.m.	6.3	Priest Valley
	10 Mar 1922	3:26 a.m.?	5.0–5.5?	Immediate aftershock?
	16 Mar 1922	3:10 p.m.	~5.3	Aftershock
	17 Aug 1922	9:12 p.m.	5.7	5 month later aftershock
	5 Sept 1922	1:05 a.m.	~5.0	6 month later aftershock
	25 Jul 1926‡	9:57 a.m.	5.8	~30 km North of Coalinga‡
	27 Dec 1926‡	1:19 a.m.	~5.5	~20 km North of Coalinga‡
1934 sequence	5 Jun 1934	1:49 p.m.	4.9–5.0	Foreshock
	7 Jun 1934	8:30 p.m.	5.0–5.2	Foreshock
	7 Jun 1934	8:48 p.m.	6.0	Parkfield
	24 Dec 1934	8:26 a.m.	4.8–5.0	6 month later aftershock
	28 Dec 1939	4:16 a.m.	5.0–5.4	Parkfield
	4 Feb 1947	10:14 p.m.	~5.0	Priest Valley
	15 Nov 1956	7:23 p.m.	4.9–5.4	Parkfield
1966 sequence	27 Jun 1966	8:08 p.m.	5.5	Foreshock
	27 Jun 1966	8:26 p.m.	6.0	Parkfield
	29 Jun 1966	11:53 a.m.	4.8–5.0	Aftershock
	13 Sept 1975	1:21 p.m.	4.8	Parkfield
	14 Nov 1993	8:25 a.m.	4.8	Parkfield
	20 Dec 1994	2:27 a.m.	4.9–5.0	Parkfield

*Appendix B specifies the type of magnitude for each earthquake.

†The 1903 and 1906 events were in the coastal zone between San Luis Obispo and Point Sur.

‡The 1905 and both 1926 events were in the area north of Coalinga near Idria.

This event was reported felt at 16 sites ranging in distance from the coordinate crossing from 45 km to the north-northwest at Metz (Fig. 3) to 155 km to the northwest to Felton, north of Santa Cruz (Fig. 4). K. Meagher *et al.* (personal comm., 1991) relocated the epicenter using Berkeley and Caltech data and assigned a M of 4.6. Their location is in the Point Sur vicinity (36.26° N, 121.88° W), ~85 km west-northwest of Bolt and Miller's (1975) epicenter and is compatible with the felt effects (Figs. 3, 5). Bolt and Miller's (1975) erroneous epicenter at the coordinate crossing

Table 2
Felt Characteristics of *M* 4.5–6.0 Parkfield Earthquakes

Date	M	Northeasterly Extent* (km)	Northwesterly Extent* (km)	SLO†	PR†	COA†
05 Jun 1934	4.9‡	Hanford (85)	Santa Cruz (85)	IV	III	IV
07 Jan 1934	5.6/6.0§	Reedley (116)	Mt. Hermon (195)	IV–V	IV–V	VI
28 Dec 1939	5.2*	Fresno (109)	Santa Cruz (85)	IV	IV	V
15 Nov 1956	4.9‖	Hanford (85)	Santa Cruz (85)	IV	IV	IV
10 Oct 1958	4.5‖	Lemoore (77)	Greenfield (85)	III	V	IV
30 Jul 1961	4.7‖	San Simeon# (70)	Soledad (100)	V	III	?
27 Jun 1966	5.6/6.0§	Reedley (116)	Felton (195)	V	V–VI	V–VI
13 Sept 1975	4.9**	Armona (80)	Seaside (150)	IV	IV	V

*Extent of felt area from Parkfield, based on USE data.

†Intensities at San Luis Obispo, Paso Robles, and Coalinga, interpreted from USE.

‡M_L redetermined by Meagher *et al.* (personal comm., 1991) from Caltech data cards, applying Richter's (1958) station corrections.

§The mean of Berkeley and Caltech M_L's for both events is 5.6 Bakun and Wentworth (1997) lists M_s (or M_w) 6.0 for both.

‖M_L redetermined by K. Meagher *et al.* (personal comm., 1991) from both Caltech and Berkeley data cards, applying Richter's (1958) station corrections.

#The 1961 event was reported only to 40 km eastward, suggesting incomplete reporting, so the westward extent was used.

**Mean of Berkeley and Caltech M_L's.

36.0° N and 121.0° W could have been due to mistakenly omitting the decimals from the coordinates in their catalog. This error was propagated by users of Bolt and Miller's (1975) catalog, such as Real *et al.* (1978), Goter (1988), and Poley (1988).

Coastal Zone Preinstrumental Earthquakes. Moving the 1932 epicenter from San Ardo to near Point Sur emphasizes the seismicity of the coastal zone. The strongest historical earthquake between Point Sur and Bryson occurred in 1903 (Fig. 3, Table 1) (*M* ~5.9). Just before midnight it awoke most people (MMI V) from Hollister to Cambria (145 km) and sent many people running outdoors at Salinas (~65 km from epicenter).

The strongest historical earthquake between Bryson and San Luis Obispo occurred in 1906 (Fig. 3, Table 1) (*M* ~5.5). It cracked the Point Piedras Blancas lighthouse and cracked plaster at San Luis Obispo City Hall. It was felt as far away as Santa Maria, 110 km southeast of Point Piedras Blancas. Coordinates of the 1903 and 1906 epicenters are listed by Toppozada *et al.* (2000).

San Joaquin Valley (SJV) Border Earthquakes. Three *M* 5.5 and larger earthquakes occurred north of Parkfield and Coalinga in 1905, 1926, and 1927 (Fig. 3, Table 1), and their epicenters are listed by Toppozada *et al.* (2000). Of these, the 1926 earthquake has the greatest density of felt intensity reports, as shown on the isoseismal map in Figure 6. This isoseismal map is compared to that of the *M* 6.5 earthquake of 11 April 1885 to determine the relative location of the 1926 and 1885 epicenters.

Parkfield–Bitterwater Earthquakes and Occurrence Rate. The San Andreas fault near the Parkfield transition (Fig. 3) between the creeping segment to the northwest and the locked segment to the southeast was predicted to have a *M* ~6 event before 1993 (Bakun and McEvilly, 1984; Bakun and Lindh, 1985). This was based on the quasi-regular occurrences of *M* ~6 earthquakes in 1857, 1881, 1901, 1922, 1934, and 1966. In the present study we have identified additional *M* ~5.0–6.0 Parkfield events, including foreshocks and aftershocks of the 1881, 1901, and 1922 earthquakes. We also found that the 1901 and 1922 earthquake sequences were more extensive than the 1934 and 1966 sequences.

After 1900, the central creeping segment of the San Andreas fault between Parkfield and San Juan Bautista (Fig. 3) has been practically devoid of $M \geq 5.5$ earthquakes (Real *et al.*, 1978; Goter *et al.*, 1996). However, we found that before 1900, $M \geq 5.5$ activity was not confined to Parkfield but extended ~70 km northwestward to the Bitterwater area (Fig. 3). This Parkfield–Bitterwater region brackets the end zone of the great 1857 earthquake rupture and had foreshocks and aftershocks of that event in the Bitterwater vicinity (Sieh, 1978a,b; Meltzner and Wald, 1999). Figure 3, and the time–distance plot in Figure 7, show that the ~75-km region of the San Andreas fault between Bitterwater and San Juan Bautista has had few $M \geq 5.5$ events since ~1800. These two figures show no spatial separation in the seismicity between Parkfield and Bitterwater, and we herein consider this ~70-km seismic zone as a whole.

We compared the felt effects of pre-1932 events to those of instrumentally determined earthquakes in the San Andreas fault zone to determine relative epicenter locations between Parkfield and Bitterwater (Figs. 4, 5).

Earthquakes near Parkfield, such as 1908 and 1966, were felt at equal strength at Salinas and Bakersfield (Figs. 4, 11). Earthquakes near Bitterwater, such as 1882 and 1885, are felt more strongly at Salinas than in the Bakersfield–Visalia region (Figs. 8, 9).

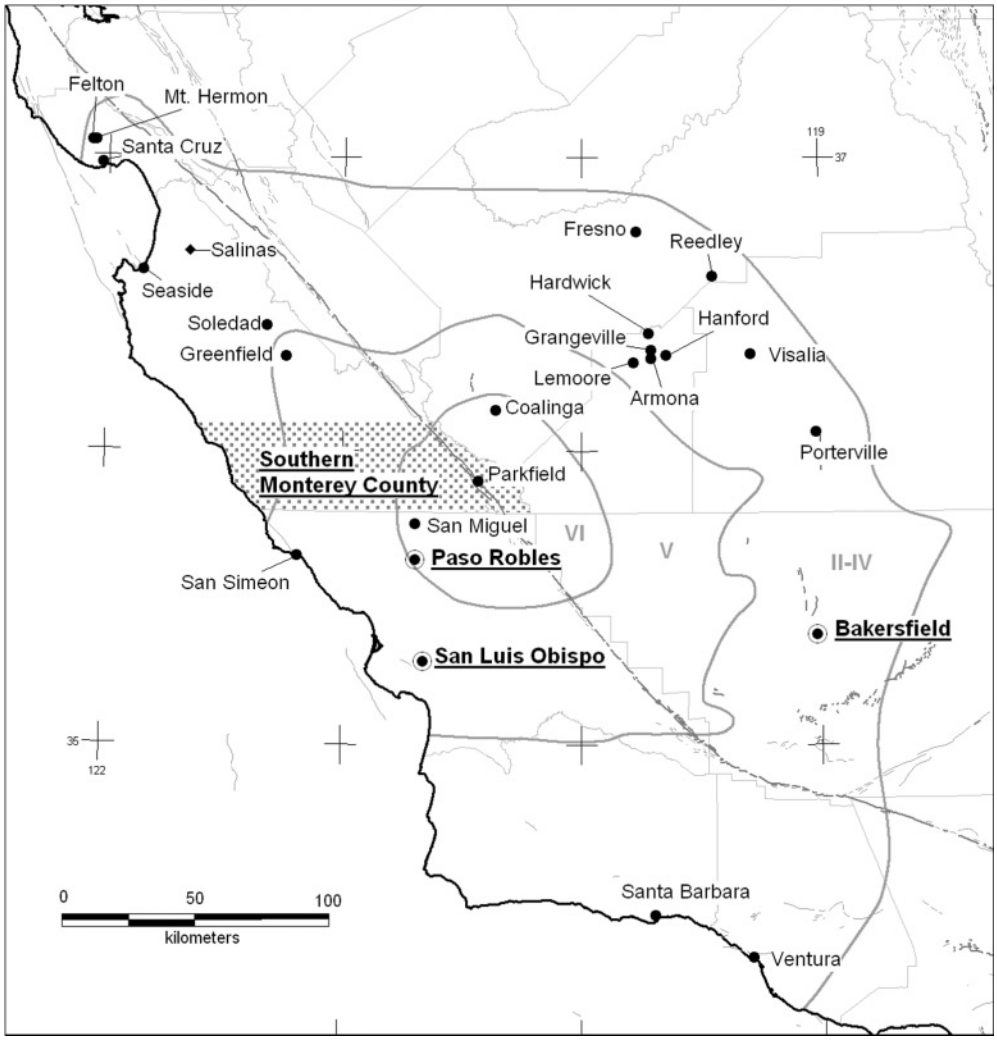

Figure 4. Intensity contour map for the 1966 Parkfield earthquake. Labeled towns apply to the earthquakes listed in Table 1. The 1877 event was felt in southern Monterey County, Paso Robles, San Luis Obispo, and Bakersfield, which are underlined.

The Parkfield–Bitterwater seismic zone was more active near Bitterwater from the 1850s to the 1880s and between Lonoak and Parkfield after the 1880s. Figures 3 and 7 show this apparent southward migration of epicenters with time, between Bitterwater and Parkfield. The rate of seismic moment released in this zone has diminished with time since the great 1857 earthquake (Fig. 10). This might reflect the decay with time of the stress loading due to the maximum 1857 fault displacements of ~9 m in the Carrizo Plain ~80 km southeast of Parkfield (Sieh, 1978a) and could explain why the predicted earthquake has not yet occurred. Ben-Zion and others (1993) modeled a decrease in stress near the terminus of the 1857 rupture, similar to our observed decrease in earthquake rate, and indicated that it could delay the predicted Parkfield earthquake from ~1988 to ~1995. Bakun (2000) suggested that the post-1906 quiescence in the San Francisco Bay area extended southward to the creeping zone between San Juan Bautista and Parkfield. However, the creeping zone quiescence started after the 1885 earthquake of M 6.5, 21 years before the 1906 earthquake.

Next we describe the $M \geq 5.5$ events in the integrated Parkfield–Bitterwater zone.

2 September 1853. The *San Francisco Daily Alta* of 19 September 1853 and the *Placerville Herald* of 24 September 1853, each crediting *The Stockton Journal* as the source, published this item suggesting that the San Andreas fault was recognized in 1853:

> Earthquakes of sufficient violence to frighten cattle, and to create some degree of apprehension among creatures in a higher sphere of animal economy, occurred on the evening of the 2d inst. in the district extending from the San Joaquin to the Salinas, through the Gavilian range, and between the 36th and 37th degrees of north latitude. The motions of the earth were from east to west. Our informant was engaged at the time in tracing the fissure made by previous convulsions in the same region. These are found to extend through a distance of two hundred and twenty-five miles from north to south, and not to vary a half point from the general course".

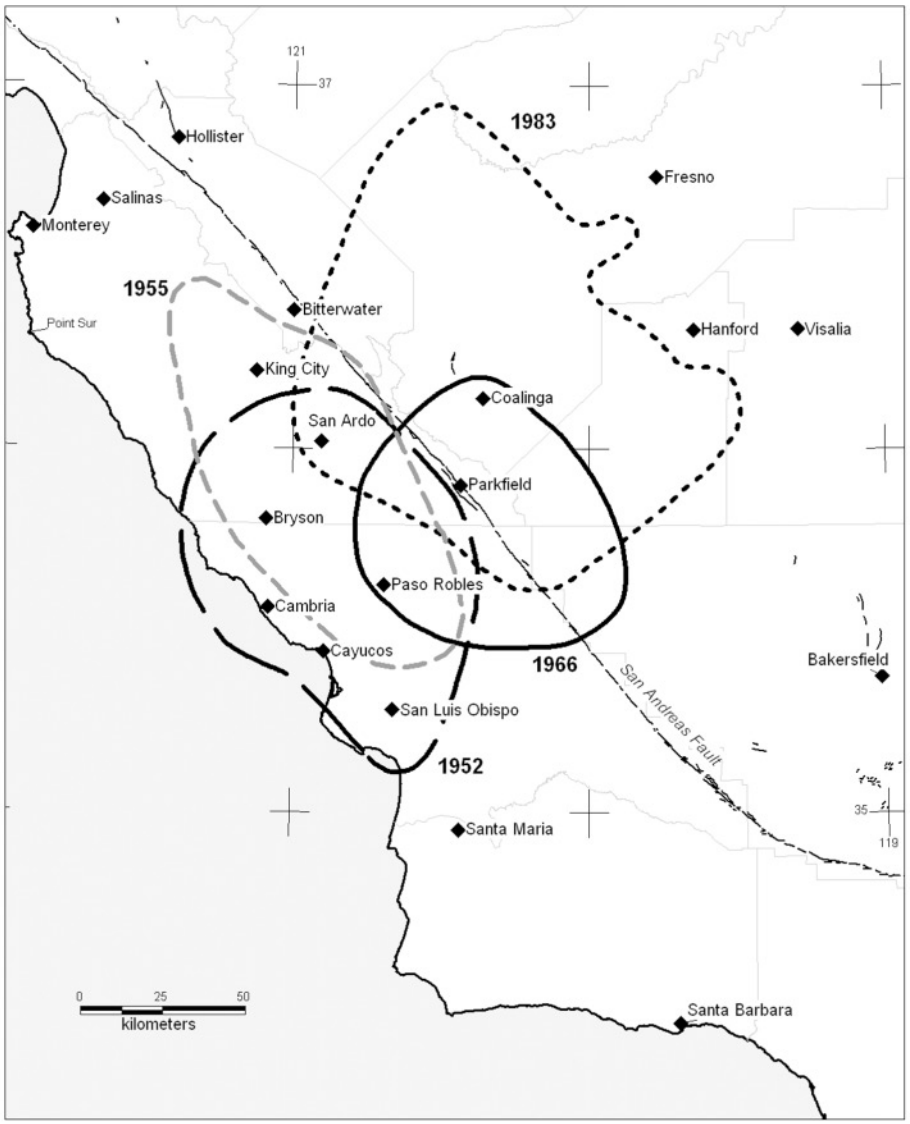

Figure 5. The isoseismal areas shaken at MMI VI or greater in the 1952 Bryson earthquake (*M* 6.0, large-dashed line), the 1966 Parkfield earthquake (*M* 6.0, solid line), and the 1983 Coalinga earthquake (*M* 6.5, dotted line). The area shaken at MMI V or greater for the *M* 5.2 event that occurred near San Ardo in 1955 is also shown (gray dashed).

This article also appeared in the 17 September issue of the *San Joaquin Republican* (Stockton). We have not found copies of *The Stockton Journal* for September 1853 but found a variation of the above item in the *Sacramento Daily Union* of 15 September 1853:

> "Earthquake—The Times and Transcript [San Francisco] learns from a gentleman who has just returned from a tour through the Southern country, that a smart shock of an earthquake was felt in the San Juan and Salinas Vallies [sic] on the 2d. It was so violent that cattle were very much frightened and bellowed piteously."

We assume that San Juan is a mistake for San Joaquin, which is mentioned in the above newspaper reports, because no San Juan Valley is known "in the district extending [from the San J . . .] to the Salinas, through the Gavilian range."

The indication that the "informant was engaged at the time in tracing the fissure . . . through a distance of two hundred and twenty-five miles" suggests that he was involved in a regional or reconnaissance survey in the Coast Range. He noted the linearity and geographical extent of the San Andreas fault, or "fissure," indicating knowledge of geology and geomorphology. When the earthquake occurred, he possibly noted fissures in the strongly shaken San Andreas fault zone or effects, such as Matthews (1869–1900) noted in Bitterwater in the 1882 earthquake "clouds of dust

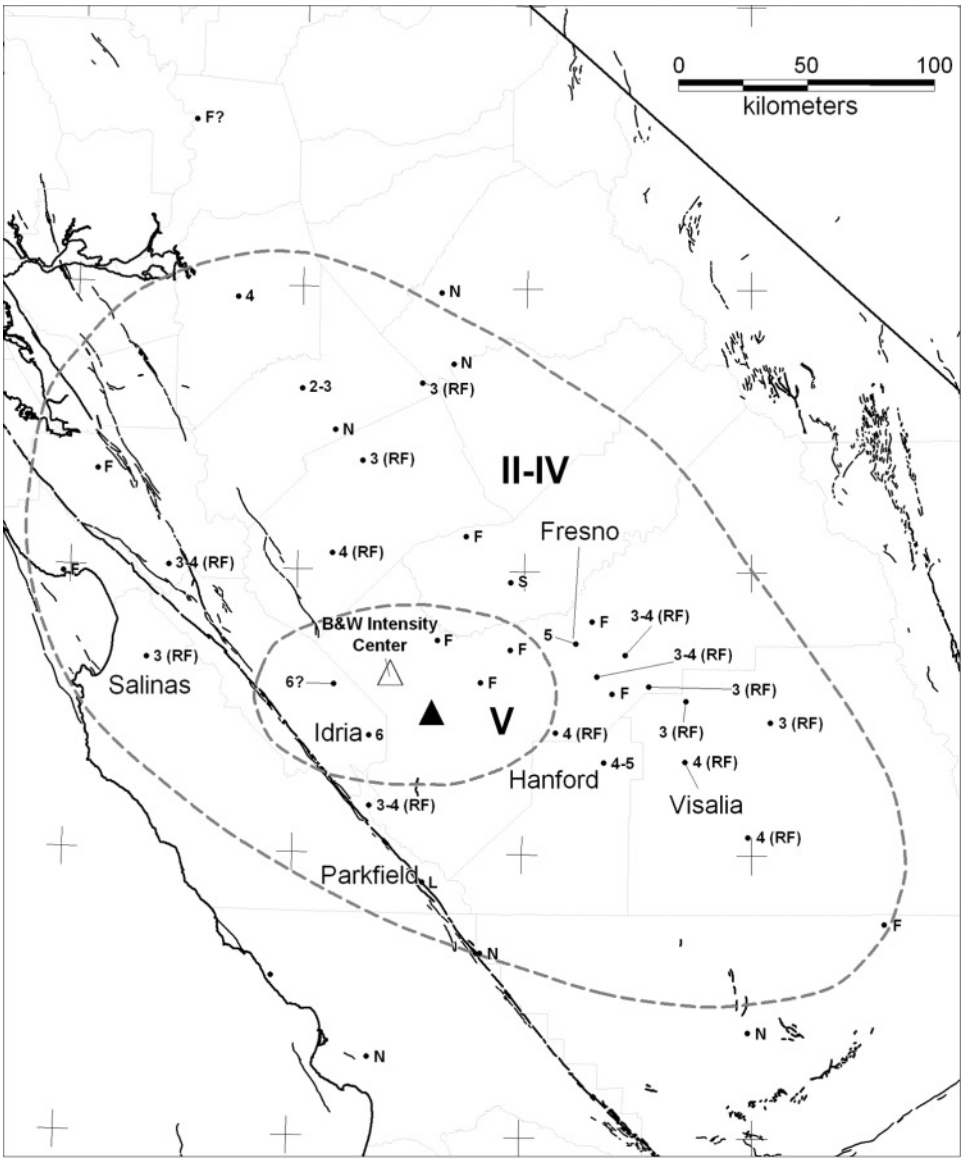

Figure 6. 1926 July 25 isoseismal map. The unfilled triangle represents the intensity center derived from using Bakun and Wentworth's (1997) method of location and magnitude determination. Their method assigns a M 5.4 $\pm$ 0.1 at the intensity center. F, felt; N, reported, not felt; S, severe; L, light; H, heavy; RF, Rossi–Forel intensity.

which rolled up from the bluffs . . . caused by rock shaken loose and precipitated down the steep declivities." The informant concluded that the 225-mile (~360 km) fault fissure was related to previous convulsions, or earthquakes. This length approximates the straight San Andreas fault segment from the San Francisco Peninsula to the Carrizo Plain. In the latter, the San Andreas fault is strikingly linear in the Temblor Range, as shown in the frontispiece photograph of Wallace (1990). *Temblor* is Spanish for earthquake and suggests that earthquakes were possibly noted in the San Andreas fault region in Hispanic California before the 1849 Gold Rush, but we have no evidence of that. The informant apparently related the earthquake to the fault, long before faulting was generally recognized as causing earthquakes, after the 1906 San Francisco event (Reid, 1910; Jennings, 1985).

We checked surveying records of the Bureau of Land Management in Sacramento for the central Coast Range for 1853 for mentions of earthquakes or earthquake features. We found none in the records searched. It is difficult to determine the completeness of the records because of ambiguity in the dates. Actual dates of the field work were not regularly recorded. Sometimes there is only a date of the start of field work, start of work contract, or end of field work. These dates could differ by weeks from the actual days in the field. We found that 1853 work was done in the western San Joaquin valley, ~25 km east of the San Andreas fault. Surveyors who worked in this area in 1853 were J. D. Jenkins,

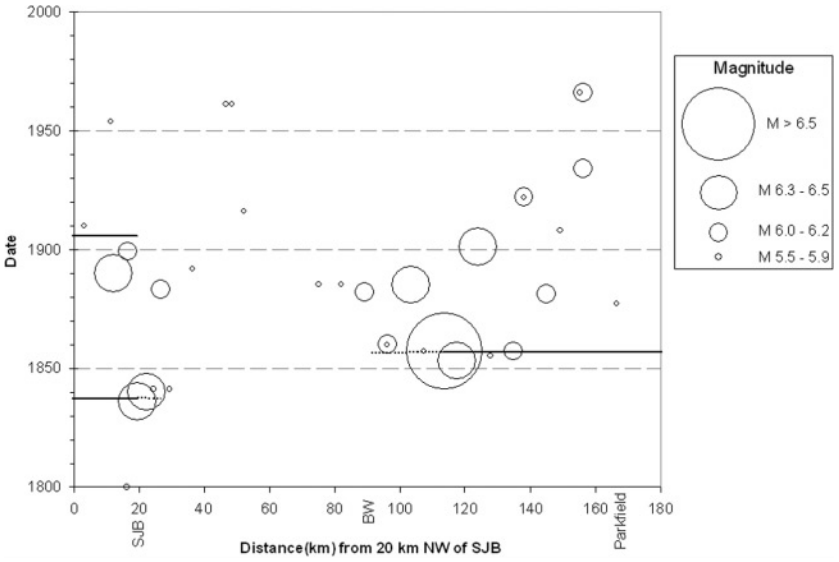

Figure 7. Time distance plot for the Parkfield to San Juan Bautista region. The straight lines represent the 1838, 1857, and 1906 fault ruptures. SJB, San Juan Bautista; BW, Bitterwater.

R. E. K. Whiting, A. W. Von Schmidt, and Gibbes (no first initial). A. W. Von Schmidt also surveyed Rancho de San Antonio (44,689 acres) in Oakland in 1852, according to his notes in the Bancroft Library, Berkeley, California. Gibbes surveyed townships southeast of Cholame Valley in 1854 and 1855 (Runnerstrom *et al.*, 2002). Further southeast near Wallace Creek, Grant and Donnellan (1994) compared 1855 surveys of townships to 1990s surveys to investigate San Andreas fault mechanics. We searched the *Reports of Exploration and Surveys to Ascertain the Most Practicable and Economical Route for a Railroad from the Mississippi River to the Pacific Ocean, made under the direction of the Secretary of War, 1853–4,* (1855–1869) performed in the 1850s to determine possible railroad routes in the west. For the region of the 1853 earthquake, we also checked possible sources of information (usually about surveyors) mentioned in Goetzmann's (1959) book on army exploraiton in the west in the 1800s. No mention of any Coast Range earthquakes in 1853 or of an extensive linear feature or faulting was found.

The distance from the San Andreas fault between the thirty-sixth and thirty-seventh parallels to the San Joaquin River Valley is about 70 km. We assume this approximates the radius of the area shaken at MMI V–VI, sufficient to significantly frighten cattle and people outdoors. Using formulas relating MMI V and VI areas to M (Toppozada and Branum, 2002), we estimate a magnitude $M \sim 6 \pm 0.5$. In 1853 there were no newspapers published between Santa Clara and Los Angeles. We have found no report of this event in the Santa Clara paper, suggesting that if it was felt there, the intensity was less than V.

Similar earthquakes have occurred in this region of the San Andreas fault and are described below. An earthquake of $M \sim 6.0$ on 30 March 1882 and of $M \sim 6.5$ on 11 April 1885 were centered near Bitterwater and the southern end of the Gavilan Range. The former was felt at intensity ~III at Santa Clara, and the latter at intensity V. We conclude that the $M \sim 6$ earthquake of 1853 was probably centered south of both these events, between Parkfield and Lonoak (Fig. 3), because it was not mentioned in the Santa Clara newspaper. Thus it could be considered an early preshock of the great 1857 earthquake that nucleated in this vicinity (Fig. 3).

14 January 1855, $M \sim 5.5$. This event was only reported from San Miguel (VI?), San Benito (IV?), and San Luis Obispo (III?). Comparing the felt intensities at these three towns to those in the 1966 Parkfield earthquake suggests a very poorly defined 1855 epicenter in the region roughly 30 km northwest of Parkfield. If so, this event also may have been a preshock of the 1857 earthquake.

The great 9 January 1857 earthquake (M 7.9) resulted from extensive San Andreas faulting from southern Monterey County to San Bernardino County (Wood, 1955). Sieh (1978a) studied the fault displacements. The mainshock caused only one death, at Tejon Ranch 22 km north-northeast of Fort Tejon, due to the scarcity of buildings near the fault (Fig. 13). It cracked some houses in downtown Los Angeles, 60 km from the fault, and caused stronger damage at San Fernando, 40 km from the fault (Agnew and Sieh, 1978). Sieh (1978b) identified two foreshocks located north of Parkfield near Lonoak at dawn and sunrise (Fig. 3), approximately 1 and 2 hr before the mainshock (Appendix B). Apparently, faulting propagated from this vicinity southeastward for ~350 km, past Fort Tejon to Cajon Pass in San Bernardino County (Fig. 13). Meltzner and Wald (1999) estimated $M \sim 6.1$ and $M \sim 5.6$ for the foreshocks and identified strong aftershocks of $M \sim 6$ in southern California 10 hr and 7 days later. Two later $M \geq 6$ possible aftershocks were identified: in 1858 near San Bernardino (Toppozada *et al.*, 1981; Meltzner and Wald, 1999) and in 1860 northwest

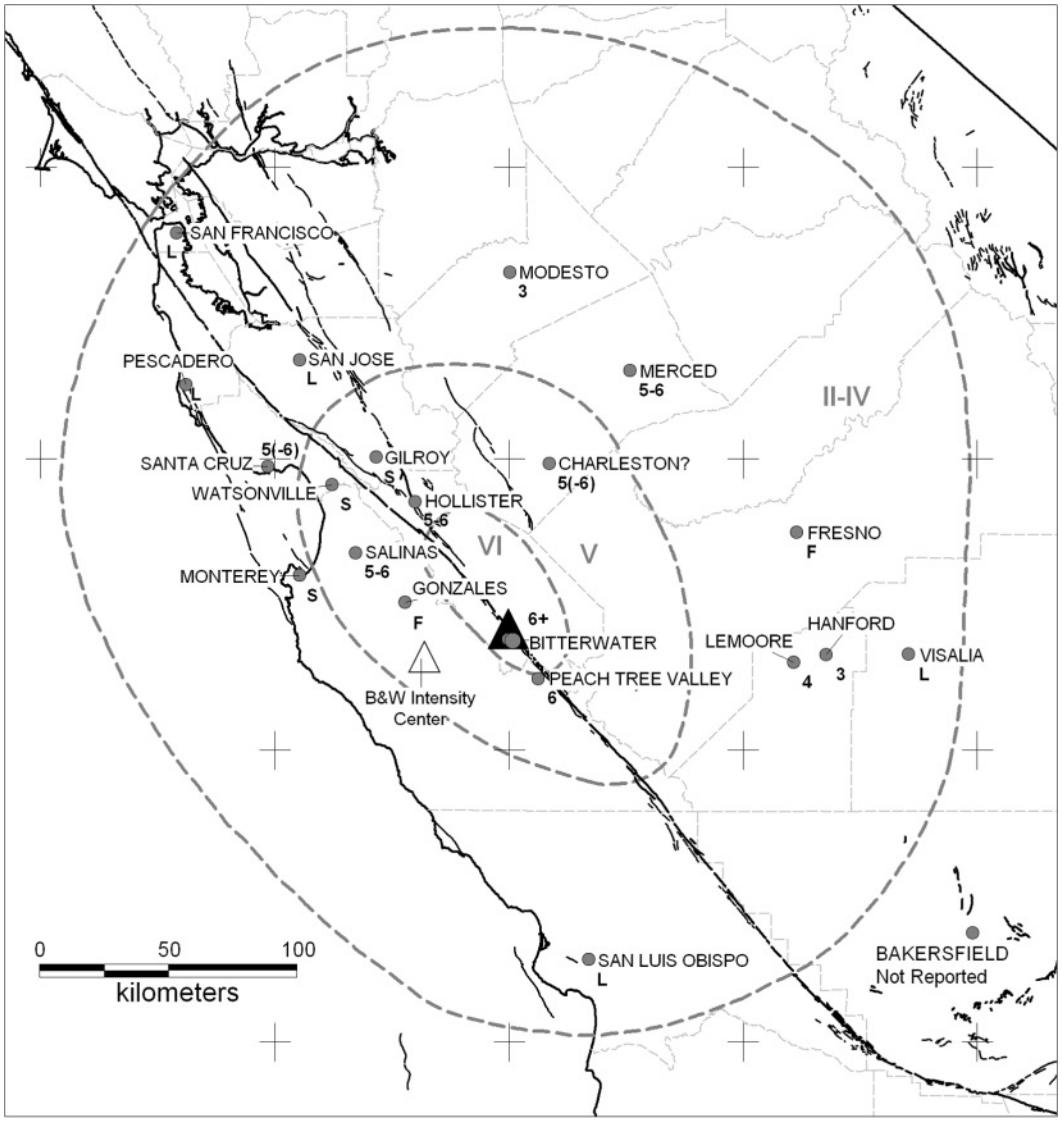

Figure 8. 6 March 1882 isoseismal map. The unfilled triangle represents the intensity center derived from using Bakun and Wentworth's (1997) method of location and magnitude determination. Their method assigns a M 6.0 ± 0.2 at the intensity center. F, felt; N, reported, not felt; S, severe; L, light; H, heavy; RF, Rossi-Forel intensity.

of Parkfield, in or near the creeping zone of the San Andreas fault (Fig. 3).

The 1860, M 6, aftershock according to our analysis was centered near the 1857 Lonoak rupture end. Meltzner and Wald (1999) also provided a location near Lonoak for this earthquake and an alternate location ~50 km southwest of there. Shaking was frightening at Monterey and Santa Cruz, distinct in all parts of San Francisco, where "it occasioned no alarm", and was also felt at Visalia, Fort Tejon, and San Bernardino (Appendix B) (Townley and Allen, 1939). About 10 hr later, an aftershock rattled dishes, "set lamps to ringing," and awakened sleepers at Monterey and Santa Cruz, suggesting M ~5.5. The occurrence 3 years after the 1857 earthquake of the 1860 aftershock near the Lonoak end of the 1857 rupture is similar to the occurrence near the probable San Juan Bautista end of the 1906 and 1838 ruptures of possible aftershocks in 1910, 1840, and 1841. Compared to the 1860 earthquake, the September 1853 event, described previously, was apparently further to the southeast because it was not reported to have been felt in San Francisco or Santa Clara.

30 May 1877, 2:30 a.m. (PST), M ~5.5. This newly discovered event was the first identified in the Parkfield vicinity after the 1857 Fort Tejon earthquake and its foreshocks and aftershocks. The only previous knowledge of an event on this date was an entry in Townley and Allen's (1939) catalog of a felt report from Paso Robles. Our research found the following:

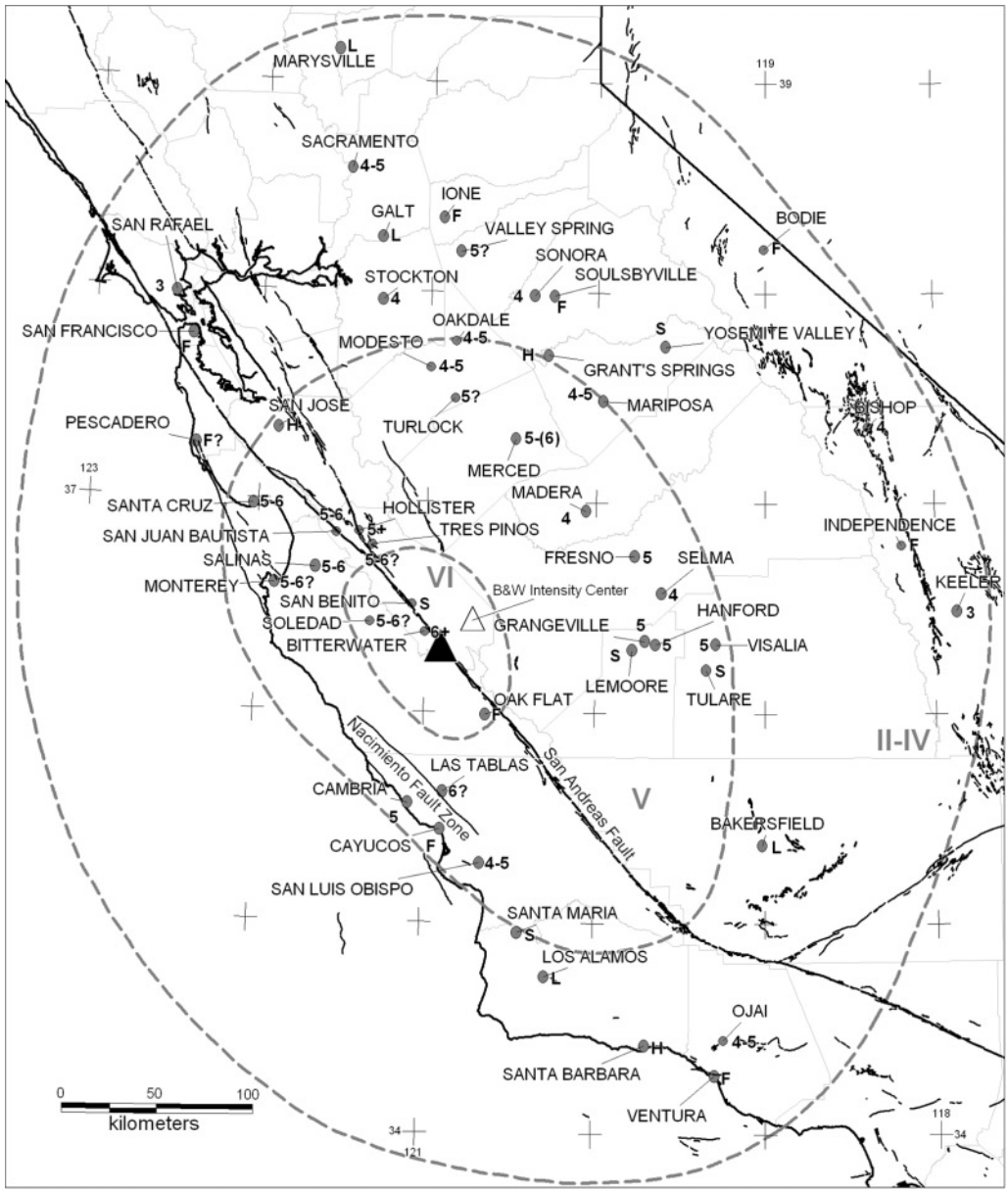

Figure 9. 11 April 1885 isoseismal map. The unfilled triangle represents the intensity center derived from using Bakun and Wentworth's (1997) method of location and magnitude determination. Their method assigns a M 6.4 $\pm$ 0.1 at the intensity center. F, felt; N, reported, not felt; S, severe; L, light; H, heavy; RF, Rossi-Forel intensity.

1. This early morning event woke up some sleepers at San Luis Obispo and was described as "The severest shock of earthquake that has been felt in this section for many years" (*San Luis Obispo Tribune*, 2 June 1877). This suggests an intensity of ~V because the 1872 Owens Valley earthquake was felt with MMI V at San Luis Obispo.
2. At Paso Robles it was "the severest in years . . . besides rolling people around in bed no damage" (*Sacramento Bee*, 30 May 1877), indicating an intensity of ~V or perhaps VI.
3. In the "southern portion of Monterey county . . . the heaviest shock of earthquake for many years past occurred there on the night of 30th ult." (*Salinas City Index*, 21 June 1877). This suggests intensity V or greater, considering that 5 years earlier the 1872 Owens Valley earthquake generated intensity V effects in Salinas and San Luis Obispo.
4. It was also reported at Bakersfield as "A slight shock of earthquake was felt at this place yesterday, about 2 o'clock in the morning." (*Southern Californian and Kern County Weekly Courier*, Bakersfield, 31 May 1877). Assuming that a few light sleepers woke up at 2:30 a.m., intensity of ~IV is indicated.

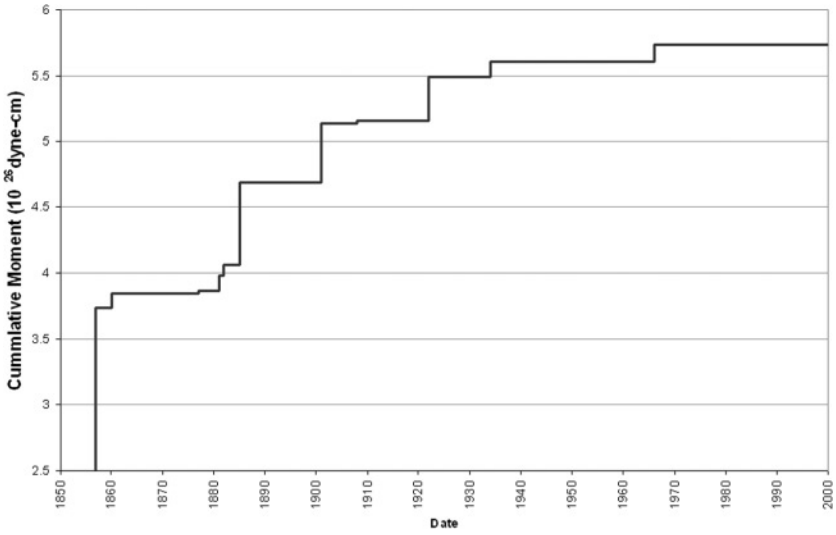

Figure 10. Cumulative moment released in the Parkfield–Bitterwater zone of the San Andreas fault from 1857 to 2001.

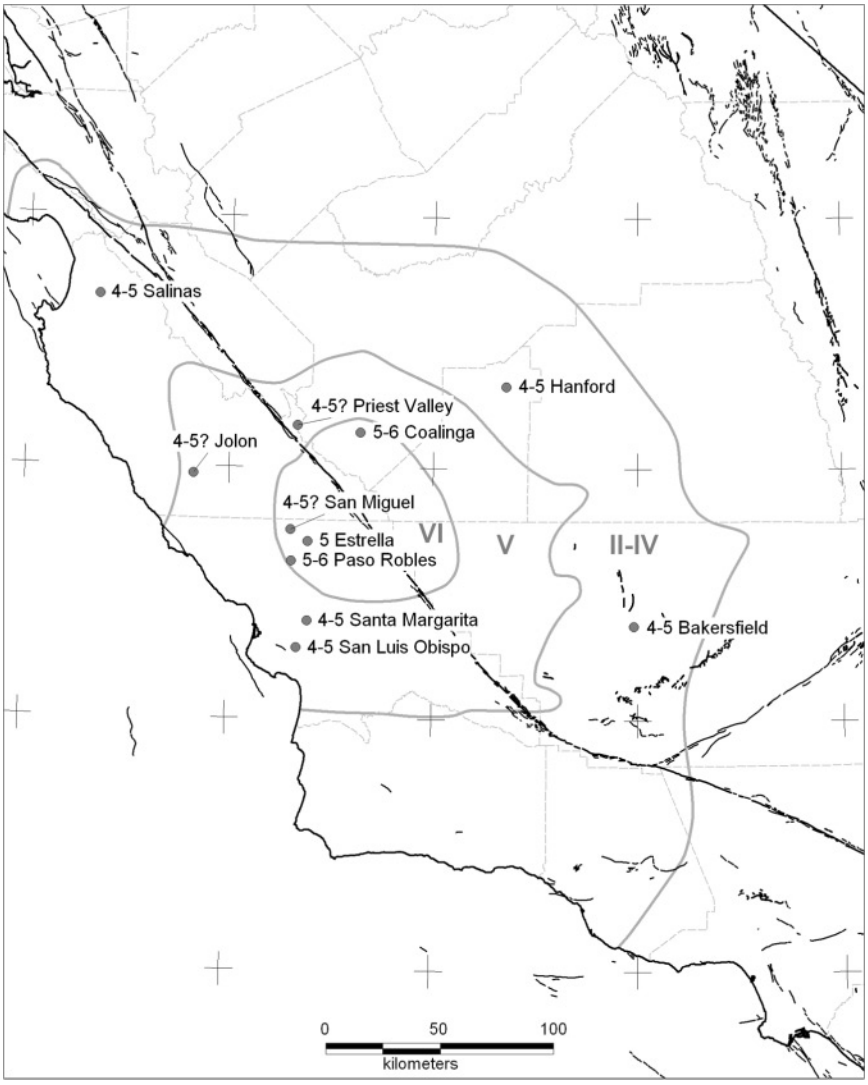

Figure 11. 1908 reported intensities, superposed on 1966 isoseismal lines.

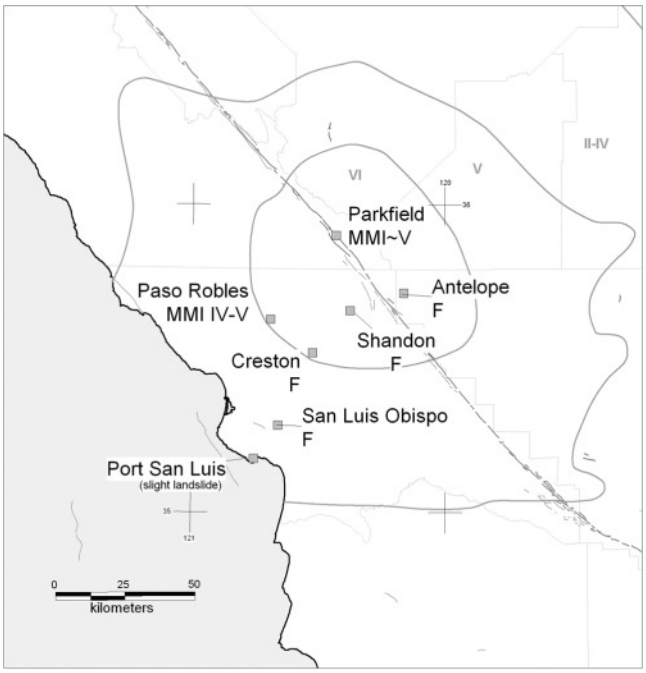

Figure 12. 1915 reported intensities, superposed on 1966 isoseismal lines. F, felt.

Figure 4 shows the few places (underlined) that reported the 1877 event superposed on contours of the 1966 Parkfield event.

More information about the 1877 event location and magnitude can be found in Appendix A.

Evidence for Incompleteness of Pre-1881 Record of M ~6.0 Events

Discovery of the 1877 earthquake illustrates the poor documentation of M ~5.5–6.0 earthquakes in central California. In 1877, the population of Monterey County was about 10,000 and was concentrated in the northern quarter of the county at Salinas and Monterey. We found descriptions of the 1877 earthquake effects at Paso Robles, San Luis Obispo, and Bakersfield in newspapers of 30 May to 2 June. The Monterey County newspapers did not even mention the earthquake until 21 June, when this surprising report appeared in the *Salinas City Index*, Monterey County: The heaviest shock of earthquake experienced in the southern portion of Monterey County for many years past occurred there on the night of the 30th [May]. Twelve days afterwards, in the mountain range that rises in the Colorado desert, a volcano broke forth accompanied by earthquake shocks. This phenomena is worthy of scientific investigation.

This suggests that if the earthquakes and supposed eruption in the Colorado Desert on 11 June near the California–Arizona–Mexico border, according to Townley and Allen (1939), had not piqued the writer's interest, he may not have reported that the 30 May event was the heaviest shock experienced in southern Monterey County for many years. Without this information we could not determine that the 1877 event was located in southern Monterey County (see Appendix A). This suggests that occurrences of M ~5.5–6.0 earthquakes in the Parkfield vicinity were not clearly documented or known until after 1877. The 1881 earthquake and its newly identified damaging aftershock described below also indicate that occurrences of M ~5.5–6.0 events were not clearly documented or known until after 1881.

1 February 1881, 4:11 p.m. (PST), M 6.0. This mainshock was discovered by chance and identified by Toppozada *et al.* (1981) while researching other California earthquakes. Without the 1881 event, the Parkfield earthquake prediction, which is based on six events occurring about 22 years apart, would not have been possible because there would have been no event between 1857 and 1901. The only previous knowledge of any event on 1 February 1881 had been an entry in Townley and Allen's (1939) catalog of a single felt report from Visalia (113 km east-northeast of Parkfield). The discovery of a letter to the editor of the *Salinas City Index* describing earthquake damage at Parkfield led Toppozada and others (1981) to search for other descriptions of this event in the newspapers of central California. They found that it was felt at seven towns, from as far south as San Luis Obispo to as far north as Santa Cruz, and determined that it was comparable to the 1966 Parkfield earthquake (Table 3). More recently, we have discovered a May 1881 aftershock that damaged the Parkfield area. More Information about the 1881 event and its damaging aftershock is in Appendix A.

6 March 1882, 1:45 p.m. (PST), M 6.0. Toppozada and Branum (2002) estimated M ~6 for this earthquake. Toppozada *et al.* (1981) estimated a location near Hollister but had no intensity reports in the vast area between Salinas, Hanford, and San Luis Obispo. The subsequent discovery of Matthews' diary, written at Bitterwater, filled a critical point in this area (Fig. 8). At Bitterwater, Matthews (1869–1900) was "startled by loud subterranean thunder accompanied by a severe earthquake lasting from ten to fifteen seconds the house rolled and pitched as if it were bound to tumble down the walls seemed to sway from west to east fully a foot and the ground seemed to volt up and down fully that much. We got out of the old house tolerably quick Rebecca with the baby in her arms beating us all into the yard by several seconds woman like though terribly frightened [sic]". In the entry of 10 March 1882 he wrote "our clock won't run since the earthquake," suggesting that the earthquake 4 days earlier broke the clock.

Matthews' description of this event (intensity at least VI) indicates that the epicenter was closer to Bitterwater than to Hollister, where clocks stopped and some crockery broke, or Salinas where dishes rattled and a few panes of glass broke in a store (both intensity V or possibly VI). The 1882 event was not located southeast of Bitterwater because Matthews indicated it was not "as heavy in Peachtree [13 km southeast of Bitterwater] as here." Consequently we moved the epicenter from near Hollister to near Bitterwater. Com-

Table 3
Comparison of 1881 and 1966 Earthquakes

Town*	1966 Intensity and Felt Effects	1881 Intensity and Felt Effects
Santa Cruz	III	"Sharp shock", "quite a shock of earthquake", IV or V.
Hollister	IV	"Heavy and prolonged . . . fully 20 seconds", IV or V.
Salinas	IV	"heavy earthquake shock . . . no damage", IV or V.
Lemoore	IV	"Three slight shocks of earthquake . . . no buildings fell," V?
Visalia	IV	"considerable . . . earthquake," V?
Parkfield (Imusdale in 1881)	Chimneys cracked, a few fell, VII	Knocked down chimneys and adobe structures, VIII.
San Luis Obispo	Felt by many. Plaster cracks, V	"A shock of earthquake was felt in this city" (no indication of intensity).

*Listed from north to south.

pared to the *M* 5.5 event of 1961, located 25 km southeast of Hollister (Fig. 3), the 1882 event was felt southward to San Luis Obispo and eastward to Visalia (Fig. 8), whereas the 1961 event was not felt at either place.

Figure 8 shows two assessments of the epicenter from the intensity data. We found that the method of Bakun and Wentworth (1997) estimates an intensity center to the west of the San Andreas fault where intensity information is lacking and *M* 6.1. Our epicenter is more consistent with the fact that intensities to the west of the San Andreas fault are no higher than the intensities in the San Joaquin Valley. Also, our Bitterwater epicenter borders the root mean square [M_i] 50% confidence contour of the Bakun and Wentworth (1997) location method, indicating that the difference in confidence between our epicenter and their intensity center is small.

11 April 1885, M 6.5. The widely felt effects of this strong earthquake are illustrated in Figure 9. A shaking duration of ~20 sec at San Luis Obispo, Hanford, Merced, San Jose, and San Francisco is consistent with the large *M* ~6.5. Townley and Allen (1939) suggested that the probable epicenter was in the general Lonoak–Priest Valley vicinity of the San Andreas fault. But Richter (1958) placed the epicenter in the vicinity of the Nacimiento fault based on the damage at Las Tablas. However, we found that the Las Tablas damage was only to one stone and possibly one brick chimney (*San Luis Obispo Tribune*, 24 April 1885). Also, the intensities within ~30 km of Las Tablas at Cambria, Cayucos, and San Luis Obispo were all V or less (Fig. 9). Based on extensive research of California newspapers and Matthews' excellent diary from Bitterwater, we conclude that the epicenter was most probably on the San Andreas fault, remarkably near Townley and Allen's (1939) estimate.

At Bitterwater "it lasted half a minuit [sic] there was a double shake vibration from SE to NW I did not know but the old brick house would tumble. It was the hardest shock we have ever felt here except the shake of March 6th 1882 Rebecca was so frightened she would not sleep in the house last night" (Matthews, 1869–1900). This was the highest intensity reported for this earthquake (other than Las Tablas) and suggests an epicenter near Bitterwater. A probable aftershock of *M* ~5.0 was felt at 3 a.m. (PST), 7 hr after the 1885 event, ~100 km to the east at Hanford. Possible foreshocks occurred on 31 March 1885 and 2 April 1885 near Bitterwater (Fig. 3).

The 1882 Bitterwater earthquake was of *M* 6.0 and was felt at Bitterwater at the same intensity as the 1885 event of *M* 6.5. This suggests that the 1882 epicenter was closer to Bitterwater than the 1885 epicenter. The 1885 event was felt more strongly at Bitterwater than at Soledad ~30 km to the west-northwest, suggesting it was centered somewhat southeast of Bitterwater (Fig. 10).

In addition to the isoseismal information, Figure 9 also shows an assessment of the intensity center from the intensity data corresponding to *M* 6.4 (± 0.1) using the method of Bakun and Wentworth (1997). But we found that the epicenter was probably not east of the San Andreas fault. Figure 6 shows the isoseismal map of the 1926 event that we located east of the San Andreas fault near the highest reported intensity and near the intensity center using the method of Bakun and Wentworth (1997). The 1926 map suggests that our 1885 epicenter on the San Andreas fault better fits the data in Figure 9 than the intensity center to the east. The 1885 earthquake was felt relatively more strongly at Salinas than at Fresno. Thus it was west of the 1926 SJV border earthquake, which was stronger at Fresno than at Salinas (Figs. 3, 6).

2 March 1901, 11:45 p.m. (PST), M 6.4. Table 4 and intensity data from Toppozada and Parke (1982) indicate that this event was significantly stronger than the 1966 Parkfield

earthquake of M 6.0. Newly identified aftershocks of M 5–5.5 also indicate that the 1901 sequence was more extensive and energetic than the 1966 sequence. This is despite the high probability that not all $M \geq 5$ aftershocks have been identified because of the sparse population in central California in 1901. Ellsworth (1990) indicated that the 1901 and 1922 Parkfield earthquakes were of similar magnitude, M_s 6.4 and 6.3, respectively, which is consistent with the intensity observations.

Information about an immediate strong aftershock, a triggered sea wave, surface faulting, and the extensive 1901 aftershock sequence can be found in Appendix A.

27 April 1908, 2:50 a.m. (PST), M ~5.8. This significant earthquake was not previously identified as a $M > 5$ Parkfield event. Townley and Allen's (1939) entry states "About 2:50 a.m. Jolon and Priest Valley, Monterey Co.; San Miguel, Paso Robles, San Luis Obispo, and Santa Margarita, San Luis Obispo Co." We discovered that this early morning event was not only felt west of the San Andreas fault but was also strongly felt in the SJV to the east, suggesting a source on the San Andreas fault. The reported intensities of the 1908 earthquake are shown in Figure 11, superposed on the isoseismals of the 1966 event. Information on the 1908 earthquake felt intensities, location, and magnitude can be found in Appendix A.

8 September 1915, 4:45 a.m. (PST), M ~5. According to Townley and Allen (1939), this event was felt at Antelope (about 35 km southeast of Parkfield), Shandon, Creston, and San Luis Obispo (duration 10 sec); at Port San Luis south of San Luis Obispo a slight landslide occurred, and at Paso Robles the intensity was V Rossi-Forel (RF) (MMI IV–V). A newspaper report from Parkfield indicated it was "quite an earthquake here . . . no damage done" (*Salinas Daily Index*, 14 September), suggesting intensity ~V (Fig. 12). The Bulletin of the Seismographic Stations, U.C. Berkeley (BSSUC), lists this earthquake as recorded on the horizontal component Wiechert seismograph at station MHC (magnification 80, period 8.0 sec) but does not provide an amplitude.

The area shaken at intensity IV–V or greater extended from Port San Luis northeastward for 80 km to Antelope, north-northeastward for 85 km to Parkfield, and northward for 50 km to Paso Robles (~4500 km^2). This indicates M ~5, which is a minimum value because we have no reports at this early morning hour from the sparsely populated region east of Parkfield. This event was reported over roughly the same area as the 16 March 1992 aftershock of M 4.8–5.3. A location near or within 15 km south of Parkfield fits the observations.

10 March 1922, 3:21 a.m. (PST), M 6.3. The mainshock was listed as M 6.5 by Gutenberg and Richter (1949) and by Richter (1958) and M 6.3 by Ellsworth (1990). The isoseismal map (Toppozada and Parke, 1982) and Table 5 support a magnitude larger than the 1966 and 1934 earthquakes. A previously unknown foreshock was widely felt 30–35 minutes before the mainshock in the region around Hanford, about 80 km northeast of Parkfield. We identified numerous aftershocks of $M > 5$ that indicate that the 1922 sequence was more extensive and energetic than the 1966 sequence. Surface fault displacements in 1922 were also apparently greater than in 1966. Information about the 1922 foreshock, mainshock, probable faulting, and extensive aftershock sequence can be found in Appendix A.

26 November 1929, 12:04 a.m. (PST), M ~5.3. Bolt and Miller (1975) located this event at Bitterwater based on felt reports but did not assign a magnitude. Foreshocks and aftershocks were also reported from Bitterwater according to USE. Toppozada *et al.* (1978) assigned M 4.5 to the mainshock based solely on the intensity data from USE. When we added intensity data from BSSUC we found that the event was felt over an area of about 30,000 km^2, from Santa Cruz to Santa Margarita (215 km) and from Mendota to the coast (135 km). This indicates M ~5.3. The 1929 event was recorded instrumentally at stations BRK (distance 200 km, duration 88 sec) and MHC (distance 120 km, duration 277 sec), but no amplitudes are listed in BSSUC.

1934 and 1966 Earthquake Sequences. The 1966 and 1934 mainshocks were both of M ~6.0 and also had similar intensity effects near Parkfield (Table 2). In both sequences the mainshock was preceded by a M_L ~5 foreshock 17 min earlier. The 1934 mainshock was recorded more strongly to the south (M_L 6.0, CIT) than to the north (M_L 5.2, BRK). Bakun and McEvilly (1979) noted that the 1966 and 1934 earthquake sequences were remarkably similar.

There were four events of $M_L \geq 5$ in 1934, including two foreshocks, and three in 1966, including one foreshock. In addition to these events, there were eight $M_L > 4.0$ events during 5–14 June 1934 and only two during June–September 1966. This suggests that the 1934 earthquake sequence was somewhat more extensive than the 1966 sequence. Another difference between these sequences is that the maximum fault slip was located further northwest in 1934 than it was in 1966 (Segall and Du, 1993).

1812 Faulting and 8 and 21 December Earthquakes

The earliest major historical earthquake determined to be on the San Andreas fault occurred on 8 December 1812. It toppled the tall tower at San Juan Capistrano onto the church, killing 40 people at Mass. This earthquake was long thought to have originated near San Juan Capistrano. However, Jacoby *et al.* (1988) determined that it was probably associated with 1812 San Andreas fault rupture that damaged the root systems and major branches of trees near Wrightwood, as interpreted from tree ring data. They estimated a rupture length of ~170 km extending southeastward from Tejon Pass (Fig. 13) and noted that this length is consistent with the ~6-m offset associated with this event at Pallett Creek by Salyards *et al.* (1987). The 1812 rupture is

Table 4
Comparison of 1901 and 1966 Parkfield Earthquakes*

Location†	1966 (8:48 p.m.) Intensity‡	1901 (11:45 p.m.) Intensity
Modesto and towns within 80 km south thereof	Not felt	Quite a shock, no damage reported (*Evening News*, Modesto, 4 March 1901) The damage was slight (IV–V) (*Stockton Record*, 4 March 1901)
San Francisco	II	Set gas fixtures swinging (*San Francisco Examiner*, 3 March 1901) Quite heavy (III–IV) (Waterman diary)
San Jose and surrounding towns	Not felt	Several seconds, vibrations from north to south (III–IV) (*San Francisco Call*, 3 March 1901)
Santa Cruz	II–III	Bric-a-brac fell (V–VI) (*Santa Cruz Surf*, 7 March 1901)
Soquel	II–III	Many awakened (IV–V) (*Santa Cruz Surf*, 7 March 1901)
Echo Valley (15 km north of Salinas?)	III–IV	Chimneys demolished, crockery broken (VI–VII) (*Salinas Daily Index*, 8 March 1901)
Salinas	IV	One of the heaviest shocks felt for years (V–VI) (*Salinas Daily Index*, 3 March 1901) (Salinas felt intensity VI in 6 July 1899)
Pacific Grove	IV	Awoke sleepers and caused general alarm (V–VI) (*Los Angeles Herald*, 4 March 1901)
Monterey	IV	Cracked some walls (V–VI) (*Monterey Cypress*, 9 March 1901)
Visalia	IV	Strong enough to arouse people from sleep (IV–V) (*Stockton Independent*, 3 March 1901)
San Lucas	Felt by all, frightened few, house creaked moderately (IV–V)	Crockery thrown from shelves, stove thrown off platform (VI) (*Salinas Index*, 7 March 1901)
Bradley	in V zone	Several chimneys fell, many windows broken (VII) (*Salinas Daily Index*, 5 March 1901)
Parkfield	Several cracked and fallen chimneys (VII)	A great many chimneys fell and houses twisted (VIII) (*Salinas Index*, 7 March 1901)
Adelaida	Felt by all, hanging objects swung moderately, furniture rocked (IV–V)	Townley and Allen assigned intensity VII RF, which corresponds to VI MM
Creston	Small objects shifted, hanging objects swung moderately (IV–V)	Brick buildings were badly damaged (VI–VII) (*San Luis Obispo Weekly Breeze*, 8 March 1901)
Cayucos	IV	Violent, stopped clocks (V+) (San Luis Obispo Tribune, 8 March 1901)
Pozo	V	Cracked several adobe houses (VI) (*San Luis Obispo Semi-Weekly Breeze*, 15 March 1901)
San Luis Obispo	Plaster cracked, felt by many (V)	People run out, thought buildings would collapse (V–VI) (*San Luis Obispo Semi-Weekly Breeze*, 5 March 1901)
Ventura	IV	Quite severe at Mound, near Ventura (IV–V) (*Ventura Free Press*, 8 March 1901)

*The 1901 event was at least as strong as the 1966 event at the 25 towns that reported both. This table lists only the 19 towns that felt the 1901 event more strongly.
†Locations are listed from north to south.
‡1966 Intensities are interpreted from USE.

not well defined, and Fumal *et al.* (1993) suggested that it extended from near Pallett Creek to ~100 km to the southeast. However, we use the ~170-km rupture of Jacoby *et al.* (1988) to present the scenario that the two 1812 events occurring 13 days apart were possibly centered on two approximate halves of this rupture.

The MMI VII damaged zone in the 8 December earthquake included missions San Juan Capistrano, San Gabriel, San Fernando, and probably San Buenaventura (Ventura), all within 90 km of the San Andreas fault (Fig. 13). The latter two missions were also damaged on 21 December. Analysis of damage to these missions, as well as earthquake damage on 21 December to the missions in Santa Barbara County, is based on the original 1812 mission documents studied and quoted by Toppozada *et al.* (1981). Crafts's (1906) description of 1812 effects in San Bernardino Valley, quoted by Toppozada *et al.* (1981) as suggesting liquefaction, is now believed to be fictitious (Harley, 1988). Missions

Table 5
Comparison of 1922 and 1966 Parkfield Earthquakes*

Location†	1966 (8:48 p.m.) Intensity‡	1922 (3:21 a.m.) Intensity
San Jose and surrounding towns	Not felt	Felt (*Hanford Journal*, 11 March 1922)
Merced and towns within 40 km south thereof	Not felt	Felt for seconds, not sufficient to awaken sleepers (III) (*Merced Star*, 11 March 1922)
Salinas	IV	Awoke a large part of the population (IV–V) (*Salinas Daily Index*, 10 March 1922)
Fresno	IV	Awoke people (IV–V) (*Fresno Morning Republican*, 11 March 1922)
Hanford	IV	Doors slammed, awoke many (V) (*Hanford Morning Journal*, 11 March 1922)
Lemoore	IV	Many left beds, some rushed to streets (V–VI) (*Hanford Daily Sentinel*, 10 March 1922)
Visalia	IV	Sleepers were awakened (IV–V) (*Hanford Daily Sentinel*, 10 March 1922) Many rushed into the street (V–VI) (*Pasadena Star-News/Stockton Daily Record*, 10 March 1922)
Porterville	IV	Dishes broken, people awakened (*Fresno Morning Republican*, 11 March 1922) Furniture overturned (V–VI) (*San Luis Obispo Telegram*, 10 March 1922)
Santa Margarita	IV	Lasted 20 seconds, shook violently, worst shake in years (V+) (*San Luis Obispo Telegram*, 16 March 1922)
Atascadero	IV	Aroused every sleeper, shook things off shelves (V–VI) (*Atascadero News*, 17 March 1922)
San Luis Obispo	Felt by many, plaster cracked, V	Store windows broken (*Hanford Daily Sentinel*, 10 March 1922) Telephones out of order, some poles down (V–VI) (*San Luis Obispo Telegram*, 10 March 1922)
Bakersfield	IV–V	Many people ran from their homes, chandeliers shook for several minutes (V–VI) (*Bakersfield Californian*, 10 March 1922)
Santa Maria	IV	Awoke most of the residents (V) (*Santa Maria Daily Times*, 10 March 1922)
Santa Barbara	IV	Awoke many (IV–V) (*Santa Barbara Morning Press*, 11 March 1922)
Ventura	IV	Hotel patrons ran into street (*Daily Oxnard Courier*, 10 March 1922) Crockery smashed, several windows broken (V–VI) (*Hanford Daily Sentinel*, 10 March 1922)
Oxnard	IV	Awoke many (IV–V) (*Daily Oxnard Courier*, 10 March 1922)
Los Angeles	II	Distinctly felt downtown (III–IV) (*Salinas Daily Index*, 10 March 1922)

*The 1922 event was at least as strong as the 1966 event at the 30 towns that reported both. This table lists the 17 towns that felt the 1922 event more strongly.
†Locations are listed from north to south.
‡1966 Intensities are interpreted from USE.

San Luis Rey and San Diego, at distances of 105 and 150 km south of the end of the proposed rupture, strongly felt the 8 December earthquake but were not damaged.

On 21 December 1812, 13 days after the Wrightwood/San Juan Capistrano event, two earthquakes 15 min apart damaged Santa Barbara, Santa Inez, and Purisima Concepcion. The San Buenaventura annual report mentions damage in "three horrible earthquakes," suggesting damage on 8 December as well as 21 December 1812. The San Fernando annual report mentions damage "due to the strong and repeated earthquakes," also suggesting damage on both 8 December and 21 December 1812. San Gabriel and San Juan Capistrano reported damage only on 8 December, whereas Santa Barbara, Santa Inez, and Purisima were only damaged on 21 December. The earthquakes of 21 December 1812 are widely assumed to have been centered in the Santa Barbara Channel because they damaged missions near the coast, where many aftershocks were felt, and generated a tsunami in the channel (Toppozada *et al.*, 1981; Jacoby *et al.*, 1988).

A strictly fault displacement source for the 21 December 1812 tsunami would require a very large submarine earthquake of $M \sim 7.7$ (Lander, 1993). This is not supported by the low shaking intensities of MMI VII observed over a relatively small area from San Fernando to Purisima Concepcion. Lander *et al.* (1993) interpreted the descriptions of the 21 December 1812 tsunami as indicating a submarine landslide source. Such sources abound in the Santa Barbara Channel (Greene and Kennedy, 1989). Greene *et al.* (2000) identified a massive submarine landslide near Santa Barbara with several lobes that have been active in the geologically recent past. Also, a 31 May 1854 Santa Barbara Channel tsunami, apparently resulting from a submarine landslide, followed earthquake shaking that frightened people at Santa Barbara but did little damage (Lander *et al.*, 1993). According to Trask (1856, p. 89) "The sea was much disturbed and a heavy swell came in after the second shock was felt, which passed some thirty feet beyond the old wreck near the embarcadero."

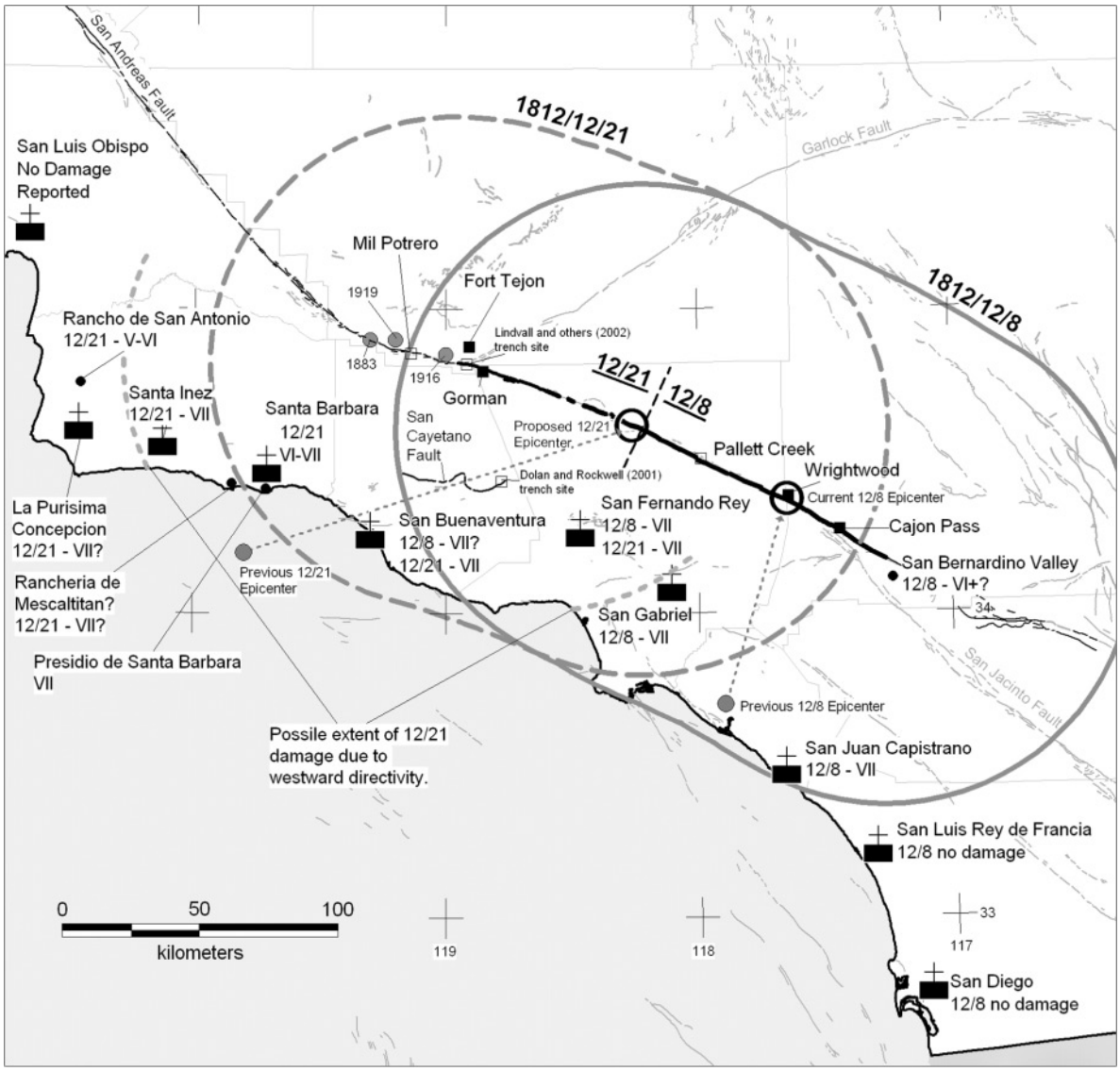

Figure 13. Contours of MMI VII at a distance of 90 km from the 170-km 1812 San Andreas fault rupture proposed by Jacoby *et al.* (1988), which is divided in two segments to account for damage observed on 8 December and 21 December 1812. Historical epicenters of three earthquakes near fort Tejon are shown.

A M ~7 earthquake located within ~30–90 km of the coast, on land or offshore, could generate the intensities observed on 21 December and could trigger a submarine landslide and tsunami. For example, the 3 July 1841 earthquake of M ~6 centered in the San Andreas fault vicinity of San Juan Bautista, discussed previously, triggered a submarine landslide and tsunami 45 km away in Monterey Bay.

Jacoby *et al.*'s (1988) length of ~170 km for the 1812 rupture is divisible into two segments, each capable of generating a $M \geq 7$ earthquake. We consider the possibility that the 21 December 1812 earthquake was on the western portion of the rupture and that the tsunami resulted from a submarine landslide.

Deng and Sykes (1996) calculated the change in the Coulomb failure function for a San Andreas earthquake with a northwest rupture end at Pallet Creek. At this end, their figure 2b shows a greatly increased chance of failure toward the northwest on the San Andreas fault. Thus, an 8 December rupture with an end at or west of Pallet Creek would promote a second rupture to the northwest (Fig. 13). The second rupture would probably start from the northwest end of the first and propagate to the northwest along the San Andreas fault.

Missions San Juan Capistrano, San Gabriel, San Fernando, and San Buenaventura, all within ~90 km of the eastern approximate half of the ~170 km length rupture, were damaged on 8 December (Fig. 13). The ~170 km estimated length did not all rupture on 8 December because

that would have damaged mission Santa Barbara, which is also within ~90 km of the rupture. But Santa Barbara was damaged only on 21 December, which suggests that the western portion of the ~170-km rupture occurred on 21 December. Annual reports from missions San Fernando and San Buenaventura suggest they were damaged on both 8 and 21 December 1812.

Missions Santa Inez and Purisima Concepcion were significantly damaged at distances of ~110 and ~140 km from the rupture, respectively. Assuming the 21 December epicenter was at the western end of the 8 December rupture, then the westward-propagating 21 December rupture would have directed seismic energy toward the west and away from the east. This directivity effect is indicated schematically in Figure 13 by the dotted arcs, suggesting that the intensity VII zone extended westward to include Santa Inez and exclude San Gabriel. The priests' descriptions from Purisima Concepcion indicate that the damage was amplified by adverse effects at that site, which was on sloping ground at the edge of a marsh (Toppozada *et al.*, 1981). The neighboring Rancho de San Antonio was undamaged, indicating that the intensity was less than VII, and no damage was reported at San Luis Obispo. The priests recognized the adverse site effects and rebuilt Mission Purisima Concepcion on dry, level ground ~5 km north of the 1812 ruins.

We divide the ~170 km estimated 1812 rupture into an eastern 8 December 1812 rupture of ~100 km and a western 21 December 1812 rupture of ~70 km and employ these lengths and a rupture width of ~13 km from Deng and Sykes (1996) to estimate M from fault dimensions using Wells and Coppersmith (1994). The eastern rupture length and area indicate M ~7.4 and 7.2 respectively, for a mean M ~7.3. The western rupture length and area indicate M ~7.2 and 7.0, respectively, for a mean M ~7.1. These two earthquakes fit the observed damage reasonably well. The eastern missions were damaged on 8 December, the western missions were damaged on 21 December, and the central San Fernando and San Buenaventura missions were damaged in both earthquakes. The shaking effects from San Diego to Santa Barbara in the two 1812 earthquakes were very similar to those in the 1857 San Andreas fault earthquake (Table 6). This supports a San Andreas fault source for both 1812 earthquakes.

There is little doubt that the 8 December 1812 earthquake was on the San Andreas fault. The likelihood that the 21 December 1812 earthquake was on the San Andreas fault depends largely on the western terminus of the 1812 San Andreas fault rupture. This has not yet been conclusively defined and could be to the west or east of Jacoby *et al.*'s (1988) estimate. Sieh *et al.* (1989), Grant (1996), and Arrowsmith *et al.* (1997) indicate a possible 1812 rupture length of up to ~200 km extending northwestward from Cajon Pass, based mainly on the suggestion from Davis (1983) that the 1812 rupture extended to Mil Potrero (Fig. 13). This would support the scenario presented here and would require the 21 December event to be on the western portion of the rupture because Santa Barbara was not damaged on 8 December. The lack of evidence of 1812 trauma in a large pine tree 3 m from the San Andreas fault near Mil Potrero places a western limit to major rupture for the 1812 event (Meisling and Sieh, 1980).

Lindvall *et al.* (2002) trenched the San Andreas fault ~5 km east of Frazier Park and ~5 km west of Gorman, near the western end of the rupture depicted in Figure 13. Their trench crossed only ~50 m of the ~75-m-wide main San Andreas fault zone. They found evidence for a pre-1600 rupture in their trench, as well as a historical rupture, which they interpreted as the 1857 event. However, they also present two other possible scenarios: one where the 1812 rupture could be in their trench, and the other where the 1812 rupture could be in the fault zone just outside their trench. Thus, they cannot rule out the 1812 rupture at this site.

Dolan and Rockwell (2001) identified a post-1600 earthquake of M ~7.5 on the San Cayetano fault (Fig. 13) and suggested that it could have been the 21 December 1812 event. Such a very large event ~30 km northwest of San Fernando and ~50 km northeast of San Buenaventura would have damaged these two missions more strongly than was observed on 21 December 1812, especially as they had just been strongly shaken on 8 December. Also, the damage observed on 21 December at San Fernando and San Buenaventura did not exceed that at Santa Barbara, Santa Inez, and La Purisima, at distances of ~90, 120, and 150 km from the San Cayetano site (Fig. 13), respectively. Thus, it is unlikely that the major post-1600 rupture in the San Cayetano trench occurred in 1812.

The uniform intensity of ~VII of the 21 December event over the ~110-km west-northwest-trending span between missions San Buenaventura and Purisima, without a distinctly higher intensity, suggests a distant M ~7 earthquake source. The western segment of the proposed San Andreas fault rupture depicted in Figure 13 is one such source. This source is favored if the 1812 rupture extended westward beyond Gorman because Santa Barbara was damaged on 21 December but not on 8 December. However, if in the future it is determined that the 1812 rupture ended east of Gorman, then a source on the San Andreas is not likely for the 21 December earthquake, and a source in the channel ~30 km or more south-southwest of Santa Barbara is possible, as proposed by Toppozada *et al.* (1981).

Three earthquakes of M 5.5–5.9 have occurred in the region between Fort Tejon and Mil Potrero (Fig. 13). They occurred before the availability of local seismographs, and their epicenters were estimated at the centers of greatest shaking intensity. The best intensity data is for the 1916 epicenter (Toppozada and Parke, 1982), and the 1883 and 1919 epicenters are determined with respect to it. These three earthquakes are the largest post-1857 events in the ~180-km San Andreas fault segment between Parkfield and Fort Tejon. Their approximate locations near the proposed 1812 fault rupture end are consistent with a segment boundary in that vicinity.

Table 6
MMI Damage during the 1812 and 1857 Earthquakes

Location	8 December 1812*	21 December 1812	9 January 1857
San Diego	Strongly felt, no damage	No report available	Many frightened, some objects upset. V
San Luis Rey de Francia	Strongly felt, no damage	No report available	No report available
San Juan Capistrano	Destroyed church tower, other buildings were "in bad condition." VII	No damage reported	No report available
San Bernardino Valley	Unreliable report (see text, p. 2575)	Unreliable report (see text, p. 2575)	All frightened, trees shook, houses cracked. VI
San Gabriel	" . . . damaged the church considerably and made cracks in the belltower, the finial of which finally fell off along with the weather-vane.", " . . . extensively damaged the living quarters . . . " VII	No report available	"In the Mission several houses are badly damaged, and the church is represented as having been very much cracked." VII
Los Angeles	No report available	No report available	All frightened, many ran outdoors, difficult to stand, some objects upset, some houses cracked but none badly damaged. VI
San Fernando	"Thirty beams to support the walls of the Church due to the strong and repeated earthquakes", probably on 8 and 21 Dec. VII	"Thirty beams to support the walls of the Church due to the strong and repeated earthquakes, probably on 8 and 21 Dec. VII	"It knocked down two houses, but did not affect the mission buildings." VII
San Buenaventura	Mission damaged by "three horrible earthquakes . . . [a] wall has a sizeable crack . . . should be rebuilt . . . The tower was [ruined] and we are going to tear it down." Damaged by 8 Dec. event and two events on 21 Dec. VII	Mission damaged by "three horrible earthquakes . . . [a] wall has a sizeable crack . . . should be rebuilt . . . The tower was [ruined] and we are going to tear it down." Damaged by 8 Dec. event and two events on 21 Dec. VII	"Several of the mission buildings, vacant at the time, were entirely destroyed and other houses in the place were more or less injured . . . ", roof at the mission fell in, and the bell tower was shattered. VII
Fort Tejon	No report available	No report available	Buildings damaged, some severely, no lives lost. VII–VIII
Santa Barbara	No damage reported	"there are many cracks in the houses, church, and other buildings." VI–VII	"Many walls of buildings were cracked . . . ", "The slight damage which ensued therefrom to our dwellings can doubtless be attributed to the great thickness of their 'adobe' walls." VI–VII?
Presidio de Santa Barbara	No report available	" . . . on the verge of falling down, and there is not one room in it that can be used." VII‡	No report available.
Rancheria de Mescaltitan	No report available	"A chapel of Saint Michael . . . fell down completely, and the land was opened up in the vicinity, to such an extent that it causes horror." Possible lateral spread VII?‡	No report available.
Santa Ines	No damage reported	Two earthquakes 15 minutes apart, cracked one corner of the church and tore down another corner, and cracked many walls. VII	No report available.
La Purisima Concepcion	No damage reported	Mission buildings on the edge of a marsh on sloping ground were damaged or destroyed, others were not. VII?	No report available.

(*continued*)

Table 6 (*Continued*)

Location	8 December 1812*	21 December 1812	9 January 1857
Rancho de San Antonio	No report available	Buildings and tall granary were not damaged at all. V–VI‡	No report available.
San Luis Obispo	No damage reported	No damage reported.	No report available.

*From Toppozada *et al.* (1981).
†From Agnew and Sieh (1978), their table 2; Items quoted are from their Appendix.
‡The presidio and ranchos were generally not as well built as the mission churches.

The 5 September 1883 M ~5.8 earthquake was previously located in Santa Barbara Channel based on moderately strong intensities in coastal Ventura and Santa Barbara Counties but on no information from the mountains to the north (Toppozada *et al.*, 1981). The only information then available north of the Santa Barbara Channel coast was that it was "quiet heavy" at Oil Center, north of Bakersfield (Ventura Free Press, 8 September 1883, p.3), but was not substantiated. We subsequently discovered that severe shaking was reported from the San Emidgio Mountains north of Mil Potrero: "severe shock . . . awakened every body from sleep and the poultry abandoned their roosts in great alarm. It would have seriously damaged ordinary brick buildings" (*Kern County Californian*, 8 September 1883). This supports the "quite heavy" report from Oil Center and exceeds our previous highest intensity from Santa Barbara where and plastering cracked and fell in one building and clocks stopped. Comparing all the intensities from Los Angeles to San Luis Obispo to those of the better constrained 1916 earthquake led us to relocate the 1883 epicenter to the general vicinity of the San Andreas fault west of Fort Tejon. We also discovered a poorly defined event of M ~5–5.5, which occurred on 7 April 1885 at 2:30 a.m. (PST). It woke people up at Visalia, Plano, Bakersfield, Ventura, and Santa Barbara and was possibly centered in the general vicinity of the 1883 event.

The 23 October 1916 M 5.5, earthquake was centered near Fort Tejon based on a well constrained isoseismal map with several MMI VI and VII points (revised from Toppozada and Parke, 1982). The 16 February 1919 M 5.7, earthquake was centered in the region between the above two epicenters, based on felt intensity information. The ~170-km 1812 segment ruptured again as part of the great 1857 earthquake rupture. This pair of overlapping ruptures in southern California is similar to the 1838 and 1906 overlapping ruptures in northern California. Such major overlapping ruptures on the San Andreas fault that are closely spaced in time may be more common than indicated by the limited resolution of paleoseismic techniques.

The Southernmost Region

The southernmost region extends from Cajon Pass to the Mexican border and includes the San Jacinto and Imperial faults. Little pre-1890 seismicity is known in or bordering this segment because of the sparse population and long distance from large population centers. Thus our contribution to this region's earthquake history is minimal.

We list the most significant events here and in Appendix B and show the epicenters in Figure 14. The uncertainties in the parameters of the pre-1932 events are ~50–100 km in epicenter and 0.5 unit in M. Isoseismal maps for the 1890–1948 earthquakes are available in Toppozada *et al.* (1981, 1982) and for the 1979 earthquake in USE.

9 February 1890, M *~6.5:* The widely felt MMI V effects between Pasadena, San Diego, and Yuma and the lack of reported damage suggest a location roughly equidistant from these three points, in the sparsely populated region near the southern San Jacinto fault (Toppozada *et al.*, 1981). However, a location in the southern Mojave Desert around 34°N, 116°W cannot be ruled out by the sparse intensity points.

24 February 1892, M *7.3:* Geological studies by Mueller and Rockwell (1995) suggest a source on the Laguna Salada fault (see Appendix B).

28 May 1892, M *~6.5:* The felt effects of this event appear similar to those of the 1890 earthquake. However, the sparse intensity data cannot rule out this event being a strong aftershock three months after the Laguna Salada earthquake near the border with Mexico.

22 July 1899, M *6.4:* Cajon Pass–Lytle Creek region; see Appendix B and Toppozada *et al.* (1981).

25 December 1899, M *6.7:* San Jacinto and Hemet region, see Appendix B and Toppozada *et al.* (1981).

21 April 1918, M *6.8:* San Jacinto and Hemet region, see Appendix B and Toppozada and Parke (1982).

19 May 1940, M *7.0:* Imperial fault–El Centro, see Appendix B and Toppozada and Parke (1982).

4 December 1948, M *6.0:* Desert Hot Springs, see Appendix B and Toppozada and Parke (1982).

15 October 1979, M *6.5:* Imperial fault–El Centro, see Appendix B and USE.

8 July 1986, M *6.0:* North Palm Springs, see Appendix B.

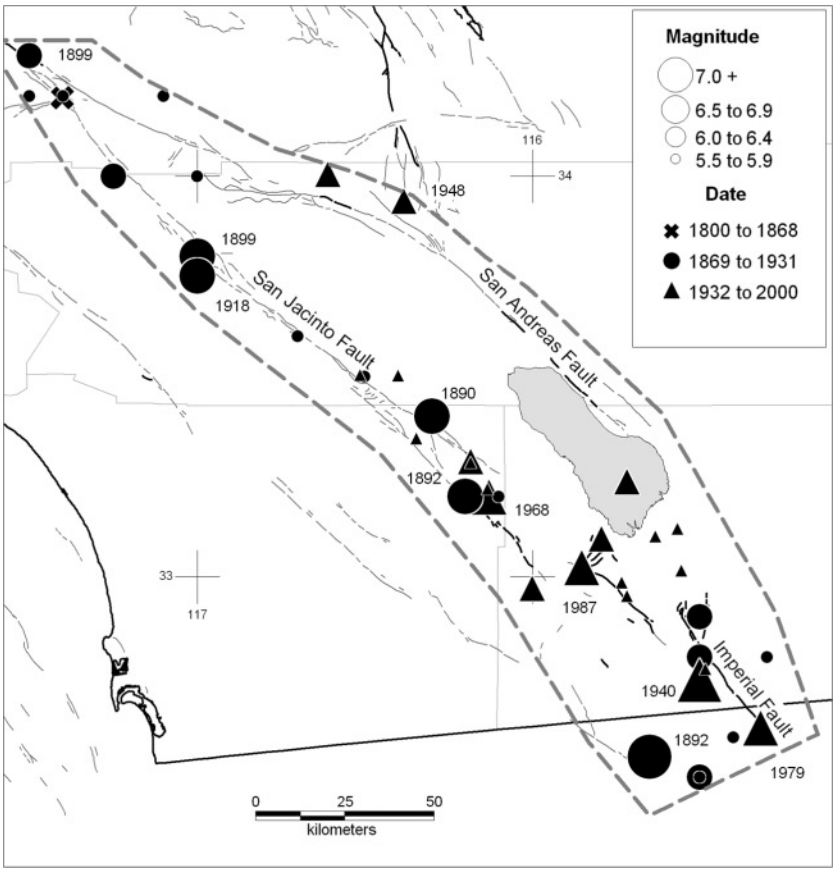

Figure 14. Southernmost region epicenters with symbol indicating time period. Dashed region represents study area.

24 November 1987, M *6.6:* Superstition Hills earthquake, preceded several hours earlier by *M* 6.2 earthquake on the transverse Elmore Ranch fault (see Appendix B).

Conclusions

The short historical record shows that major earthquakes ($M \geq 7$) in the San Francisco Bay region were preceded by one to several decades of increased $M > 5.5$ seismicity and followed by a similar duration of seismic quiescence. *M* 5.5–6.5 events, which can cause significant damage, do not appear to significantly relieve seismic stress. Significant stress is relieved only in earthquakes of $M \geq 7$ larger, as indicated by the seismically quiet periods that follow them.

The apparent shaking and faulting effects of the 1838 San Andreas fault earthquake were unequalled between San Francisco and Monterey by those of any other event except the 1906 earthquake. This suggests 1838 faulting between San Francisco and San Juan Bautista similar to the 1906 faulting in this segment. The occurrence in the 3 years after 1838 of several $M \sim 6$ earthquakes in the San Juan Bautista vicinity is unusual in the historical record and suggests aftershocks near the proposed southern rupture end. We use Wells and Coppersmith (1994) to estimate *M* from the rupture dimensions. The ~140-km rupture length indicates *M* 7.56, and a rupture area of 140 × 13 (WGCEP, 1999) indicates $M \sim 7.3$, for an average $M \sim 7.4$.

In the end zone of the 1857 rupture, extending ~70 km northwest of Parkfield, the rate of seismic moment release has decreased with time since 1857. This might reflect the decay with time of the stress loading from the ~9-m 1857 displacements ~80 km southeast of Parkfield. This could explain why the earthquake predicted to occur before 1992, based on the assumption of regular recurrence of Parkfield earthquakes, has not yet occurred.

The hypothesis that the two major 1812 earthquakes that occurred 13 days apart were centered on adjoining segments of the San Andreas fault from ~20 km southeast of Cajon Pass to Tejon Pass is consistent with the felt effects of both earthquakes. However, this hypothesis requires the 1812 rupture to extend westward at least to Fort Tejon. If it is determined that the 1812 rupture did not extend that far west, it would not materially change the source of the first event, but the source of the second event would be more likely offshore, ~30–70 km south of Santa Barbara.

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Appendix A

Additional Parkfield Earthquake Data

30 May 1877 2:30 a.m. (PST), *M* ~5.5

Location of 1877 Earthquake. Figure 4 shows the few places (underlined) reporting the 1877 earthquake, superposed on the contours of the 1966 Parkfield event. A location in the San Andreas fault zone in southern Monterey County near Parkfield is suggested by the few felt reports found.

The intensity contours of the M 6.0 Parkfield earthquake of 1966 show San Luis Obispo, Paso Robles, and southern Monterey County in the zone of intensity V or greater and Bakersfield in the zone of intensity II–IV. This agrees with the intensities reported for the 1877 event and supports a location near Parkfield. The probable epicentral area of the 1877 event is near Parkfield, eastward of San Ardo and westward of Coalinga (Fig. 3).

A location west of the San Andreas fault is unlikely because the intensity at San Luis Obispo was not 3 or more units greater than at Bakersfield, as it was in the M 5.2 San Ardo earthquake of 1955 (USE). A location east of the San Andreas Fault is unlikely because the intensity at Bakersfield was lower than those at San Luis Obispo and Paso Robles.

Magnitude of 1877 Earthquake. A magnitude for the 1877 event similar to that of the 1966 event is compatible with all the available information and with the isoseismal zones of the 1966 event. The dearth of reported effects is due to the scarcity of 1877 population within the assumed intensity V zone, which is the zone of general awakening of sleepers at 2:30 a.m. The 1877 event was larger than the M 4.9–5.2 Parkfield earthquakes of 1934, 1939, 1956, and 1975 (Table 2), because their felt areas did not extend southeasterly to include Bakersfield (USE). The 1877 event was felt at intensity V at both San Luis Obispo and Paso Robles. In Table 2, the only earthquakes to be felt at intensity ~V at both San Luis Obispo and Paso Robles are the 1934 and 1966 mainshocks. Consequently, we estimate M ~5.5 to perhaps ~6.0 for the 1877 earthquake.

1 February 1881, 4:11 p.m. (PST), M 6.0

Comparison of 1881 and 1966 Earthquakes. The effects at the seven towns reporting the 1881 event are compared to the 1966 intensities in Table 3. The 1881 event appears to have been somewhat stronger than the 1966 event at most of the reporting locations. If the ~22,000 km^2 V zone of Toppozada *et al.* (1981) is expanded to include Lemoore, Hollister, and Salinas, but not Visalia or Santa Cruz, it becomes ~28,000 km^2, indicating M 6.1 using the relations of Toppozada and Branum (2002). This is consistent with the descriptions below of significant ground breakage and of large aftershocks.

Probable Faulting in 1881. Ground deformation was described from near Parkfield as follows: "I counted thirty quite large cracks in the ground running across the road; it also opened several springs of water on Mr. Parkinson's ranch, one I notice between his house and the road boiling up quite strong, and just back of the house, it started sulphur springs and, just where those sulphur springs are, the ground, about 20 paces square, is sunk about 4 feet." (*Salinas City Index*, 10 February 1881). The contemporary assessor's records show that Parkinson's ranch was located about 2.5 km west of Parkfield. The west strand of the San Andreas fault that broke in 1966 and the Parkfield–San Miguel road are both in the northeast corner of Parkinson's ranch. This suggests that the features described in the 1881 Salinas newspaper could have resulted from displacement on the San Andreas fault. The descriptions of large cracks, springs, and 4 ft of vertical collapse suggest that the deformation and possible fault displacement were greater in 1881 than in 1966. This vicinity in 1966 had fractures of maximum length of 4–5 ft and maximum separation of 0.5 in. (Brown *et al.*, 1967).

1 February 1881, 9:00 p.m., Aftershock. This aftershock occurred less than 5 hr after the mainshock and was reported felt at Paso Robles, San Luis Obispo, and Visalia. It was probably the second damaging event described from Imusdale, near Parkfield, in the Salinas City Index of 10 February 1881 as follows: "On the first of this month we had seven shocks of earthquakes, the *two* first very hard ones, they knocked down several chimneys one adobe store room . . . ". The 9:00 p.m. event was the second event reported from Paso Robles, San Luis Obispo, and Visalia. The 113-km felt distance to Visalia is comparable to the 109-km distance to Fresno, as can be seen in Figure 4. Table 2 indicates that the 1939 earthquake of M 5.2 was felt to Fresno. We estimate that the 1 February 1881 9 p.m. aftershock that was felt to a similar distance had at least a similar M ~5.2 or larger. The radius of 113 km to Visalia and the resulting minimum area of 41,000 km^2 suggests M ~5.5.

Smaller aftershocks were reported at *2 a.m.* and *4 a.m.* on 2 February 1881, both at Paso Robles and at San Luis Obispo (72-km distance). This indicates a felt area of 15,000 km^2 and M ~4.7, which is consistent with the information in Table 2 for the 1958 and 1961 events of M 4.5 and M 4.7, respectively.

6 May 1881 5:45 a.m. Aftershock. This damaging aftershock of the 1 February 1881 event was not previously identified. No earthquake on this day is mentioned in any list or catalog of California earthquakes, including Townley and Allen's (1939). We discovered it through Matthews' diary. On 8 May 1881 Matthews traveled from Bitterwater southward through Slack Canyon (15–20 km northwest of Parkfield) to Willow Springs (13 km east of Parkfield). There he wrote: "Since the beginning of the year the people of this section have had two hard earthquakes the last one happened last Friday morning [May 6th] the other occurred in January or February and were both hard enough to crack chimneys and in many instances to tumble them down throwing crockery and bottles off shelves and cupboards the one in the winter must have been very hard from the way the people describe it we felt both of them in the valley though they were not severe". Matthews indicates feeling both earthquakes at his home in Bitterwater Valley, ~70 km northwest of Parkfield. Following up on his lead we uncovered this report in the *San Francisco Daily Alta* and the *Sacramento Daily Record Union*, both of 7 May 1881: "Another Earthquake Shock. San Luis Obispo, May 6th—A heavy shock of earthquake occurred here this morning, at fifteen minutes

to six o'clock. It lasted several seconds but no damage was done", indicating intensity IV or V. This is comparable to intensities at San Luis Obispo from Parkfield earthquakes of $M \sim 5$ to $M \sim 6$ (Table 2). Damaging chimneys and crockery indicates intensity VI or VII in the Parkfield–Willow Springs area, suggesting $M \sim 5.0$–5.5.

Comparison of the 1881 Sequence to Later Parkfield Sequences. As indicated previously, the February 1881 mainshock was apparently stronger at most of the places where it was possible to compare it to the 1966 event and probably had a comparable or slightly higher magnitude. This is consistent with the probable faulting and with the 1881 event having three $M \geq 4.5$ aftershocks within 12 hr and the 1966 event having only two $M \geq 4.5$ aftershocks within 3 days. Also, the 1881 record of $M \geq 4.5$ aftershocks is probably incomplete as indicated by the fortuitous discovery of the May 1881 event of $M \sim 5$–5.5. As in 1881, the 1901, 1922, and 1934 earthquakes each had a $M \geq 5$ aftershock in the 3 to 6 months following. Only the 1966 Parkfield sequence did not include such a late $M \geq 5$ aftershock. This is consistent with other evidence presented below indicating that the 1966 sequence was not as extensive as the earlier sequences.

2 March 1901 11:45 p.m. (PST), M 6.4

Immediate Aftershock. Large aftershocks occurred within about 5 min of the mainshock as reported from the following locations, listed from north to south, showing their distance and azimuth from Parkfield:

Modesto, ~200 km north: severe earthquake that lasted about 5 min and gave them quite a shaking (*Stockton Independent*, 3 March 1901).
Salinas, ~140 km northwest: felt two distinct shocks (*The Monterey Cypress*, 9 March 1901). The first lasted several seconds, the second was longer (*San Jose Daily Mercury*, 4 March 1901; *Los Angeles Times*, 4 March 1901).
Monterey, ~150 km northwest: A couple of sharp shocks of earthquake shook Monterey at 11:45 (*The Monterey New Era*, 6 March 1901).
Jamesburg, ~120 km northwest: three distinct shocks of earthquakes were felt Saturday night (2 March) about 11:30 (*Salinas Weekly Journal*, 9 March 1901).
San Lucas, ~60 km northwest: two heavy shocks and several slight ones (*Salinas Index*, 7 March 1901).
Jolon, ~70 km west: several severe shocks.
Shandon, ~30 km southeast: At 11:45 p.m., a sharp earthquake shock occurred here, followed shortly by another (*San Luis Obispo Breeze*, 6 March 1901).
Cayucos ~65 km southwest: The first shock was by far the severest. The second distinct shock followed within about two minutes, after which there seemed to be vibratory motion almost continually for about 10 min (*San Luis Obispo Semi-Weekly Breeze*, 12 March 1901).
San Luis Obispo, ~70 km south: tremor was first felt at 11:45 p.m. A number of clearly felt shocks followed, the last one about 6:00 a.m. (*San Luis Obispo Breeze*, 4 March 1901).
Ventura County, ~205 km southeast: severe earthquake . . . two other lighter ones.

These reports, particularly the Ventura, San Lucas, Modesto, Monterey, Shandon, and Cayucos reports, suggest that the mainshock was followed within minutes by at least one aftershock that was felt as far as 150–205 km away. The immediate aftershock was apparently of $M \sim 5.0$–5.5.

Other Early Aftershocks. In the 6 hr after the 1901 earthquake "a very large number of minor events" were felt at Cayucos 65 km southwest of Parkfield (*San Luis Obispo Tribune*, 8 March 1901). Also, San Luis Obispo 72 km south of Parkfield reported "a number of clearly felt shocks" in the 6 hr following the mainshock. Several of these were distinctly felt at La Panza and Simmler, about 75 km southeast of Parkfield. A felt extent of 75 km indicates $M \sim 4.5$ from Table 1 and $M \sim 4.8$ from the total felt area relation of Toppozada (1975) (corrected). The 1966 earthquake had only six aftershocks of $M \geq 4$ in the first 3 days, of which two were of $M \geq 4.5$ (Hileman *et al.*, 1973; Bolt and Miller, 1975).

Magnitude of the 1901 Mainshock. The 1901 mainshock was stronger than the 1966 mainshock at the 19 places listed in Table 4. Six other places reported both earthquakes as being of similar intensity (Priest Valley, Fresno, Paso Robles, San Miguel, Estrella, and Porterville). The comparison at Modesto suggests that the IV–V zone in 1901 extended 80 km further north than the II or total felt zone in 1966. The area shaken at intensity V or greater extended from near Modesto to near Ventura (~390 km) and from near Visalia to the coast (~190 km), substantially larger than that for the 1966 event. This V area is comparable to that of the M 6.5 Coalinga event and suggests a comparable $M \sim 6.5$, which is consistent with Abe's (1988) M_s 6.4 and with the long duration, that is, "fully sixty seconds" at San Miguel and "about half a minute" at Pacific Grove.

Sea Wave. In 1901 a wave occurred in the southern end of Monterey Bay as indicated in reports from Pacific Grove (150 km northwest of Parkfield): "the shock was the longest and heaviest felt in years and the tide was phenomenally high" (*Salinas Daily Index*, 5 March 1901); "phenomenally high wave followed the Temblor" (*Monterey Cypress*, 9 March 1901); "The longest and heaviest earthquake . . . The motion was from west to east in continuous long waves instead of the usual sudden shake-up, and was accompanied by a deep rumbling noise. The bay was deeply stirred, and the waves dashed upon the rocks along the shore with unusual fury. The water marks this morning showed a phenomenal high tide. The shock lasted about half a minute. At Del Monte the shock was longer and more severe." (*Los Angeles Times, San Francisco Examiner, San Francisco Call, Sacramento Union*, 4 March 1901).

Lander *et al.* (1993) rated these observations as "validity 3—probably a valid tsunami report." A local tsunami could result from a submarine landslide in Monterey Bay triggered by the earthquake. Numerous landslides are mapped in the submarine Monterey Canyon area (Greene and Kennedy, 1989). A minor tsunami in Monterey Bay was caused by submarine landslides triggered by the Loma Prieta earthquake (Gardner-Taggart and Barminski, 1991).

1901 Probable Faulting. Ground breakage, possibly indicating faulting, was reported: (1) near Stone Canyon 18 km northwest of Parkfield, cracks hundreds of feet long and a foot wide were reported, sometimes with a vertical displacement of one foot (Hamlin, 1905; Townley and Allen, 1939); and (2) Mrs. Fretwell was credited in the *Hanford Weekly Sentinel*, 14 March 1901, with this description from Parkfield "the ground was opened in a crevice eight miles [13 km] in extent"; this probably occurred near Parkfield where she lived. Records at the Monterey County Assessor's office show three Fretwell properties near Parkfield during that period. They were located a mile west, a mile south, and 4 miles southeast of Parkfield, and each contained or bordered a segment of the San Andreas fault zone. According to a resident, the rift or fault a mile west of Parkfield ruptured in the 1901 earthquake for several miles (Lawson, 1908, p. 40). The observation by a lay person of "a crevice eight miles in extent" suggest that probable faulting in 1901 was more obvious and perhaps greater than the subtle faulting features (less than 6 in. of separation) observed in 1966 by geologists (Brown *et al.*, 1966).

5 March 1901, 10:45 p.m. Aftershock. Townley and Allen (1939) have the simple entry "1901 March 5. Paso Robles, Porterville." We show that this was a M 5.0–5.5 Parkfield aftershock that was also reported felt at Cayucos, San Luis Obispo, and Hanford:

Cayucos: "several shocks of earthquake were felt here last night. No damage is reported." (*Los Angeles Times*, 6 March 1901).
San Luis Obispo: "was again visited by an earthquake last night. The temblor came on at about twenty minutes to eleven, and, though not severe, was very distinct. It lasted about two seconds. No damage resulted from the shock." (*San Luis Obispo Breeze*, 6 March 1901).
Hanford: "Another earthquake is reported to have occurred Tuesday night [5th] at a quarter of eleven. A number of parties were sensitive enough to detect the same and say that there were two distinct shocks. The report was verified this morning by telephone messages from the upper end of the Valley, where it was reported to have been quite severe," (*Sentinel*, 7 March 1901).
Paso Robles: "heavy earthquake Saturday [2nd] evening at 11:45. The heaviest felt here for years. The best built buildings rocked on the ground for 25 seconds . . . After the first one several slight ones were felt and at 10:45 Tuesday [5th] evening a rather violent earthquake was felt" (*Semi-Weekly Breeze*, San Luis Obispo, 8 March 1901).

The Paso Robles report suggests a Parkfield source. A location east of the San Andreas fault is unlikely because earthquakes there that are "rather violent" at Paso Robles would be more violent to the east at Hanford. A location to the west of the fault is unlikely because earthquakes located there would be felt more strongly at San Luis Obispo and Cayucos than at Paso Robles and Hanford.

The felt report from Hanford, at a distance of 85 km, suggests $M \geq 5$ because Hanford was at or near the eastern limit of the felt area for $M \sim 5$ Parkfield earthquakes (Table 2). The event was felt as far east as Porterville, 128 km east of Parkfield, as indicated by Townley and Allen (1939), which suggests $M \sim 5.5$. The report at Paso Robles (a rather violent earthquake was felt) is comparable to the effects of the 1966 earthquake (a few cans and bottles fell from shelves), and suggests $M \sim 5$–5.5.

14 August 1901, 3:11 and 3:22 a.m. Aftershocks. Townley and Allen indicated that this event was felt at Cayucos, Hollister, Santa Cruz, San Luis Obispo and Salinas. They note, however, "The time of the shock at Cayucos is given as 2 a.m., but as Cayucos is about 100 miles (160 km) from Salinas, this may have been another shock. No time is given for the earthquake at San Luis Obispo." We discovered that San Miguel and Paso Robles, both within 40 km of Cayucos, felt the event at about 3 a.m., suggesting that the same event was felt at Cayucos and that the 2 a.m. time is erroneous.

San Miguel: "A heavy earthquake was felt at 3:20 this morning. It rattled things up pretty lively, but did not do much damage. The shock lasted ten seconds and the vibrations were from north to south." (*Fresno Morning Republication*, 15 August 1901; *San Jose Mercury*, 15 August 1901) The intensity was probably V or VI, depending on what was meant by "did not do *much* damage."
Paso Robles: "Two distinct shocks of earthquake were felt Wednesday (14th) morning about 3 o'clock." (*Paso Robles Record*, 17 August 1901). The indication of two distinct shocks at 3 a.m. suggests waking people up (intensity IV or greater).
Salinas: "The earth trembled yesterday morning between 3:00 and 3:15 o'clock. Three sharp shocks of earthquake were felt in Salinas. The first shock was but a quiver, followed by another of sharper vibrations while the last one was very sharp and lasted for several seconds. Lamps, bottles, etc. were shaken upon the shelving, and many of the clocks on the mantels in the city were stopped. The temblor seemed to be from southwest." (*Salinas Daily Index*, 15 August 1901). This description indicates intensity IV or V.
Santa Cruz: "Two distinct earthquake shocks were felt in this city Wednesday morning, the first being at 3:11 and the second at 3:13. The vibrations were north and south. (*Santa Cruz Morning Sentinel*, 14 August 1901). Slight earthquake shocks were felt here this morning at 3:11 and 3:22. The

vibrations were from north to south." (*Evening Post* (San Francisco), 14 August 1901; *San Francisco Call*, 15 August 1901; *San Francisco Bulletin*, 14 August 1901). Apparently two shocks were felt separated by 2 to 11 min. Intensity IV is suggested by people presumably waking up to "distinct earthquake shocks."

Location Magnitude and Significance of 1901 August 14 Aftershocks. The highest intensity being reported at San Miguel (Fig. 4) suggests a Parkfield location. A San Ardo location like that of the *M* 5.2 event of 1955 is also possible. The San Ardo location is not favored because the 1955 event generated intensity V or greater at San Miguel, Paso Robles, San Ardo, San Lucas, King City, and Bryson, whereas the August 1901 event was not even reported at the latter four places. Also, the *M* 5.2 earthquake of 1955 is the only historical $M > 5$ San Ardo event.

The *M* 5.5–6.0 Parkfield earthquake of 1966 was felt eastward in the San Joaquin Valley to Hanford, Visalia, and Fresno at intensities less than V, whereas the August 1901 event was not reported there. Because intensities less than IV or V awaken no one at 3 a.m. except sensitive sleepers, they would not necessarily be reported in the 1901 newspapers. The mainshock of March 1901, 11:45 p.m., was reported in the San Joaquin Valley only at Porterville, Visalia, Fresno, and Modesto, because these four places bordered the V zone of that much larger earthquake.

An area of intensity IV or greater extending from Cayucos and San Luis Obispo to Santa Cruz (225 km) is comparable to the felt (intensity II) areas of *M* 5.0 to 5.5 Parkfield earthquakes (Table 2). At San Miguel, the intensity was comparable to that of the 1966 Parkfield event that broke a few dishes. Consequently $M \sim 5.5$ is assumed.

The August aftershocks suggest that the 1901 sequence was more extensive and energetic than the 1966 sequence. This is despite the high probability that not all events of $M \geq 5$ have been identified, due to the scarcity of population and poor reporting in 1901.

Late aftershocks of $M \geq 5$ have also occurred in other Parkfield sequences: In 1881, a $M \sim 5.5$ aftershock (identified above) occurred 3.5 months after the mainshock; in 1922 a $M \sim 5$ aftershock occurred 5 months after the mainshock; in 1934, a *M* 4.8–5.0 aftershock occurred 6 months after the mainshock (Meagher, personal comm. 1991; Hileman *et al.*, 1973). Only the 1966 earthquake was not followed in 3 to 6 months by a $M \sim 5$ aftershock.

27 April 1908, 2:50 a.m. (PST), $M \sim 5.8$

San Luis Obispo and Salinas. "Did you feel it? Did your bed shake and the windows rattle? No? Then you are a sound sleeper. At about 2:50 o'clock this morning many people of this city were awakened from their slumbers by one of the most severe earthquake shocks experienced here in a long time. The vibrations seemed to be from north to south, and the duration of the quake was several seconds. The timid ones were naturally nervously wrought up, but no damage of any kind resulted. Advices from Salinas state that the quake was felt there, but the reports from other places have been kept in the background." (*San Luis Obispo Daily Telegram*, 27 April 1908). We conclude that the intensity at San Luis Obispo was IV or V, because many were woken up or disturbed and excited, and ~IV at Salinas, where some sleepers presumably were awakened and concerned.

Hanford. "Quite a quake was felt in this city early Monday morning by many people. The topic first to be discussed about town last monday [27th] was the earthquake. Many people who were lying in bed and awake at about fifteen minutes to three o'clock noticed a distinct shock. In some instances it was enough to move the bed and swing the doors open or shut, depending upon the structure of the building. Some were awakened by the movement . . ." (*Hanford Weekly Sentinel*, 30 April 1908). Intensity IV–V is suggested by waking up of some people and swinging "doors open or shut."

Coalinga. "An earthquake shock was felt here at 3 o'clock this morning. The movement was from west to east and had a heavy swing. No Damage was done. At Coalinga, fifty miles west of [Hanford] the shock was much heavier." (*Stockton Daily Record*, 27 April 1908). Above, we assigned intensity IV–V to Hanford. Lacking information other than it was "much heavier" at Coalinga than at Hanford, we assume intensity V–VI for Coalinga.

Estrella. "The earthquake was quite heavy here Sunday night, but no damage done." (*Paso Robles Record*, 9 May 1908). This suggests an intensity of perhaps V. The Sunday before 9 May 1908 was 4 May, but there were no earthquakes reported anywhere in California between 2 and 9 May. We assume that this report was intended for the previous issue of the weekly *Paso Robles Record* (2 May) and that it refers to the event of 2:50 a.m. Monday 27 April 1908. Townley and Allen (1939) indicated that the event of 27 April 1908 was felt at Paso Robles and San Miguel, 10 km northwest and 11 km southwest of Estrella, respectively.

Building damage at Paso Robles was denied in this report from the *San Luis Obispo Semi-Weekly Breeze* of 1 May: "Earthquake shocks were felt in this city about 3 o'clock this morning. It was reported that the Hotel El Paso de Robles had been damaged, but there was no truth in the report. No damage was done whatsoever." In 1908 Paso Robles was a resort built around the hotel (M. Hall-Patton personal comm., 1991 San Luis Obispo Historical Society Museum). Our interpretation is that the intensity at Paso Robles was V or VI, approaching the intensity that damages buildings. The mistaken date is not an unusual error for semi-weekly newspapers and suggests that although the article appeared on 1 May 1908, it was intended for the previous issue of the *Semi-Weekly Breeze* (27 April 1908).

Bakersfield. "Did you feel an earthquake shock at 4:10 o'clock on Saturday morning? Quite a number of people

about the city reported a shake at that hour, and some say that it was quite severe, although no damage was reported." (*Bakersfield Morning Echo*, 28 April 1908), suggesting MMI IV. As written, the date (25 April) and time do not match 27 April, 2:50 a.m. It is likely that the 27 April event was felt at Bakersfield because it generated intensity IV–V at Hanford 120 km to the north and V–VI at Coalinga 150 km to the northwest. The ~1-hr time error is not surprising at such an early morning hour. The date error can also be explained. The 1908 earthquake occurred at 2:50 a.m. on 27 April, on which day the *Bakersfield Morning Echo* was not published because it was a Monday.

The *Bakersfield Morning Echo* of Tuesday, 28 April, reports an event early Saturday (25 April), which could be a mistaken date for the event that occurred after midnight Sunday. There were no other felt earthquake reports for 25 April south of Monterey County, which suggests that the Bakersfield report of an early morning event on the weekend refers to the event of early Monday, 25 April 1908.

Location and Magnitude of 1908 April 27 Event. The 1908 earthquake occurred at 2:50 a.m. and was poorly reported outside the zone of general awakening of sleepers (V zone). Unfortunately there are no descriptions for Townley and Allen's (1939) felt reports from Priest Valley, San Miguel, Jolon, and Santa Margarita. Because these towns fall in the general area between San Luis Obispo (IV–V) and Coalinga (V–VI), they were probably in the V intensity zone.

Intensities IV–V at San Luis Obispo, IV at Salinas, IV–V at Hanford, V or VI at Paso Robles, V–VI at Coalinga, and V at Estrella are similar to the intensities of the 1966 Parkfield earthquake at these locations (Fig. 11). The only events in Table 2 to be felt at intensity IV–V or greater at Coalinga, Paso Robles, and San Luis Obispo are the 1934 and 1966 mainshocks. For example, both the M 5.2 event of 1949 and the M 4.9 event of 1975 generated intensity V at Coalinga, IV at Paso Robles, and IV at San Luis Obispo. Also, at Bakersfield, the 1908 felt intensity was apparently similar to that in 1966 (Fig. 11). Thus, we estimate M ~5.8 for the 1908 event.

This suggests that earthquake occurrences, closely approaching the size of the predicted Parkfield event, were not completely known until 1908. The considerably larger 1901 Parkfield earthquake of M 6.4 was better identified and well known.

10 March 1922, 3:21 a.m. (PST), M 6.3 Earthquake Sequence

1922 March 10, 2:40 a.m. Foreshock. This previously unidentified foreshock ~40 min before the destructive 1922 10 March 3:21 a.m. Parkfield earthquake was reported from the area about 50 miles (80 km) northeast of Parkfield:

> "Hanford, Cal., March 10—For the first time since the earthquake of 1906, this part of the San Joaquin Valley felt a lengthy but not violent earthquake shock at 3:30 this morning. The motion was slow and undulating. No damage was reported. Earth tremors, varying from a slow swinging motion to somewhat violent motions which swayed buildings and rattled dishes were felt in nearly every part of Kings county this morning. At Kings River the shocks were bordering on the violent and Hardwick, Grangeville, Armona, Lemoore and other districts near here, report two distinct shocks, one at 2:40 and a final and more severe shock at 3:25. No damage was done, but people were mildly panic-stricken, earth shocks being practically unknown in this vicinity. Telephone messages poured into Hanford asking for information, the belief prevailing that either the bay [sic] district or Southern California had been visited with a calamity". (Pasadena Star-News, 10 March; Oakland Tribune, 10 March). "Hanford, Calif., March 10—Slight earthquake shocks were felt here at 2:40 a.m. and 3:20 a.m. today." (*Bakersfield Californian*, 10 March 1922).

A few people presumably woke up at Hanford, Hardwick, Grangeville, Armona, and Lemoore at 2:40 a.m., suggesting intensity III–IV. In the same area the 1966 Parkfield earthquake was felt at intensity IV. However, it is unlikely that the 2:40 a.m. foreshock was of M ~5.5 because we found no definite reports outside the Hanford–Lemoore area. The 1956 event of M 4.9 (Table 2) was felt at intensity IV at Lemoore and III at Hanford (USE). Lemoore was the northeasterly felt limit of the 1958 event of M 4.5 (Table 2). Consequently the 1922 foreshock was probably of M ~5. It is unlikely that the 2:40 a.m. event was a M ~4 earthquake in the Hanford–Lemoore area because no earthquakes of M ≥4 are known to have occurred in this area this century (Real *et al.*, 1978), or last century (Toppozada *et al.*, 1981). A M ~5.5 event in Owens Valley, 140 km east of Hanford, is unlikely because of the absence of earthquake reports in the Mono and Inyo county newspapers of March 1922. Lacking information from the local newspapers, we base our estimate that the 2:40 a.m. event was probably a M ~5 foreshock that occurred 40 min before the destructive 1922 Parkfield earthquake. Such a foreshock conforms to the pattern of occurrence of M ≥5 events minutes before the 1934 and 1966 mainshocks.

Magnitude of the 1922 Mainshock Compared to the 1966 and 1983 Events. Thirty towns reported both the 1922 and 1966 earthquakes. The 1922 event was reported at least as strongly as the 1966 event as each town. Table 5 lists the 17 towns that felt the 1922 event more strongly, at various azimuths and distances.

The 1922 earthquake was felt in the San Joaquin Valley at Fresno, Hanford, Lemoore, Visalia, and Porterville at intensity V (Table 5). The 1983 Coalinga event, which occurred 30 km north-northeast of Parkfield, was felt at these towns also at intensity V (USE). Because the 1922 event occurred at greater distances from these towns than did the

Coalinga event, its magnitude should equal or exceed that of the *M* 6.5 Coalinga earthquake. Also, the Coalinga event was weaker than the 1922 event at San Luis Obispo (V), Bakersfield (V), Santa Barbara (III), and Ventura (IV) (USE, 1983; Table 5).

The area shaken at intensity V or greater extended from near Oxnard to Salinas (350 km) and from Visalia to the coast (190 km), covering ~67,000 km^2, indicating *M* 6.4 from the relations of Toppozada and Branum (2002). This area is larger by 47,000 km^2 and 15,000 km^2 than the areas shaken at intensity V or greater in the 1966 and 1983 events, respectively. Thus, *M* 6.3 (Ellsworth, 1990) is a reasonable minimum *M*.

Bakun and McEvilly (1984) concluded from teleseismic observations of long period (~20 sec) seismographic records that the seismic moment of the 1922 event was comparable to those of the 1934 and 1966 events. This conclusion assumes that characteristics of the seismographs were the same in 1922 and 1966. The intensity observations indicate that short period (~0.2 sec) shaking was stronger in 1922 than in 1934 and 1966. This suggests that the 1922 event had a higher stress drop, resulting from a higher fault displacement, than the 1934 and 1966 events. To maintain the same moment, which is proportional to fault area multiplied by displacement, the 1922 source area may have been smaller than in 1934 and 1966.

Possible Faulting. H. I. Jespersen reported "A crack opened in the Cholame Valley six to twelve inches wide and a quarter of a mile long." (1924, p. 169.)

According to the *King City Herald* of 17 March:

> "The Parkfield correspondent of the Paso Robles Press says that last Friday morning, at about 3:30, people were aroused from their slumbers by a terrible rumble and clatter which proved to be the severest earthquake in twenty-one years. The homes in the Melville district received the full force of angry earth's shaking. The school house and one home were moved from their underpinnings. The fireplace in the latter house was moved a foot and a half without shaking to pieces, though the chimney from the roof up was destroyed as was every chimney in the district."

The Melville school was located 7 km southeast of Parkfield on a 1917 map. It is within 30 m of the San Andreas fault trace (Alquist-Priolo zone, Cholame Hills quadrangle). The movement of the fireplace in the house a foot and a half (~50 cm) is probably related to the house moving from its underpinnings, although the sense of movement, whether tensional or shear, is not given. However, being within 30 m of the fault trace suggests that some of the movement could be due to fault displacement.

The San Luis Obispo Telegram of 13 March states that "The house occupied by the Charles Fretwells was torn off the foundation and set on the ground and the porch moved a foot away from the house . . . The ground in many parts of the country are covered with cracks-some an inch and two inches wide." This suggests strong shaking (VIII or IX). According to the assessor's records, Charles Fretwells' property was located 200 m south of the Melville schoolhouse.

The San Francisco Bulletin of 10 March reported the following:

"Oil Pipe Line Is Broken By Temblor. San Luis Obispo, March 10—(The United Press.)—The oil pipe line of the Union Oil Company of California was broken in four places early today by a heavy earthquake shock . . . The breaks in the oil pipe lines occurred between the stations of Antelope and Shandon, east of San Luis Obispo."

The oil pipelines cross the San Andreas fault between the stations of Antelope and Shandon, suggesting that the breaks were due to faulting (Fig. 12). This location is about 16 km southeast of Melville. The pipeline did not exist during the 1901 event, and it was not injured in the 1934 event (Moody, 1934). In the 1966 event, an oil pipeline was ruptured near this location according to Brown *et al.* (1967, p. 47), who also indicate that the maximum 1966 surface displacement was ~15 cm, but not necessarily at this location.

If the pipeline rupturing in 1966 and 1922 but not in 1934 is indicative of the amount of displacement, it would support Segall *et al*'s (1990) conclusion that the maximum fault slip was located further northwest in 1934 than it was in 1966.

Comparison of the 1922 and 1901 Mainshocks. To the southeast in the Santa Barbara, Ventura, Oxnard area, the 1922 intensity was V–VI, whereas the 1901 intensity was only IV to V. The Shandon Postmaster also indicated that the 1922 event was stronger to the south: "I have resided in the district for forty-three years, and experienced the strong shock of 1901, as well as the 1906 earthquake which destroyed San Francisco, and the 1915 shock which damaged Los Alamos, as they were felt in the Cholame region, but this shock [1922] was harder than any of the shocks mentioned, as felt in Shandon" (28 km south of Parkfield).

The 1901 event was stronger than the 1922 event to the northwest:

in Salinas, the intensity was V–VI in 1901 compared to IV–V in 1922; in Santa Cruz, the intensity was V–VI in 1901 compared to not reported in 1922; and in San Francisco, the intensity was IV in 1901 compared to not reported in 1922. The 1901 event was felt to Modesto, 40 km north of the northernmost Central Valley felt reports in 1922, 1934, and 1966, and also induced a tsunami in Monterey Bay. These differences suggest that the 1901 event was located northward of the other events. Possible faulting cracks were observed in 1901 by Hamlin (1905) near Stone Canyon 18 km northwest of Parkfield. Bakun and McEvilly (1984) suggested that the 1922 event was located northwestward of the 1934/1966 location. This would suggest a southeastward progression of epicenters from 1901 to 1922 to 1934 and 1966.

16 March 1922, 3:10 p.m. Townley and Allen (1939) report this event thus:

"V + [Rossi Forel Intensity, or RF]. Cholame Valley. Rather strong aftershock, recorded over the United States. Reported at San Luis Obispo, V, direction northeast to southwest, duration ten seconds, felt by many; Antelope Valley, Kern Co., IV, rocking motion southeast to northwest, two shocks of five seconds each; Paso Robles, San Luis Obispo Co., V, east to west, felt by many; Shandon, San Luis Obispo Co., Sharp." Based on this, Toppozada *et al.* (1978) assigned *M* 4.5. Additional historical information and comparison to the mainshock seismographic records are here used to derive *M* ~5.3.

This earthquake was recorded seismographically at BRK and MHC with horizontal amplitudes about 0.1 and 0.067 times those of the 10 March mainshock, respectively (BSSUC). This indicates magnitude about 1.0 and 1.2 units smaller than the mainshock, or *M* ~5.3. This is consistent with intensity V RF (MMI IV–V) being reported from San Luis Obispo and Paso Robles, as occurred in the 1934 (*M* 6.0), 1939 (*M* 5.2), 1956 (*M* 4.9), and 1975 (*M* 4.9) earthquakes (Table 2).

1922 August 17, 9:12 p.m. and Associated Event. According to Townley and Allen (1939), "Recorded at 15 seismographic stations, this shock appears to have originated in the thinly settled Cholame region." We have further researched the reported felt effects and found that this event was felt 113 km eastward to Visalia, indicating it was larger than known *M* 5 Parkfield events (Table 2). The seismographic record at the University of California–Berkeley station at MHC, described below, also indicates *M* >5.

Townley and Allen (1939) stated that intensity IV RF (MMI IV) was reported at Lemoore, which also reported the 1966 Parkfield earthquake as intensity IV. Descriptions from Hanford also indicate intensity IV effects similar to the 1966 event. This suggests that the August 1922 aftershock was comparable in size to the 1966 earthquake.

This is supported by the following description from the *Coalinga* Record of 18 August: "One of the most severe earthquakes felt in this section for several years occurred last evening shortly after 9 o'clock, and lasted several seconds. So far as has been learned, no damage was done here except the cracking of plaster in some of the dwellings and business blocks about town." This suggests that at Coalinga, it was comparable to the March mainshock and was similar to that of the 1966 Parkfield earthquake when plaster cracked and merchandise fell from store shelves (V–VI).

The Los Angeles Evening Express of 18 August describes intensity VI or VII effects but does not specify their location: "an earthquake began north of Fresno and . . . felt as far south as Bakersfield . . . the damage occurred at isolated spots, where weakened chimneys were shaken loose, dishes broken and fixtures shattered. It was also reported several women became hysterical and fled from their homes panic-stricken at a number of places." This probably occurred between Coalinga and Paso Robles. The VI–VII effects described exceed the maximum intensities reported for the *M* ~5 events of 1934, 1939, 1956, and 1975 (USE) an indicate an event of *M* > 5.

Closely Associated Earthquake. The *Salinas Daily Index* of 18 August states "slight earthquake shocks were felt by local residents a few minutes after nine o'clock last night. Windows rattled and houses creaked, but no damage was reported. There were two perceptible tremors, ten minutes apart. Fresno and Bakersfield also report slight shocks." This is the only report that specifies two shocks separated by 10 min. An event 10 min before or after the mainshock was not obvious on the MHC vertical-component seismogram, indicating it was significantly smaller. However, a Parkfield event must be *M* 4.5–5.0 to be felt in Salinas, 140 km to the northwest (Table 2). This would be near the detection threshold of the Wiechert seismograph at MHC, 200 km to northwest (gain 50 at 3.3-sec period). Townley and Allen state that at San Luis Obispo, two shocks were felt by many, and at Spreckels (5 km South of Salinas), two shocks were felt of 5 and 10 sec duration. We conclude that apparently a *M* 4.5–5.0 foreshock or aftershock occurred within 10 min of the damaging August 1922 earthquake.

Location, Magnitude, and Significance of Main 1922 August 17 Event. The intensity effects reported indicate a Parkfield location. Intensities at San Luis Obispo and at Coalinga were IV–V and V–VI, respectively, comparable to the 1966 (*M* 6.0), 1939 (*M* 5.2), and 1934 (*M* 6.0) intensities at these sites (Table 2).

The reported felt area is larger than the areas over which the *M* ~5 Parkfield earthquakes of 1975, 1956, 1939, and 1934 were felt. The 17 August 1922 Parkfield earthquake was felt 140 km northwestward to Salinas, 109 km northeastward to Fresno, 113 km eastward to Visalia, 150 km southeastward to Bakersfield, and 130 km southward to Los Alamos. The felt area was ~60,000 km^2 indicating *M* ~5.7. Duration of 10 sec at Spreckels (135 km northwest of Parkfield) and 20 sec at Lemoore (77 km northeast of Parkfield) also suggest *M* >5.5.

The seismographic amplitude at MHC using the available vertical-component records was 0.37 that of the March 1922 mainshock, indicating a 0.4 difference in magnitude, or *M* 5.9. The BSSUC indicates that the horizontal amplitude ratios of the mainshock and aftershock varied greatly with frequency, but the MHC horizontal records for the March mainshock are not available for checking. Also, the August 17 aftershock horizontal amplitudes on MHC microfilm are 5 times those of the March 16 aftershock, which indicates that it was 0.7*M* unit larger, or *M* 6.0.

The MHC Wiechert instrument has been restored, and it recorded the 1983 Coalinga earthquake at Berkeley. The 1983 amplitude was 4.5 times the August 1922 amplitude, indicating a 0.66 difference in magnitude. A distance correction of $-0.4M$ must be applied (Richter's $-\log A_o$ term) to account for the different distances in 1922 (190 km to MHC) and 1983 (270 km to BRK). This comparison of

Wiechert records, indicating M [6.5 − 0.66 − 0.4] or M 5.4 for 17 August 1922, assumes similar magnification in 1922 and 1983 and similar site conditions at MHC and BRK.

W. L. Ellsworth (personal comm.) computed magnitudes for the 17 August event from Milne amplitudes listed for Victoria (~13° distant) and Toronto (~32° distant) of M 5.3 and M 5.0, respectively. However, the Toronto M 5.0 is based on a listed amplitude of 0.05 mm, which seems untenable (a 0.5-mm aplitude would result in M 6.0).

Values of M range from 5.3 from the Victoria station to 5.9, 6.0, and 5.4 for the MHC seismograph and M 5.7 from felt area. The average value (of 5.7, 5.9, 6.0, 5.4, 5.3) is M 5.7, which is compatible with the size of the felt area, and with felt effects in the region including San Luis Obispo, Paso Robles, Coalinga, and Lemoore.

The August 1922 aftershock indicates that the 1922 Parkfield sequence extended for months after the mainshock, which also happened in 1881, 1901, and 1934, but not in 1966. The August 1922 aftershock was of magnitude approaching that of the 1966 mainshock, indicating that the 1922 sequence was significantly more extensive and energetic than the 1966 sequence.

By remarkable coincidence, the March 1922 mainshock and the M ~5.7 aftershock in August almost repeat the dates of the 1901 occurrences of the March mainshock and August M 5.5 aftershock discussed above.

5 September 1922, 1:05 a.m.

Townley and Allen (1939) stated only that two shocks of 1- and 5-sec duration were felt at San Luis Obispo and indicate that the intensity was V RF (IV–V MMI). We found that the event was felt as far away as Visalia, 170 km northeast of San Luis Obispo: "Earth Shock Shakes City—An earthquake lasting only a couple of seconds was felt at Visalia at 1:01 yesterday morning by a number of Visalians. There was only one minor shock, apparently, felt there." (*Visalia Morning Delta*, 6 September 1922). If some sleepers were awakened, intensity III–IV is indicated.

At Paso Robles, 37 km southwest of Parkfield "The quake lasted approximately ten seconds and was distinctly felt." (*Paso Robles Star*, 6 September 1922).
At Stone Canyon, 17 km northwest of Parkfield "Two earthquake shocks were felt here early Tuesday (5th) morning." (*Paso Robles Star*, 13 September).
At Armona, 80 km northeast of Parkfield the event was felt distinctly (*Fresno Morning Republican*, 6 September 1922).
At San Ardo, 45 km west-northwest of Parkfield: "Early Tuesday [5th] morning two very distinct earthquake shocks were felt here. The first occurred about two o'clock and the other some time later. Although not violent enough to cause any damage they were long enough to interfere with many perfectly good sound sleeps." (*King City Herald*, 8 September 1922). This indicates intensity IV–V. There is a one hour time discrepancy, which could be either an error in reporting, or due to confusion when waking up at 1 a.m.
At Santa Margarita, 59 km south of Parkfield "Quite an earthquake visited us Tuesday (5th) morning about 1:30; although not as severe as the former ones it was sufficient to awaken pretty nearly everyone and it rocked the houses badly." (*San Luis Obispo Daily Telegram*, 8 September 1922). This indicates intensity IV–V.
It was also felt at Pozo, 70 km south of Parkfield.

The reporting of two earthquake shocks at San Luis Obispo, Stone Canyon, and San Ardo indicates a M ~4.5 foreshock or aftershock, which is a common occurrence for M ~5 Parkfield events. A possible interpretation of the San Ardo report of two shocks is that the mainshock woke people up, and "the other some time later" was a M ~4.5 aftershock.

Location, Magnitude, and Significance of 1922 September 5 Event. The intensity distribution suggests a Parkfield location. A location west of the San Andreas fault is unlikely. Although the 1955 Bryson event was felt at intensity IV at Visalia, as was this 1922 event, at San Ardo, chimneys fell in 1955, but in 1922 no damage occurred. A location east of the San Andreas fault is not supported by the intensity at Visalia being much lower than the intensities in the Santa Margarita–Paso Robles–San Ardo area.

We are aware of two M ~5 Parkfield events that were felt eastward to near Visalia: the 7 June 1934 foreshock that occurred 17 min before the mainshock and the 1939 event (Table 2), which was felt to Fresno 60 km northwest of Visalia. K. Meagher *et al.* (personal comm., 1991) calculated M 5.2 for both these events. Based on this and on the fact that the M 4.9 events of 1934, 1956, and 1975 (Table 2) were not felt as far east-northeast as Visalia 113 km, we estimate M ~5. This is also consistent with intensities IV–V being felt at San Ardo, Paso Robles, and Santa Margarita, as they were in the M 4.9 and M 6.0 Parkfield earthquakes of 1975 and 1966 (USE). The MHC amplitude is 0.16 that of the 17 August aftershock. This indicates that the August aftershock was about 0.8 M larger and supports our M ~5.7 estimate for that event.

We conclude that, of all the known Parkfield sequences, 1922 had the most $M \geq 5$ events. It is probable however, that not all $M \geq 5$ aftershocks were identified in the 1901 and 1881 sequences because of the sparseness of population and of newspaper coverage.

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Appendix B

Date (GMT)	Latitude	Longitude	Magnitude*	Region / Notes
11 Nov 1800	36.800	−121.500	~5.5 M_A	San Juan Bautista: Earthquakes in October cracked walls at San Juan Bautista, but were not sufficiently damaging to be noted in the annual reports of Mission San Juan Bautista or any of the neighboring missions.
21 Jun 1808	37.800	−122.600	~5.5 M_A	San Francisco: From 21 June to 17 July, 18 earthquakes cracked poorly built walls at San Francisco Presidio. These were not mentioned in the annual reports of missions San Francisco de Asis Dolores, San Jose, Santa Clara, or Santa Cruz. This suggests a moderate earthquake and aftershocks near the Presidio, as happened south of San Francisco in 1957 near Daly City.
8 Dec 1812	34.370	−117.650	~7.3 M_A	Orange County–Los Angeles–Wrightwood: The belltower at San Juan Capistrano was shaken down onto the mission church and destroyed it, killing 40 people at early morning mass. Thereafter services were held in an adjoining adobe. This earthquake also damaged missions San Gabriel, San Fernando, and probably San Buenaventura. Its ~170-km-long rupture on the San Andreas fault indicates a M_w ~7.5 earthquake (Jacoby *et al.* 1988; Sieh *et al.* 1989). Forty-four years later in January 1857, major faulting in the M_w 7.9 San Andreas fault earthquake overlapped and ruptured this segment again.
21 Dec 1812	34.750	−118.600	~7.1 M_A	Los Angeles–Ventura–Santa Barbara: The proposal to move the 1812 "Santa Barbara Channel" earthquake to this San Andreas fault location is discussed in the text.
Sep 1825	37.100	122.300	~5.5 M_A	Santa Cruz: Tuttle and Sykes (1992, p. 1808) indicate that the annual report of Mission Santa Cruz dated 31 Dec 1825 refers to feeling many light earthquakes during the autumn. This seismicity was not mentioned in the annual reports of surrounding missions. We tentatively interpret this as a possible swarm of earthquakes of M_w ~5.5 or less near Santa Cruz.
3 Apr 1827	37.700	−122.500	~5.5 M_A	San Francisco: Duhaut–Cilly (1929) described effects of MMI VI to VII at San Francisco Presidio and at Mission Dolores. We found no mention of this earthquake at other missions. We find it comparable to the 1957 Daly City earthquake of M 5.3 and assign it similar location and M.
10 Jun 1836	36.900	−121.500	~6.5 M_A	Between Monterey and Santa Clara: MMI VI–VII from Carmel to Santa Clara. This was previously considered a major earthquake on the Hayward fault. Toppozada and Borchardt (1998) revised the epicentral location to the area between Santa Clara and Monterey, and estimated M ~6.25 (the new M_A relations indicate M 6.5). Considering the increased seismicity in the Santa Clara Valley vicinity in the 25 years leading up to the great 1906 earthquake (below), the 1836 earthquake is probably part of the increased seismicity prior to the major 1838 San Andreas fault earthquake.
Jun 1838	37.300	−122.150	~7.4 M_A	San Francisco to San Juan Bautista: This major San Andreas fault earthquake was considered as M ~7 with a ~60-km rupture length by the Working Group on California Earthquake Probabilities (1990). Bakun (1999) estimated M ~6.8 but stated that his may be too small because of the of inadequate distribution of reporting localities. Toppozada and Borchardt (1998), and Toppozada (2000) describe damage from San Francisco to Gilroy and Monterey that is of similar intensity to that in 1906. This suggests a rupture length of ~140 km from near San Francisco to near San Juan Bautista, indicating M ~7.4. Most of the 1838 descriptions are from reminiscences in the 1860s and 1870s. See text for more information.
18 Jun 1840	36.850	−121.500	~6.5 M_A	San Juan Bautista: Ma from estimate of V–VII zone radius. See text for more information.
3 Jul 1841	36.825	−121.500	~5.9 M_A	San Juan Bautista: Ma from estimate of V–VI zone radius. Duflot de Mofras (1844) reported strong earthquake shaking in Monterey (MMI V–VI) and that the effects were felt in "the farms of the interior," probably in Salinas Valley, ~25 km northeast of Monterey. He also described the effects of a tsunami in Monterey Bay, associated with this earthquake. The tsunami was probably due to the earthquake shaking triggering one of the numerous submarine landslides mapped in and around the offshore Monterey Canyon by Greene and Kennedy (1989).
29 Jul 1841	36.800	−121.450	~5.8 M_A	San Juan Bautista: Robinson (1858, 1969) described frightening MMI VI–VII earthquake damage at Alisal. 17 km south of San Juan Bautista. He indicated it was the 25th earthquake that was felt most severely at Alisal within 2 months. These earthquakes probably included the previous 03 July 1841 shock, and were often "Violent" at Alisal, but "seldom severe" at Monterey (Simpson, 1930). This strongly suggests a source on the San Andreas fault, which is 15 km from Alisal and 43 km from Monterey. We employed the equations from Toppozada and Branum (2002) to determine for the 3 July event M ~6 from MMI V–VI radius of ~43 km, and for the 29 July earthquakes M ~5.8 from MMI VI–VII radius of ~15 km. We know about the 3 July and 29 July earthquakes because of the fortuitous notes of travelers, but they were probably not the only strong aftershocks in the 3 years following the major 1838 earthquake when documentation was very scarce.

(*continued*)

Appendix B (*Continued*)

Date (GMT)	Latitude	Longitude	Magnitude*	Region / Notes
2 Sep 1853	36.250	−120.800	~6.0 M_A	~50 Km Northwest of Parkfield: This earthquake was described in the press only as "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." This suggests a M 6 to 6.5 earthquake on the San Andreas. See text for more information.
14 Jan 1855	36.150	−120.700	~5.5 M_A	Priest Valley: Toppozada and Borchart (1998, table 6)
27 Aug 1855	38.100	−122.500	5.5 M_A	Petaluma–San Francisco: Furniture was moved at St. Ann's Valley in San Francisco, and an old adobe house on General Vallejo's ranch near Petaluma was "very much cracked" (MMI VI). This earthquake was apparently centered near the Sonoma Co. shore of San Pablo Bay. A possible foreshock (M ~5) was strongly felt at San Francisco and Petaluma on the preceding day, at 1 p.m.
02 Jan 1856	37.300	−122.500	5.7 M_A	San Francisco Peninsula: Cracked a few masonry walls in San Francisco. In Monterey and San Jose, some were frightened and ran outside. No aftershocks were reported.
15 Feb 1856	37.500	−122.300	5.9 M_A	San Francisco Peninsula: Cornices were thrown down, brick walls were cracked, and people were thrown from their feet in San Francisco (MMI VI–VII). In Berkeley, the Domingo Peralta adobe was injured (Hendry and Bowman, 1940–1945). The earthquake was felt as far north as Marysville. Two probable foreshocks were felt at San Francisco, during the 9 hr preceding the earthquake. Probable epicenter south of San Francisco in the San Andreas–San Gregorio fault area.
9 Jan 1857	36.100	−120.650	6.1 M_i^+	North of Parkfield area: Dawn foreshock; Meltzner and Wald (1999)
9 Jan 1857	36.290	−120.850	5.6 M_i	North of Parkfield area: Sunrise foreshock; Meltzner and Wald (1999)
9 Jan 1857	36.200	−120.800	7.9 M_W	Great Fort Tejon EQ: Extensive San Andreas faulting from southern Monterey County to San Bernardino County (Wood, 1955; Sieh, 1978a). The mainshock caused one death, cracked some houses in downtown Los Angeles, 60 km from the fault, and caused stronger damage at San Fernando, 40 km from the fault (Agnew and Sieh, 1978), Sieh (1978b) identified two foreshocks located near Parkfield in the hours before the mainshock. Meltzner and Wald (1999) estimated M ~6.1 and M ~5.6 for the foreshocks and identified strong aftershocks of M ~6.25 on 9 January and M ~6.7 on 16 January near the southern half of the rupture. Two $M \geq 6$ possible aftershocks were identified an 1858 earthquake near San Bernardino and an 1860 earthquake northwest of Parkfield, in or near the creeping zone of the San Andreas fault.
10 Jan 1857	34.760	−118.710	5.6 M_i	Fort Tejon: aftershock, $M_i^\dagger$ Meltzner and Wald (1999) provide this SAF location, and a location near the Garlock Fault to the east.
16 Jan 1857	34.520	−118.040	6.3 M_i	Palmdale: aftershock, M_i Meltzner and Wald (1999) provide this SAF location, and a location to the west, near Catalina Island.
26 Nov 1858	37.500	−121.800	6.2 M_A	San Jose region: This is the first and strongest of a series of earthquakes during 1858 through 1864 that were centered in the eastern San Francisco Bay area. At San Jose, an adobe building and the corner of a new building were thrown down (MMI VII–VIII). A cornice was thrown down in San Francisco and part of a chimney was thrown down in Mountain View (MMI VI–VII). The epicenter was closer to San Francisco than was the 31 March 1986 Mt. Lewis epicenter, and closer to Stockton than was the 24 April 1984 Morgan Hill event. A newly found desription indicates MMI VI at Alviso (Edwards, 1843–1908). The earthquake was felt to Downieville to the north, Mariposa to the east, and Monterey to the south. No reports of aftershocks have been found.
16 Dec 1858	34.200	−117.400	~6.0 M_A	San Bernadino region?: Possible aftershock of 09 Jan 1857, very poorly constrained.
17 Apr 1860	36.350	−120.950	6.0 M_A	Bitterwater/Lonoak: Meltzner and Wald (1999, table 3) have M ~6.25 at 36.31 and −120.88 (very near our location) or 35.9 and 121.15, which has a slightly lower rms. Strongly felt at Monterey, "and frightened the good people of that town of their propriety", and Santa Cruz (MMI ~V–VI?), lightly felt at Visalia and San Francisco. Townley and Allen (1939) reported that it was felt at Ft. Tejon and Santa Barbara. About 10 hr later, "on the following morning just before day," an aftershock awakened sleepers at Monterey and Santa Cruz, suggesting $M \geq 5$. Probably in or near the creeping zone of the San Andreas (comparable to 6 March 1882 event, below).

4 Jul 1861	37.750	−121.950	5.8 M_A	San Ramon Valley: Jenning's (1994) map shows ~4.5 km of possible rupture on Calaveras fault. At Dougherty's ranch, near the present town of Dublin, most of the roof tiles (of the kitchen) were shaken down, chimneys were thrown down, and several persons were thrown violently to the ground (MMI VII–VIII). In the *Mining and Scientific Press* (San Francisco, 20 July 1861), a fissure 8 miles long (?) was described in Murray Township (Dublin is in Murray Township). This fissure, as along the west side of San Ramon Valley, is probably not entirely surface rupture along the Calaveras fault but may be partly related to the landslides in the area. Jennings (1994) showed only 2.8 miles (4.5 km) of faulting for this event. A newly obtained description indicates MMI IV–V at Alviso, 39 km south of Dublin: "a slight earthquake occurred our clock stopped" (Edwards, 1843–1908). An event that by all indications, including the size of the area shaken at MMI V or greater, is in the M ~5.5 range is not likely to have generated 8 miles (13 km) of surface faulting.
26 Feb 1864	37.200	−121.600	6.1 M_A	Southeast of San Jose: Adobe walls were cracked, and women rushed outside (MMI VI) in Monterey. In Santa Cruz it was "very severe." The earthquake was felt as far as Napa to the North and San Luis Obispo to the south. In Watsonville, small articles and furnishings were tipped over and moved around. MMI V–VI at San Leandro (Edwards, 1843–1908). The location was compared to the 1979 Coyote Lake, 1984 Morgan Hill, 1986 Quien Sabe, and 1989 Loma Prieta earthquakes.
05 Mar 1864	37.553	−121.855	6.0 M_A	East of San Francisco Bay: Windows and plastering were broken and some walls were considerably cracked (MMI VI–VII) in San Francisco. The earthquake was felt as far as Visalia. MMI V–VI at San Leandro (Estudillo, 1861–1867), and at San Jose where folks were frightened and ran out (MMI V–VI). Comparison to the 1986 Mt. Lewis event, suggests a location on or near the Calaveras fault.
21 May 1864	37.600	−121.900	~5.8 M_A	South Hayward area: This east San Francisco Bay area earthquake was felt from Monterey to Sacramento. It was apparently centered in the area between the 1858 and March 1864 earthquakes. A few windows were broken at San Francisco, and at San Jose it was supposedly "heavier than the March event" [that damaged some plastering and caused people to run out].
24 May 1865	37.100	−121.800	5.9 M_A	Santa Cruz Mountains: This shock was described as violent at Santa Cruz, and severe at San Jose and Watsonville. At South San Juan (San Juan Bautista), crockery was broken and many people ran out, at 3:21 am (MMI VI). Holden's (1898) report that this earthquake was "remarkably heavy in southern California" is erroneous. The Daily Evening Bulletin (29 May 1865) states that the earthquake was "remarkably heavy in the southern counties," referring to southern San Francisco Bay counties. At Alviso it was "heavy . . . woke us all up" (Edwards, 1843–1908). At Pacheco it was sharp according to the newspapers. At Santa Cruz the event was followed by several light aftershocks. If the approximate location in the Santa Cruz Mountains is valid, it may have been a possible preshock 4½; months before the major 1865 Oct 8 event.
8 Oct 1865	37.200	−121.900	6.5 M_A	Southern Santa Cruz Mountains: Toppozada and others (1981). Centered some 10 km north of Loma Prieta, this event was most destructive in the Watsonville–Santa Cruz–San Jose area. Samuel Clemens, or Mark Twain as he was known, described it in "Roughing It", published in 1872, as the "great earthquake in San Francisco" because the losses were great there (around $500,000 in property loss). The available sparse triangulation data suggests there was thrusting on a southwest-dipping fault northeast of Loma Prieta (Yu and Segall, 1996).
26 Mar 1866	37.000	−121.700	5.8 M_A	Gilroy: Several chimneys were knocked down in Gilroy (MMI VII). People rushed outside at San Jose and San Francisco. Monterey felt a light aftershock the following day, and Watsonville felt several strong aftershocks. This event may be a southerly aftershock of the Oct 1865 earthquake. This was perhaps the strongest of numerous strong shocks felt at Alviso following the Oct 1865 mainshocks (Edwards, 1843–1908)
21 Oct 1868	37.700	−122.100	7.0 M_W	Hayward Fault: This major Hayward fault earthquake (Lawson, 1908) was the strongest event in the Bay area since the major 1838 San Andreas fault earthquake. It was named "the great San Francisco earthquake" because in 1868 San Francisco suffered much of the damage. Yu and Segall (1996) indicated an 1868 rupture on the Hayward fault extending ~50 km southward from the Berkeley region. This earthquake cause 30 deaths and $350,000 in loss.
08 Oct 1869	39.100	−123.100	5.6 M_A	Ukiah: Chimneys were reported knocked down at Ukiah (MMI VII) and in "the Clear Lake Country" (unlocated). The shock was reported felt from Healdsburg, north to Potter Valley. At Ukiah, a foreshock was felt 2.5 hr before and an aftershock was felt 5 hr after the earthquake.
17 Feb 1870	37.100	−122.000	5.9 M_A	Los Gatos: Several chimneys were thrown down at Los Gatos and chimneys were dislocated at Santa Cruz (MMI VII). The earthquake was felt from Monterey to Sacramento. A possible foreshock on the 13 Feb was strongly felt at Los Gatos, San Francisco, and Martinez.

(*continued*)

Appendix B (*Continued*)

Date (GMT)	Latitude	Longitude	Magnitude*	Region / Notes
02 Apr 1870	37.900	−122.300	5.8 M_A	Hayward Fault: Minor damage was done in Oakland and San Francisco (MMI VI). The shock was felt in Santa Cruz, Stockton, and Santa Rosa. This is possibly an aftershock of the 1868 Hayward earthquake.
15 Nov 1875	32.500	−115.500	6.2 M_i	Imperial Valley to Colorado River delta?: Ellsworth (1990)
30 May 1877	35.900	−120.400	~5.5 M_A	Parkfield: See text and Appendix A for more information.
12 Apr 1880	34.700	−118.400	~5.9 M_A	Gorman–Palmdale: New event, MMI V from Ventura to San Bernardino
22 Nov 1880	34.000	−117.000	?5.5 M_A	East of San Bernadino: possible preshock, described in 19 Dec accounts from san Bernardino and Los Angeles
19 Dec 1880	34.000	−117.000	~5.9 M_A	East of San Bernadino: New event Could be $M > 6.5$ if located in Mojave Desert
2 Feb 1881	36.050	−120.550	6.0 M_A	Parkfield: Toppozada *et al.* (1981) identified and located this earthquake at Parkfield. This was the missing link between the 1857 Parkfield foreshocks of the great Fort Tejon earthquake and the 1901 Parkfield earthquake. It allowed Bakun and Lindh (1985) to base their prediction on the 22-year historical occurrence rate of Parkfield earthquakes from 1857 to 1966. Two possible M ~5.3–5.5 aftershocks on 2 February (GMT) and 6 May 1881. See text and Appendix A for more information.
06 Mar 1882	36.400	−121.000	6.0 M_A	Bitterwater: The new location near Bitterwater, about 60 km northwest of the Parkfield activity, makes this 1882 earthquake one of the most southerly of the rare M 6 events in the "creeping zone" of the San Andreas fault. Several panes of glass were cracked in a Salinas store, and many people rushed into the streets in Santa Cruz. At Hollister, people hurried from houses. The relatively strong effects at Merced (damage to plaster ceilings) and Charleston (Fresno Co.) suggest an epicenter east or southeast of Hollister. The strongest intensity reported was MMI VI at Bitterwater where the walls and ground "seemed to sway from west to east fully a foot and the ground seemed to volt up and down fully that much", and where it created panic, broke the clock, and triggered rockfalls; "it was not as heavy in Peachtree" (Matthews, 1869–1900). This event was stronger at Bitterwater than was the neighboring larger *M 6.5 event of 2 April 1885*, described below. Compared to the 1961 earthquake of M 5.6 south of Hollister, the 1882 event was to the southeast and stronger, particularly at Visalia, Fresno, and Merced. See text for more information.
27 Jun 1882	37.100	−121.900	5.8 M_A	South Santa Cruz Mountains: Newly identified earthquake. At San Jose walls were cracked and plaster fell (MMI VI). At Santa Cruz Mountains chimneys were overturned and windows were broken (MMI VII) (Monthly Weather Review). At Santa Cruz, Alma, Los Gatos, and Saratoga, "people ran out in dire alarm" some in their night clothes (MMI VI). At San Francisco crockery was broken (MMI V–VI). At Hollister "A number of people living in brick houses were seriously frightened and took refuge in wooden buildings. No damage resulted" (MMI V–VI). At Watts tract (in the delta) the shock awoke sleepers, and those awake ran out (MMI V). At Stockton, the shock awakened sleepers (MMI IV–V). The quake was strongly felt from Hollister to San Rafael, as far north as Santa Rosa, and as far east as Stockton and Merced. The epicenter was roughly located near those of the strong October 1865 and 1989 Loma Prieta earthquakes.
30 Mar 1883	36.800	−121.500	6.0 M_A	San Juan Bautista: At Hollister crockery, glassware, and several large windows broke, and plaster in brick buildings fell. Chimneys were thrown down at Sargents and Old Gilroy (MMI VII), Santa Clara Co. Violent at Watsonville, breaking crockery, and plaster. In Santa Cruz people ran into the streets. Gilroy reported 8 to 12 aftershocks. Two widely felt aftershocks occurred 9 and 30 min after the earthquake. Reported felt from Sacramento to San Luis Obispo, and San Francisco to Merced.
5 Sept 1883	34.900	−119.300	~5.8 M_A	San Emigdio: Moved from Santa Barbara Channel based on new information from Kern County. See text for more information.
31 Mar 1885	36.500	−121.100	5.7 M_A	Northwest of Bitterwater: At Hollister some plaster fell and people rushed into the streets; a foreshock was felt about 3 hours before, and three aftershocks were felt in the 7 hours after the mainshock. At Mulberry, 20 km to the southeast of Hollister, chimneys were thrown down. Thirty kilometers further to the southeast at Bitterwater, Matthews reported two shocks, one of which "lasted quite a while but was not severe." The event was felt as far away as San Rafael.
02 Apr 1885	36.450	−121.050	5.9 M_A	Northwest of Bitterwater: At Salinas, crockery was rattled and people ran out. A possible foreshock was felt at Salinas at midnight. At Merced several shocks were felt from 2:00 to 7:25 am, suggesting foreshocks. At Bitterwater, Matthews reported it as "very near as heavy as the one we had on March 6th three years ago . . . some of the women . . . were badly frightened." Felt to Cambria, Visalia, and Sacramento. It was previously thought to be centered on the San Andreas fault east of Salinas. New information shows that it was as strong or stronger at Bitterwater as at Salinas and indicates moving the epicenter ~50 km east-southeast of the Toppozada *et al.* (1981) epicenter, to within ~25 km of the 11 April epicenter.

12 Apr 1885	36.300	−120.900	6.5 M_A	Lonoak: This is one of the largest historical earthquakes in the Central California region between San Juan Bautista and the Parkfield area. Richter (1958, p. 472 and 533) placed the epicenter west of the San Andreas fault, on or near the Nacimiento fault where some damage was reported. Toppozada *et al.* (1981) placed the epicenter on the San Andreas fault near Bitterwater, because the effects in the Great Valley towns were generally as strong as those in the coastal towns. This contrasts with the 1952 Bryson earthquake, near the Nacimiento fault, which was much more strongly felt on the coast than in the Great Valley. Toppozada *et al.* (1990) suggested a locator east of the San Andreas fault in the Great Valley border region (Wakabayashi and Smith, 1994). However, descriptions from Bitterwater (Matthews, 1869–1900) and comparison to more recent nearby earthquakes support a San Andreas fault location near Lonoak. See text for more information.
18 Feb 1888	39.200	−123.600	5.5 M_A	Mendocino-Uklah
15 Apr 1889	36.950	−121.400	~5.5 M_A	Hollister
31 July 1889	37.800	−122.200	5.6 M_A	Hayward Fault: Damage at San Leandro and Oakland.
09 Feb 1890	33.400	−116.300	~6.8 M_W	San Jacinto fault?: Hanks and Kanamori (1979). The widely felt effects at Los Angeles, San Diego, and Yuma, Arizona, and the lack of reported damage suggest this earthquake was centered in the sparsely populated region near the southern San Jacinto fault and the juncture of San Diego, Riverside, and Imperial Counties.
24 Apr 1890	36.900	−121.600	6.3 M_A	Pajaro Gap: Extensive damage was done to chimneys, and some damage was reported in brick and frame buildings for 30 km from San Juan Bautista, San Benito County to Corralitos, Santa Cruz County (MMI VIII). At Corralitos, most chimneys were thrown down and buildings were "twisted half around." Possible fault rupture occurred along the San Andreas fault ~1 mile northwest of San Juan Bautista (Lawson, 1908, p. 38, Bakun, 1998). A railroad bridge across the Pajaro River, near the San Andreas fault, shifted 1.5 ft out of line probably due to ground failure triggered by shaking (Prentice and Schwartz, 1991; Tuttle and Sykes, 1992).
02 Oct 1891	37.300	−121.800	5.8 M_A	San Jose: At Mt. Hamilton and Santa Cruz plaster was knocked down (MMI VI). Windows were broken in San Jose (MMI VI). Reported felt from Petaluma to Monterey, and E to Merced.
12 Oct 1891	38.300	−122.400	5.9 M_A	Napa: The shock was most severe at Napa and at Sonoma, where people were shaken out of bed, chimneys demolished, windows broken, and the interior of almost every plastered house in the town showed effects of the shock (MMI VIII). Reported felt from Colusa to Salinas, and east to Stockton. Comparable in size (but not location) to the 1969 *M* 6.7 Santa Rosa event. Napa and Sonoma felt a slight foreshock 40 min before the mainshock and 8 to 12 aftershocks.
24 Feb 1892	32.550	−115.650	~7.3 M_W	Laguna Salada, Baja California: Centered in the California–Mexico border region, this earthquake caused some damage in San Diego, and stronger damage in the mountains to the east, near the western border of Imperial Valley. Numerous aftershocks were felt between San Diego and Imperial Valley. Strand (1980) and Mueller and Rockwell (1995) have suggested that this earthquake was associated with large displacements on the Laguna Salada fault in Baja California (40 km southwest of the Imperial fault), indicating an event of *M* ~7.3 (Stein and Hanks, 1998).
28 May 1892	33.200	−116.200	~6.5 M_A	San Jacinto fault: As in the 09 February 1890 earthquake, widely felt effects at Los Angeles San Diego, and Yuma, Arizona, and the lack of reported damage, suggest this earthquake was centered in the sparsely populated region generally near the San Diego–Imperial County border. However, there is a small possibility it was a strong aftershock of the major 24 February 1892 earthquake on the Laguna Salada fault.
14 Jun 1892	34.200	−117.500	5.5 M_A	Cucamonga
13 Nov 1892	36.750	−121.400	5.9 M_A	Hollister: A chimney was displaced at Hollister. In Salinas ceilings cracked, and some crockery, glassware, and windows were broken. In Monterey chimneys were cracked, and crockery and other articles were thrown from shelves. At Gilroy clocks stopped, ceilings cracked, and small articles were knocked over. Aftershocks were reported at Monterey, Salinas, and Green Valley. This event appears comparable to 1961 Cienega (Hollister) *M* 5.5 event.
09 Aug 1893	38.400	−122.700	5.6 M_A	Santa Rosa: In Santa Rosa, chimneys were shaken down, and plaster fell. At Petaluma, plaster was cracked and crockery was thrown from shelves. The earthquake was reported felt from Middletown, Lake Co., to Alameda, and east to Sacramento. This event is comparable to 1969 Santa Rosa *M* 5.7 earthquake.
30 July 1894	34.300	−117.600	6.2 M_A	Lytle Creek region

(*continued*)

Appendix B (*Continued*)

Date (GMT)	Latitude	Longitude	Magnitude*	Region / Notes
20 Jun 1897	37.000	−121.500	6.3 M_A	Gilroy: Considerable damage was done to brick buildings in the area of Gilroy and San Felipe (MMI VIII). The earthquake was felt from Woodland on the north, to San Luis Obispo on the south, and as far east as Visalia. A fissure was reported near Soap Lake House on the Pacheco Pass Road. On Frank Silva's ranch near San Felipe, a fissure 90 feet long was reported. The Calaveras fault crosses the Pacheco Pass Road 5 km northwest of San Felipe. The reported fissures could be the result of rupture on the Calaveras fault. The intensity distribution is similar to that of the 6 August 1979 earthquake of *M* 5.7 (USE 1979).
31 Mar 1898	38.200	−122.500	6.4 M_A	Mare Island: $350,000 loss; 6.5 M_S from one or two stations, Abe (1988). Considerable damage ($350,000 loss) from Mare Island to Petaluma and Napa, in the area of the southern Rodgers Creek fault (Toppozada *et al.*, 1992). Houses were knocked from their foundations at Schellville, on the Greenwood Estate, and along Petaluma Creek, Sonoma Co. Extensive ground cracks were reported at Mare Island Naval Yard, Schellville, and Greenwood Estate.
15 Apr 1898	39.200	−123.800	~6.7 M_S	Fort Bragg–Mendocino: M_s from one or two stations, Abe (1988); Bakun (2000) has M_i 6.8 −0.4, +0.3) at 39.3? 123.9?: In Mendocino County, considerable damage was done on the coast within 40 km south of Fort Bragg. The earthquake source was probably the San Andreas fault some 5 km west of Mendocino, Mendocino County. This is one of the largest earthquakes to affect the northern Coast Ranges in the late nineteenth century. Newspaper reported the shock was felt from Eureka (MMI V) to San Francisco (MMI V). A foreshock was reported at Mendocino 22 minutes before the earthquake, and numerous aftershocks were felt there. The area on land shaken at MMI VIII or greater was ~580 sq km.
30 Apr 1899	36.850	−121.600	6.0 M_A	Watsonville: Chimneys were shaken down in Watsonville and Green Valley, Santa Cruz Co. (MMI VII). At Santa Cruz bric-a-brac and clocks were shaken from shelves. In Hollister, San Benito Co., some plaster was knocked down. In Salinas, Monterey Co. some crockery and window panes were broken, and a train, engine jumped the track.
02 Jun 1899	37.700	−122.500	5.6 M_A	San Francisco area: In San Francisco, a few weak chimneys were loppled and several cornices fell in part. In Oakland many people rushed into the streets. The earthquake was felt as far as Sacramento, Modesto, and Santa Cruz and appears comparable to the 1957 Daly City earthquake.
06 July 1899	36.900	−121.400	5.8 M_A	San Juan Bautista: In Watsonville, Santa Cruz Co., several chimneys were thrown down. In Salinas a few windows and lamp chimneys were broken and people ran out. Reported felt from Petaluma to San Luis Obispo. The quake is somewhat comparable to the 1986 Jan 26 Quien Sabe event of *M* 5.5. Epicenter relocated to ~40 km south of that in Toppozada *et al.* (1981). Townley and Allen (1939) suggest a second shock at Pleasanton, where goods were thrown from shelves and brick walls cracked. We think there was a site effect at Pleasanton, because 10 km to the east the shock was slight at Livermore, and 16 km to the south-southwest, people ran out at Irvington, which is normal for the MMI V zone that extended from Modesto to Monterey.
22 July 1899	34.200	−117.400	5.9 M_A	Lytle Creek–Cajon Pass: Foreshock
22 Jul 1899	34.300	−117.500	6.4 M_W	Lytle Creek region: M_W Hanks *et al.* (1975); M_S from one or two stations, Abe (1988). Preceded 20 hr earlier by a strong *M* 5.9 foreshock, this earthquake was most damaging in the Cajon Pass–Lytle Creek area, about 20 to 30 km northwest of San Bernardino. It caused some concern (MMI V–VI) as far away as Ventura and San Diego.
25 Dec 1899	33.800	−117.000	6.7 M_W	San Jacinto and Hemet: M_S 6.4, Abe (1988), M_W. Hanks and Kanamori (1979). The Riverside County towns of San Jacinto and Hemet were severely damaged by this earthquake which was located on or near the San Jacinto fault. Six people were killed by falling adobe walls at Saboba, a few kilometers east of San Jacinto. This earthquake caused $50,000 in loss.
03 Mar 1901	36.200	−120.700	6.4 M_S	Parkfield–Priest Valley: Ms, Abe (1988). This event caused considerable damage in Parkfield and neighboring towns, and was felt to San Francisco in the north and to Porterville, Tulare county, in the east. A tsunami was generated in Monterey Bay by a probable submarine landslide triggered by the earthquake (Lander *et al.*, 1993). Numerous landslides are mapped in the submarine Monterey Canyon region (Greene and Kennedy, 1989). Four possible *M* 5–5.5 aftershocks. See text and Appendix A for more information.
11 Jun 1905	37.200	−121.800	6.1 M_A	San Jose: Chimneys were damaged at San Jose, Santa Clara, Santa Cruz, Watsonville, Hayward and Livermore. In San Francisco a few windows broke and plaster fell. In Oakland bric-a-brac and crockery fell.

03 Aug 1903	37.300	−121.800	6.2 M_A	San Jose: In San Jose, ". . . Stone trimmings and chimneys were hurled from their fastenings into the streets . . ." (*San Jose Mercury*, 3 Aug 1903). In Santa Clara chimneys broke, walls cracked, and plaster fell. In Oakland plaster and mortar fell and people ran out. Similar effects were felt in San Francisco. At Mt. Hamilton chimneys and plaster fell. This event is apparently located northward of the 11 June event.
18 Apr 1906	37.700	−122.500	7.8 M_W	Great San Francisco 1908 EQ: Ellsworth (1990). The great San Francisco earthquake resulted from rupture of the San Andreas fault from the Monterey–San Benito County line to the Humbold–Mendocino County line (Lawson, 1908; Jennings, 1994). This rupture overlapped the 1838 rupture from San Francisco to San Juan Bautista. Significant damage (MMI VII–VIII) occurred from northern Monterey County to southern Humboldt County, and as far inland as Napa (Toppozada and Parke, 1982). About 3000 deaths and $524 million in propery loss; duration of shaking, ~1 min.
19 Apr 1906	32.900	−115.500	~6.2 M_W	Imperial Valley: M_W, Stein and Hanks (1998); Ellsworth (1990). Location uncertain, Toppozada and Parke (1982)
18 May 1906	36.840	−121.540	5.6 M_i	San Juan Bautista: Meltzner and Wald (2002), 18 April aftershock.
20 Sept 1907	34.200	−117.100	~5.8 M_A	San Bernardino region: Richter (1958), p. 469, Stein and Hanks (1998) assign $M < 6$; 5.3 M_W Hanks *et al.* (1975)
27 Apr 1908	36.000	−120.550	~5.8 M_A	Parkfield region: See text for more Information.
11 Mar 1910	36.950	−121.700	5.8 M_S	Watsonville: M_S, Abe (1988). At Chittenden bottles were thrown from shelves and houses rocked and creaked. At Santa Cruz plaster fell, crockery shattered, and windows broke. Watsonville had broken windows and crockery. At Salinas sleepers woke up and some ran outside. Reported felt from San Luis Obispo to Nevada City, and east to Visalia. This is probably a late aftershock of the 1906 earthquake near the southern end of the fault rupture.
11 Apr 1910	33.500	−116.500	5.8 M_A	Anza–Borrego Springs: Comparable to 1980 Anza M 5.5 and 1969 Borrego Springs M 5.8 events
01 Jul 1911	37.250	−121.750	6.4 M_A	Southeast of San Jose: Brick walls cracked and chimneys were destroyed over a distance of 35 km in Santa Clara Valley between Santa Clara and Morgan Hill. Toppozada (1984) compared this event to the 1984 Morgan Hill earthquake and found that the areas shaken at MMI VI and VII were roughly comparable. M preferred is mean of M_A and M_{gr}.
23 Jun 1915	32.800	−115.500	6.0 M_W	Imperial Valley: Stein and Hanks (1998)
23 Jun 1915	32.800	−115.500	5.9 M_S	Imperial Valley: 5.5 M_W, Hanks *et al.* (1975)
06 Aug 1916	36.670	−121.250	5.6 M_A	Palcines area: At Paicines chimneys at a hotel were destroyed; slight damage at Hollister. Huge boulders rolled onto the highway at Chittenden Pass, Santa Cruz County. Reported felt from Sausalito to Paso Robles, and east to Merced.
30 Sept 1916	33.200	−116.100	5.7 M_A	Borrego Mountain: Calexico felt foreshock 14 hr earlier
23 Oct 1916	34.850	−119.000	5.5 M_A	Tejon Pass region: M ~5 aftershock 10 min later. Modified from Toppozada and Parke (1982). 5.3 M_W, Stein and Hanks (1998)
28 May 1917	32.800	−115.300	~5.5 M_A	Imperial Valley
21 Apr 1918	33.750	−117.00	6.8 M_W	San Jacinto: Hanks *et al.* (1975). Major damage at San Jacinto and Hemet resulted in several injuries, one death and $200,000 in damage (Stover and Coffman 1993). This earthquake was quite similar to the 25 Dec 1899 event on the San Jacinto fault.
01 May 1918	32.600	−115.400	5.6 M_A	Imperial Valley
06 Jun 1918	33.600	−116.700	5.5 M_A	San Jacinto Mountains: aftershock of April 1918 San Jacinto earthquake
16 Feb 1919	34.900	−119.200	5.7 M_A	Tejon Pass region: preceeded on 25 January by M ~4 foreshock
10 Mar 1922	36.100	−120.600	6.3 M_S	Parkfield–Priest Valley: Bakun and McEvilly (1984), Stein and Hanks (1998); Ellsworth (1990); Possible M 5–5.5 aftershock ~5 min later; See text and Appendix A for more information and aftershocks.
18 Aug 1922	36.100	−120.600	5.7 M_A	Parkfield–Priest Valley: See text and Appendix A for more information and aftershocks.
23 Jul 1923	34.000	−117.250	6.2 M_W	San Bernadino region: Stein and Hanks (1998).
07 Nov 1923	32.500	−115.500	~5.5 M_A	Imperial Valley: Had M ~5 foreshock on 5 November.

(*continued*)

Appendix B (*Continued*)

Date (GMT)	Latitude	Longitude	Magnitude*	Region / Notes
01 Jan 1927	32.500	−115.500	5.5 M_{gr}	Mexicalli: Gutenburg and Richter (1949); Toppozada *et al.* (1978)
01 Jun 1927	32.500	−115.500	5.8 M_A	Mexicalli: Aftershock. Gutenburg and Richter (1949); Toppozada *et al.* (1978).
02 Oct 1928	33.600	−116.700	~5.5M_A	San Jacinto: Roughly located.
08 Jan 1934	35.950	−120.500	6.0 M_W	Parkfield: Bakun and McEvilly (1984); Stein and Hanks (1998); See text for more information.
25 Mar 1937	33.500	−116.400	5.6 M_W	Buck Ridge: Location, Sanders *et al.* (1986); *M*, Hutton and Jones (1993); Hanks *et al.* (1975), and Doser (1990) list M_W 5.6
12 Sept 1938	40.000	−124.000	5.5 M_L	Pepperwood: Ferndale
19 May 1940	32.733	−115.500	7.0 M_W	Imperial Valley: Stein and Hanks (1998); Hutton and Jones (1993); Ellsworth (1990). The El Centro earthquake took nine lives and caused property damage estimated at $6 million, which included damage from a *M* 5.5 aftershock near Brawley, 75 min later. Right-lateral displacements of up to 5.8 m were observed on the imperial fault. Surface faulting extended ~60 km southeast from Brawley and ~30 km south of the U.S.–Mexican border.
19 May 1940	32.767	−115.483	5.5M_L	Imperial Valley: Aftershock.
19 May 1940	32.767	−115.483	5.5 M_L	Imperial Valley: Aftershock.
19 May 1940	32.767	−115.483	5.5 M_L	Imperial Valley: Aftershock.
20 Dec 1940	40.000	−124.000	5.5 M_L	Fort Bragg
21 Oct 1992	32.967	−116.000	6.4 M_W	Fish Creek Mountains, Lower Borrego Valley: Stein and Hanks (1998); Hutton and Jones (1993); Ellsworth (1990). Centered near the remote Borrego Valley in Imperial County, this earthquake resulted in only minor damage.
22 Oct 1942	33.233	−115.717	6.0 M_W	Salton Sea: Aftershock. Stein and Hanks (1998).
15 Aug 1945	33.217	−116.133	5.7 M_L	San Jacinto: Hutton and Jones (1993).
04 Dec 1948	33.933	−116.383	6.0 M_W	Desert Hot Springs: Hutton and Jones (1993); Hanks *et al.* (1975); Nicholson (1996).
29 Jul 1950	33.117	−115.567	5.5 M_L	Imperial Valley: Hutton and Jones (1993).
24 Jan 1951	32.983	−115.733	5.8 M_L	Imperial Valley: Hutton and Jones (1993).
14 Jun 1953	32.950	−115.717	5.5 M_L	Brawley: Hutton and Jones (1993).
19 Mar 1954	33.283	−116.183	6.3 M_W	Arroyo Salada: Stein and Hanks (1998); Hutton and Jones (1993).
19 Mar 1954	33.283	−116.183	5.5 M_L	Arroyo Salada: Aftershock
25 Apr 1954	36.903	−121.610	5.6 M_L	Watsonville: Uhrhammer (1999). Along the Chittenden Road, east of Watsonville, several poorly built houses were shifted on their foundations and damaged severely; ground cracks formed along the Pajaro River. At Interlaken District and Aromas, several chimneys toppled. Reported felt along the coast from Santa Rosa to San Ardo, and east to Fresno. Bolt and Miller (1975) listed M_L 5.3.
09 Apr 1961	36.680	−121.300	5.5 M_L	Hollister: Uhrhammer (1999). Two strong earthquakes damaged many buildings in Hollister and vicinity causing an estimated $250,000 of property damage. Major damage occurred at the County Courthouse, the Dabo Hotel, and the Elks building. South of Hollister, on Cienega Road, a 15-m fissure occurred near the winery, which was severely damaged. Bolt and Miller (1975) listed M_L 5.6 and 5.5.
09 Apr 1961	36.700	−121.300	5.5 M_L	Hollister: Uhrhammer (1999). See description above.
28 Jun 1966	35.960	−120.505	5.5 M_L	Parkfield: M_W 5.5, Bakun (1984); Stover and Coffman (1993), foreshock. See text for more information.
28 Jun 1966	35.950	−120.500	6.0 M_W	Parkfield: Bakun and McEvilly (1984); Stein and Hanks (1998); See text for more information.
09 Apr 1968	33.190	−116.129	6.6 M_W	Borrego Mountain: Stein and Hanks (1998); Hutton and Jones (1993). The Borrego Mountain earthquake was accompanied by surface rupture on the Coyote Creek segment of the San Jacinto fault in the sparsely populated area near the San Diego–Imperial County line. Damage was limited.

28 Apr 1969	33.343	−116.346	5.8 M_W	Borrego Springs: Hutton and Jones (1993); M_W; Thatcher *et al.* (1975)
02 Oct 1969	38.470	−122.690	5.6 M_L	Santa Rosa: Two earthquakes 83 min apart caused one death, and severe property damage estimated at $8.35 million in Santa Rosa. Several old brick and wood-frame buildings were damaged beyond repair; chimneys destroyed; sidewalks buckled; and underground pipes ruptured. Other buildings severely damaged included the County Social Services Building, Fremont Elementary School, J.C. Penny Store, and the Veterans Memorial Building. Both earthquakes were felt south to Santa Cruz and east to Sacramento. Bolt and Miller (1975) listed M_L 5.6 and 5.7.
02 Oct 1969	38.460	−122.690	5.7 M_W	Santa Rosa: See description above.
06 Aug 1979	37.104	−121.512	5.7 M_W	Coyote Lake: In Hollister and Gilroy, 16 people were injured and property damage was estimated at $500,000. These two towns had damaged chimneys, broken glassware in stores, and structural damage to five buildings in Gilroy. At Hollister a parapet toppled, and several ceilings partly collapsed. Horizontal displacement (5–6 mm) occurred about 10 km east of Gilroy along the Calaveras fault.
15 Oct 1979	32.614	−115.318	6.5 M_W	Imperial Valley: Stein and Hanks (1998); Hutton and Jones (1993); Hartzell and Heaton (1983). This Imperial Valley earthquake injured 90 people and caused ~$30 million in damage. Much of the damage was to the Imperial County Services building, designed under the 1967 California Uniform Building Code, which had to be razed because of failure of the soft first story. Surface faulting in 1979 extended from 5 to 36 km northwest of the Mexican border, along part of the segment that ruptured in 1940. Within 5 km northwest of the border, in the area of 2.5- to 5.8-m displacements in 1940, there was no surface faulting in 1979. The 1979 fault displacements had a maximum of 0.75 m, and from 11 to 33 km northwest of the border had the same general amplitude as in the 1940 earthquake (Sharp, 1982).
16 Oct 1979	33.014	−115.555	5.5 M_L	Imperial Valley: M_L, Hutton and Jones (1993); 5.4 M_L(PDE), aftershock.
25 Feb 1980	33.501	−116.513	5.5 M_L	Anza
26 Apr 1981	33.099	−115.632	5.9 M_W	Westmorland, Imperial Valley: Ellsworth (1990); Hutton and Jones (1993).
24 Apr 1984	37.310	−121.677	6.2 M_W	Morgan Hill: Estimated property damage of $8 million and 27 injuries mainly in the Morgan Hill area; 522 private dwellings and 43 commercial buildings were damaged MMI VIII effects were confined to two streets, a small area east of Morgan Hill. Jackson Oaks area had five houses condemned, houses off their foundations and partly collapsed, and 17 mobile homes shaken off their supports. Near Coyote, damage was estimated at $1.5 million.
26 Jan 1986	36.803	−121.284	5.5 M_W	Palcines–Hollister: Near the Quien Sabe fault. Damage to wine vats in Paicines was estimated at $800,00. Hollister had broken gas pipes and ruptured water lines. At Tres Pinos two chimneys fell.
08 July 1986	33.999	−116.609	6.0 M_W	North Palm Springs: Stein and Hanks (1998); Hutton and Jones (1993).
24 Nov 1987	33.090	−115.793	6.2 M_W	Elmore Ranch fault: Hutton and Jones (1993); Sipkin (1989). In western Imperial County, a strong earthquake occurred on the northeast-trending Elmore Ranch fault. Its left-lateral slip appears to have relieved normal locking stress on the adjoining northwest-trending Superstition Hills fault, triggering an even stronger earthquake and extensive rupture 11 hr later. The location and geometry of these faults is shown on the Fault Activity Map of California (Jennings, 1994). The remoteness of these earthquakes from any substantial population centers accounts for the low estimated damage of ~$3 million.
24 Nov 1987	33.015	−115.852	6.6 M_W	Superstition Hills: Hutton and Jones (1993); Sipkin (1989); see description above.
18 Oct 1989	37.040	−121.877	6.9 M_W	Loma Prieta: Bakun (1999). The major Loma Prieta earthquake was centered on or near the San Andreas fault in the relatively remote southern Santa Cruz mountains. It caused 63 deaths, 3,757 injuries, and an estimated $6 billion in damage. Most of these losses occurred in densely urban Oakland and San Francisco, about 90 km north-northwest of Loma Prieta. Substantial losses also occurred much closer to Loma Prieta, especially in Santa Cruz and Watsonville. McNutt and Sydnor (1990) describes the earthquake's setting and effects.

*M_A is based on the areas shaken at or above certain MMI values (Toppozada and Branum, 2002).

†M_i is from Bakun (1999, 2000), unless otherwise noted, using MMI at individual points from Toppozada *et al.* (1981, 1982).

Events with magnitudes of M_L, unless otherwise noted are from University California, Berkeley (UCB) or from the California Institute of Technology (CIT) earthquake catalogs. Magnitudes: M_A, area-determined magnitude (Toppozada & Branum, 2002); M_i, intensity magnitude (Bakun and Wentworth, 1997); M_W, moment M; M_S, surface-wave magnitude; M_{gr}, Gutenburg and Richter magnitude; M_L, local magnitude.