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Aftershocks and Triggered Events of the Great 1906 California Earthquake

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Abstract The San Andreas fault is the longest fault in California and one of the longest strike-slip faults in the world, yet little is known about the aftershocks following the most recent great event on the San Andreas, the M_W 7.8 San Francisco earthquake on 18 April 1906. We conducted a study to locate and to estimate magnitudes for the largest aftershocks and triggered events of this earthquake. We examined existing catalogs and historical documents for the period April 1906 to December 1907, compiling data on the first 20 months of the aftershock sequence. We grouped felt reports temporally and assigned modified Mercalli intensities for the larger events based on the descriptions judged to be the most reliable. For onshore and near-shore events, a grid-search algorithm (derived from empirical analysis of modern earthquakes) was used to find the epicentral location and magnitude most consistent with the assigned intensities. For one event identified as far offshore, the event's intensity distribution was compared with those of modern events, in order to constrain the event's location and magnitude.

The largest aftershock within the study period, an $M \sim 6.7$ event, occurred ~ 100 km west of Eureka on 23 April 1906. Although not within our study period, another $M \sim 6.7$ aftershock occurred near Cape Mendocino on 28 October 1909. Other significant aftershocks included an $M \sim 5.6$ event near San Juan Bautista on 17 May 1906 and an $M \sim 6.3$ event near Shelter Cove on 11 August 1907. An $M \sim 4.9$ aftershock occurred on the creeping segment of the San Andreas fault (southeast of the mainshock rupture) on 6 July 1906. The 1906 San Francisco earthquake also triggered events in southern California (including separate events in or near the Imperial Valley, the Pomona Valley, and Santa Monica Bay), in western Nevada, in southern central Oregon, and in western Arizona, all within 2 days of the mainshock. Of these triggered events, the largest were an $M \sim 6.1$ earthquake near Brawley and an $M \sim 5.0$ event under or near Santa Monica Bay, 11.3 and 31.3 hr after the San Francisco mainshock, respectively. The western Arizona event is inferred to have been triggered dynamically. In general, the largest aftershocks occurred at the ends of the 1906 rupture or away from the rupture entirely; very few significant aftershocks occurred along the mainshock rupture itself. The total number of large aftershocks was less than predicted by a generic model based on typical California mainshock–aftershock statistics, and the 1906 sequence appears to have decayed more slowly than average California sequences. Similarities can be drawn between the 1906 aftershock sequence and that of the 1857 (M_W 7.9) San Andreas fault earthquake.

Introduction

The 18 April 1906, 5:12 a.m. (unless noted otherwise, all times are given in Pacific Standard Time [PST]) M_W 7.8 San Francisco earthquake, which broke the northern San Andreas fault (SAF) from San Juan Bautista to near Shelter Cove (Fig. 1a), has been a centerpiece of seismological investigation in California, yet little attention has been paid to its aftershocks and triggered events. Questions as to the size, location, and timing of the largest aftershocks have not heretofore been addressed, even though an earthquake as large as the 1906 mainshock might be expected to have potentially damaging aftershocks. At least one sizable triggered event occurred in the Imperial Valley in southern California (11.3 hr after the mainshock), but the possibility of additional triggered events in other locations has not been explored. This study is an attempt to shed light on some of these unresolved issues and to improve our understanding of the behavior of

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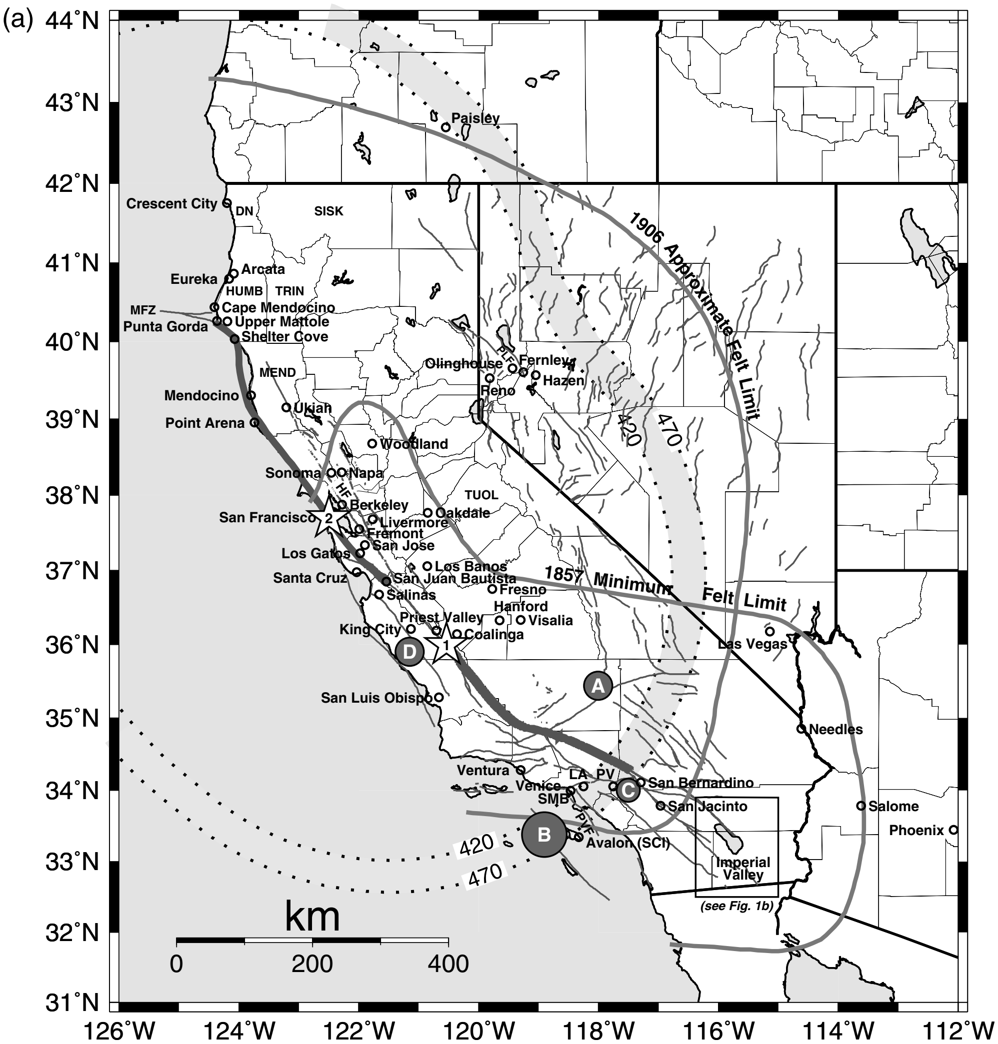

Figure 1. Caption on next page.

aftershocks following large earthquakes on the SAF. It is also an attempt to expand our knowledge of historical earthquake triggering. Until recently, the seismological community did not generally appreciate the fact that large earthquakes are capable of triggering events at distances far greater than those associated with classic aftershocks; since the 1992 Landers, California, earthquake, however, numerous studies have documented the reality of triggered earthquakes (e.g., Hill *et al.*, 1993; Anderson *et al.*, 1994; Bodin and Gomberg, 1994; Gomberg and Davis, 1996; Brodsky *et al.*, 2000; Mohamad *et al.*, 2000; Gomberg *et al.*, 2001; Hough, 2001; Hough *et al.*, 2001; Hough and Kanamori, 2002; Papadopoulos, 2002; Vilanova *et al.*, 2003). Most recently, the November 2002 M_W 7.9 Denali fault, Alaska, earthquake triggered seismicity up to an epicentral distance of 3660 km (Hill *et al.*, 2002; Husen *et al.*, 2002; Johnston *et al.*, 2002; Moran *et al.*, 2002; Pankow *et al.*, 2002). This report provides additional data for triggering studies.

Although several efforts have been made to catalog the aftershocks and triggered events of the 1906 earthquake (e.g., Lawson, 1908; Townley and Allen, 1939), those efforts were spotty in their completeness and often lacking in enough detail to permit reliable assessments or estimates of magnitude and location. Steeples and Steeples (1996) looked at triggered events that occurred within 24 hr of the 1906 San Francisco mainshock, but their data appear to be flawed by at least one substantial error. (Their erroneous datum—a report taken from Lawson [1908] of an event supposed to have taken place at 12:31 p.m. on 18 April 1906 in Los Angeles—was not substantiated by a single newspaper or diary in southern California; rather, it appears to be a misdated report of the earthquake that was widely documented to have hit Los Angeles at 12:31 p.m. on 19 April 1906.)

In spite of this, the historical record is full of useful and valuable information that can enhance the existing catalogs. For the present study, we have searched newspapers, diaries, and other historical documents for felt reports of potential aftershocks and triggered events of the 1906 earthquake. (A “felt report” is any written statement in which the author describes shaking and/or effects caused by an earthquake or

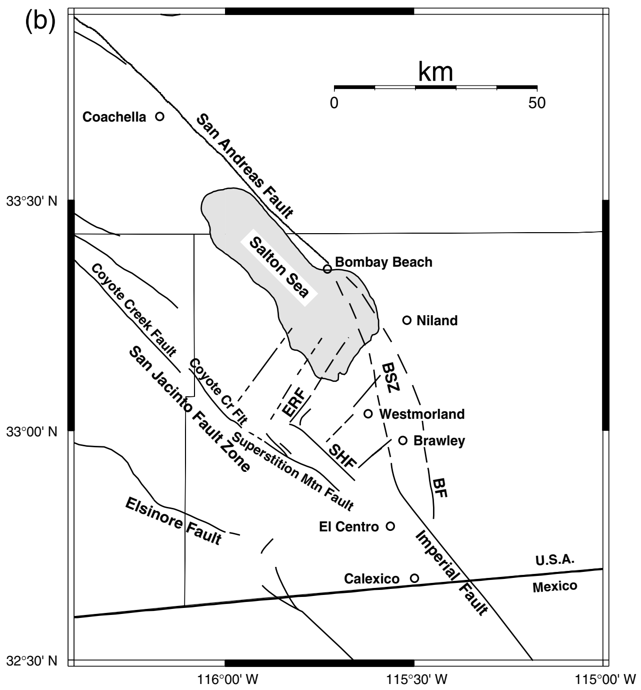

Figure 1. (a) Comparison of the surface ruptures (thick lines adjacent to stars) of the 18 April 1906 (M_W 7.8) and 9 January 1857 (M_W 7.9) earthquakes on the San Andreas fault. The map shows the 1906 epicenter (star 2) of Bolt (1968) and the 1857 epicenter (star 1) suggested by Sieh (1978b), as well as the approximate felt limit of the 1906 earthquake (from Lawson, 1908) and the minimum felt limit of the 1857 earthquake (from Sieh, 1978a). Other faults within California and Nevada are shown as thin lines. Distance contours of 420 and 470 km (the equivalent of one rupture length, given its uncertainties) from the 1906 mainshock rupture are shown as dotted lines. Also shown are the preferred locations of the largest aftershocks (annotated circles) of the 1857 earthquake: A, 9 January 1857, $M \sim 6.25$; B, 16 January 1857, $M \sim 6.7$; C, 16 December 1858, $M \sim 6$; and D, 16 April 1860, $M \sim 6.3$. The magnitudes and locations for A, B, and D are from Meltzner and Wald (1999); C is from Ellsworth (1990). The reader should be reminded that there are considerable uncertainties in magnitude and location for all four events. Superimposed on this map are locations discussed in the text. LA, Los Angeles; PV, Pomona Valley; SCI, Santa Catalina (Catalina) Island; SMB, Santa Monica Bay; HF, Hayward fault; MFZ, Mendocino fracture zone (Mendocino fault); PLF, Pyramid Lake fault; PVF, Palos Verdes fault. Counties: DN, Del Norte; HUMB, Humboldt; MEND, Mendocino; SISK, Siskiyou; TRIN, Trinity; TUOL, Tuolumne. The location of panel (b) is also shown. (b) Index map of the Imperial Valley vicinity showing locations and faults discussed in the text. BF, Brawley fault; BSZ, Brawley Seismic Zone; ERF, Elmore Ranch fault; SHF, Superstition Hills fault. See panel (a) for general location.

in which the author simply notes that an earthquake was felt.) A catalog of these felt reports is published separately as a U.S. Geological Survey open-file report (Meltzner and Wald, 2002). Altogether, this catalog represents the most comprehensive compilation to date of earthquake data from the historical record during the period immediately following the 1906 San Francisco earthquake.

In general, the distinction between an aftershock and a triggered event is based on the distance of said event from its mainshock. An aftershock is generally defined as any earthquake that occurs within one fault rupture length of its mainshock (in this case, within 420–470 km of the mainshock rupture [Sieh, 1978a]) and during the span of time that the seismicity rate in that region remains above its pre-mainshock background level (e.g., Hough and Jones, 1997). It is not clear that this general definition is applicable given the extraordinary length of the 1906 rupture. Likewise, no definition of a triggered event is universally accepted, but in this report, the term "triggered event" will apply to any earthquake that occurred more than 470 km from the mainshock rupture and days to weeks after the mainshock. It will also apply to a number of earthquakes that occurred in or near the periphery of the aftershock zone in Oregon and Nevada—since these events occurred in the Basin and Range province, a tectonic region distinct from most of California, it was felt that they should not be classified as aftershocks—and also to several events that occurred in the periphery of the aftershock zone in southern California.

Hough and Jones (1997) suggested that the distinction between aftershocks and triggered events may reflect imprecise taxonomy rather than a clear distinction based on physical processes. Indeed, Bak *et al.* (2002) argued that earthquakes in California (and presumably elsewhere) behave in a hierarchical fashion in time, space, and magnitude, and they proposed a unified scaling law for the waiting times between earthquakes, whereby time, space, and magnitude are not independent. If real, their results imply that there is no fundamental difference between aftershocks and triggered events. Nevertheless, the distinction is adopted in this article as a means to emphasize the surprising number of significant "far-field aftershocks" that occurred in the hours and days following the San Francisco mainshock. It should be emphasized that no particular mechanism of earthquake triggering is being evaluated in this article; rather, we are merely suggesting that these far-field aftershocks (which are not aftershocks by conventional definitions) are triggered by (that is, they are related to) the mainshock.

This report includes only those triggered events that occurred within the first week of the mainshock and only those aftershocks that occurred within a 20-month period following the 1906 mainshock, that is, between April 1906 and December 1907. The cutoff of 1 week for triggered events seems logical, as there was a marked clustering of earthquakes in the western U.S. during the first 48 hr following the mainshock, and this regional spurt of activity apparently died off rather soon thereafter. The cutoff of December 1907 for aftershocks is arbitrary, however; analysis of earthquakes in existing catalogs (e.g., Townley and Allen, 1939) makes it clear that the aftershock sequence continued long after the year 1907. Ellsworth *et al.* (1981) used the record of aftershocks felt at Berkeley to suggest that the aftershock sequence lasted until about 1915. Nevertheless, an investigation limited to the first 20 months has already been a formidable undertaking, and expanding the duration of the study period is left as a possible avenue for further research.

It may also be productive to compare the aftershock sequence of an earlier event on the SAF, the January 1857 M_W 7.9 Fort Tejon earthquake on the Carrizo and Mojave segments of the fault, with that of the 1906 earthquake. Previous work (Meltzner and Wald, 1999) has shown that the aftershock rate for the 1857 event was below average, but within one standard deviation of the number of aftershocks expected based on statistics of modern southern California mainshock–aftershock sequences. The largest aftershocks of the 1857 earthquake included two significant events during the first 8 days of the sequence, with magnitudes $M \sim 6.25$ and ~ 6.7, near the southern half of the rupture. Later aftershocks included an $M \sim 6$ event near San Bernardino in December 1858 and an $M \sim 6.3$ event near the Parkfield segment in April 1860. All of the largest 1857 aftershocks appear to have occurred off the SAF (Fig. 1a), although there is considerable uncertainty in the aftershock locations as a result of the ambiguous nature of some of those earlier data.

Methodology

Bakun and Wentworth (1997, 1999) developed a method for the analysis of modified Mercalli intensity (MMI) values that results in an intensity magnitude M_I calibrated to equal moment magnitude M_W (Hanks and Kanamori, 1979). This method is an objective approach for analyzing intensity data, even for earthquakes for which only a small number of MMI values are known, and it provides objective uncertainties, empirically tied to confidence levels, for M_W and for source location. The method of analysis we employ in this article is adapted from that of Bakun and Wentworth (1997, 1999). The modifications we made to their method are discussed in the appendix of Meltzner and Wald (1999): specifically, for cases in which there are 30 or fewer intensity data points, Bakun and Wentworth's (1997) distance weighting function increases the error in their results, and consequently, we do not employ said function in this article. The method can be summarized in the following three steps:

1. Calculate the best magnitude, M_I, at each point of a grid of trial source locations in the felt region. Here, M_I is the mean of M_i, and

$$M_i = [(\mathrm{MMI}_i - C_i) + 3.29 + (0.0206 * \Delta_i)]/1.68, \quad (1)$$

where MMI_i is the MMI value at site i, Δ_i is the distance (km) from a trial source location to site i, and C_i is Bakun and Wentworth's (1997) empirical MMI correction for site i. Site corrections are not used in this study, so, effectively, $C_i = 0$ for all i. Also compute the total root mean square (rms) error between observed and predicted intensities, $\mathrm{rms}[M_I]$, for the magnitude, M_I, at the trial source location. Here,

$$\mathrm{rms}[M_I] = [\mathrm{rms}(M_I - M_i) - \mathrm{rms}_0(M_I - M_i)], \quad (2)$$

where $\mathrm{rms}_0(M_I - M_i)$ is the minimum rms over the grid of trial source locations.

2. The $\mathrm{rms}[M_I]$ contours bound the epicentral region. The level of confidence can be assigned to each contour based on the number of MMI observations. Values for the $\mathrm{rms}[M_I]$ contours corresponding to the 95%, 80%, and 50% levels of confidence, for various quantities of MMI observations, are taken (or interpolated) from Meltzner and Wald (1999). The trial source location for which $\mathrm{rms}[M_I]$ is minimum is the point source of seismic energy that best satisfies the available intensity data (Bakun, 2000). This location, called the "intensity center," corresponds more to the moment centroid than to the epicenter (Bakun, 1999a). The contours of $\mathrm{rms}[M_I]$ appropriate for the 95%, 80%, and 50% levels of confidence appear as solid gray lines in Figures 2–6 and 8–13, and the intensity center appears as a white star. Generally, the "best" or "preferred" source location is assigned based upon *both* the lowest rms $[M_I]$ contours and tectonic considerations; that is, we look for tectonically feasible locations (i.e., faults large enough to support a given earthquake magnitude) in light of the rms contours. Our preferred source location is indicated by either a shaded star or a shaded box in the aforementioned figures. Like the intensity center, the preferred location should correspond more to the moment centroid than to the epicenter.
3. The magnitude associated with a particular trial source location can be read from the magnitude contours for the grid, which appear as dotted black lines in Figures 2–6 and 8–13. M_I at a tectonically feasible source location within an appropriate confidence-level contour is the best estimate of M_W for that source location. The statistical uncertainty in M_W appropriate for the number of MMI observations and the desired level of confidence are taken from Bakun and Wentworth (1999) and are listed in Table 1.

This method works in many cases, although there are some considerable caveats. While the method is useful for most onshore and near-coast offshore events, Bakun (2000) established that the confidence contours for location generally fail to usefully constrain the source regions for earthquakes located more than a few tens of kilometers offshore. Bakun substantiated this problem while analyzing earthquakes off California's north coast, and it seems logical that this problem would exist any time an epicenter is far offshore

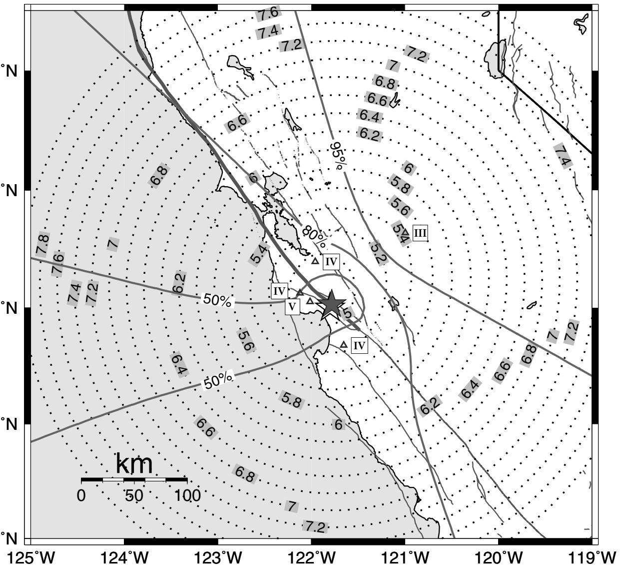

Figure 2. Map of the 18 April 1906 (14:28) aftershock. Triangles designate locations for which there is intensity information; adjacent to each triangle is a Roman numeral that indicates the MMI value. (On other figures, "NF" or "NF?" indicates that an event was reported or is inferred, respectively, to have not been felt at a particular location. Locations where the earthquake is reported to have been felt, but for which an MMI value could not be determined, are not shown.) The rms[M_I] contours corresponding to the 50%, 80%, and 95% confidence levels for the location are shown as solid lines. The intensity center is a white star, and the preferred source location is shown as a dark star. Contours of M_I are dotted lines. Thin lines are faults, and the thick line represents the 1906 rupture. See Table 14 for the preferred magnitude and for coordinates of the preferred location.

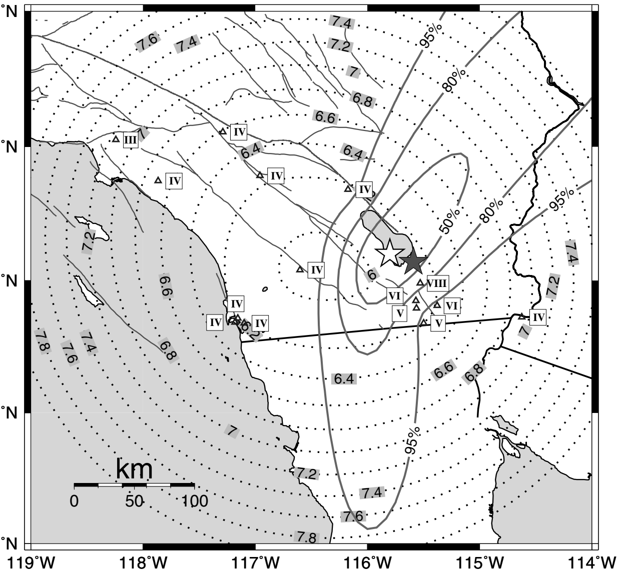

Figure 3. Map of the 18 April 1906 Imperial Valley triggered event. See Figure 2 for explanation.

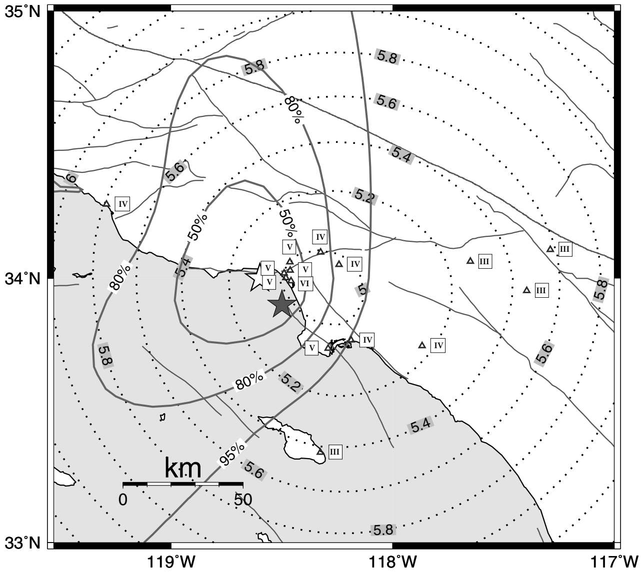

Figure 4. Map of the 19 April 1906 Santa Monica Bay triggered event. See Figure 2 for explanation.

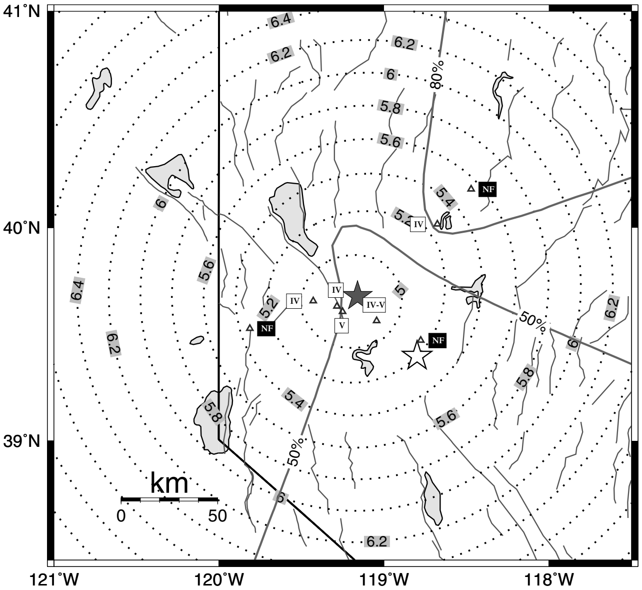

Figure 5. Map of the 19 April 1906 western Nevada triggered event. See Figure 2 for explanation. Note that the 95% confidence-level contour is off the map; the entire area shown is within the 95% confidence contour.

or otherwise not surrounded by observations. Determining accurate epicenters for earthquakes external to any local network is difficult (Lee and Stewart, 1981); error ellipses for such epicenters typically are elongated with major axes perpendicular to the near edge of the network. Similarly, the confidence contours for location from intensity data for offshore earthquakes generally are elongated perpendicular to the coast, the edge of the network of MMI observation sites (Bakun, 2000). The inability of the method to usefully con-

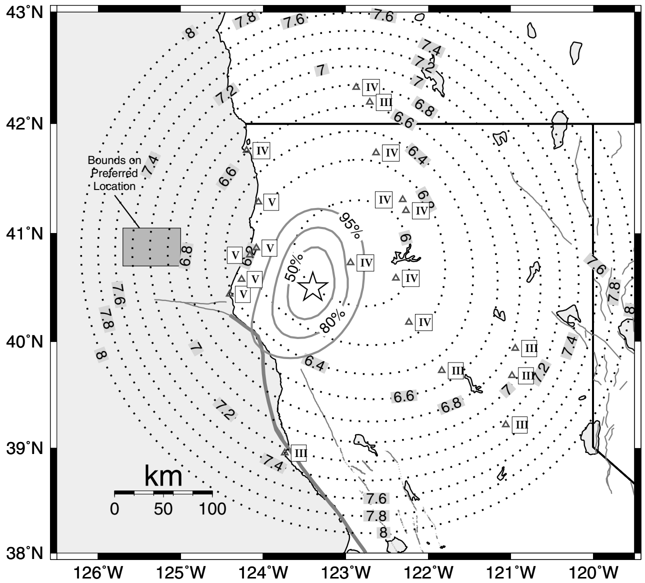

Figure 6. Map of the 23 April 1906 aftershock. See Figure 2 for explanation. For this event, the preferred source region is shown as a shaded box.

strain the source locations notwithstanding, Bakun (2000) demonstrated that M_I's at the (instrumentally determined) epicenters of offshore earthquakes generally agree with the instrumental magnitudes. Still, Bakun (1999a) identified at least two events where M_I differed from instrumental magnitudes by more than 0.6; he suggested that, for events more than 100 km offshore, M_I may not be a reliable estimator of M_W because these events and the training-set events have very different distributions of epicentral distance. (The training-set events are those used by Bakun and Wentworth [1997] to establish the empirical formulas of their algorithm.)

Bakun (2000) suggested a modified analysis strategy for north-coast events suspected of being offshore. Large earthquakes far offshore can sometimes be distinguished from smaller events near the coast or onshore based upon the strongest intensities and the areas over which the moderate to highest intensities extend. In general, moderate to large coastal earthquakes have a small area of high intensities near the epicenter, but are not felt strongly inland, whereas larger events farther offshore tend to lack observations of the highest intensities but are felt over much broader areas: farther inland and farther north and south. Using guidelines suggested by Bakun (2000), and by comparing the intensity distributions of potentially offshore north-coast events with those of modern north-coast events of known source parameters, one can constrain the location of the historic events in question.

For the present article, felt reports were grouped temporally, and MMIs were assigned for the larger events based on the accounts judged to be the most reliable. (For all of the felt reports, see Meltzner and Wald [2002]; lists of assigned MMIs for each significant event are included in this article as Tables 2–6 and 8–13.) For onshore and near-shore events, the grid-search algorithm of Bakun and Wentworth (1997) was used (as described earlier) to find the epicentral location and magnitude most consistent with the estimated intensities. We used a grid of trial source locations spaced 0.1° (or on the order of 10 km) apart, so the maximum resolution of the intensity center is roughly ±5 km. One event was suspected of occurring off the Humboldt County coast; for this event (23 April 1906), we applied the guidelines of Bakun (2000) and compared the event's intensity distribution with that of other twentieth-century north-coast events, to constrain the event's magnitude and location. For that event, we were also able to use Abe's (1988) analysis of instrumental data to help constrain the source parameters. (This is discussed further later.)

Aftershocks and Triggered Events in the First 48 hr

In the first 2 days of the aftershock sequence, the most noteworthy events were those that occurred beyond or in the periphery of the classically defined aftershock zone. During the first 48 hr following the mainshock (which occurred at 05:12 PST), local earthquakes were reported in southern

Table 1
Limits of Confidence Parameters for Magnitude

No. MMI	Confidence Parameter 95%	90%	80%	67%	50%
3	−0.71, +0.56	−0.57, +0.47	−0.42, +0.37	−0.30, +0.29	−0.20, +0.20
5	−0.58, +0.45	−0.47, +0.38	−0.35, +0.30	−0.25, +0.23	−0.16, +0.17
7	−0.50, +0.39	−0.41, +0.33	−0.31, +0.26	−0.23, +0.21	−0.15, +0.15
10	−0.45, +0.35	−0.37, +0.29	−0.29, +0.24	−0.21, +0.18	−0.14, +0.13
15	−0.39, +0.30	−0.34, +0.26	−0.26, +0.21	−0.20, +0.17	−0.13, +0.12
20	−0.36, +0.27	−0.31, +0.24	−0.25, +0.19	−0.19, +0.16	−0.13, +0.12
25	−0.35, +0.26	−0.29, +0.22	−0.24, +0.18	−0.19, +0.15	−0.13, +0.11
30	−0.33, +0.24	−0.29, +0.21	−0.24, +0.17	−0.19, +0.14	−0.13, +0.11

From Bakun and Wentworth (1999).

Table 2
Intensity and Felt Data for the 18 April 1906, 14:28 Aftershock

City	County	State	MMI, Felt (F), or Not Felt (NF)
Alameda (pier)	Alameda	CA	F
Berkeley	Alameda	CA	F?
Antioch	Contra Costa	CA	F
Salinas	Monterey	CA	IV
Sacramento	Sacramento	CA	F
San Francisco	San Francisco	CA	F
Southampton Shoal	San Francisco	CA	F?
Stockton	San Joaquin	CA	F
San Simeon	San Luis Obispo	CA	F
Agnew	Santa Clara	CA	IV?
Los Gatos	Santa Clara	CA	F
Mount Hamilton	Santa Clara	CA	F
Santa Clara	Santa Clara	CA	F
Boulder Creek	Santa Cruz	CA	IV?
Scotts Valley	Santa Cruz	CA	V?
"4 miles south of Wrights"*	Santa Cruz	CA	F
Mare Island	Solano	CA	F
Modesto	Stanislaus	CA	III

*The locality given in Lawson (1908) is "4 miles south of Wright's Station." According to Durham (1998), Wright's Station is an old name for Wrights, a village in Santa Clara County, near the Santa Cruz County line. Four miles south of this point would be in Santa Cruz County.

California, western Arizona, western Nevada, and southern central Oregon; some of these events were large enough to cause damage or to knock items off shelves. In contrast, very few notable aftershocks were located in northern or central California during that time period. The largest aftershock or triggered event to occur within 48 hr was located in the Imperial Valley of southern California, well beyond the defined aftershock zone, 11.3 hr after the mainshock.

18 April 1906 Western Arizona Triggered Event

On the morning of the great San Francisco earthquake, several earthquake reports were received from points in Arizona (see table 2 in Meltzner and Wald [2002]). Reports from Phoenix place the shaking at between 05:48 and 05:59:13, although the time zone in which the times are given is not clear. Lawson's (1908, Vol. I, p. 410) list of 1906 aftershocks, which includes reports from Phoenix at 05:48 and 05:59:13, is prefaced by the statement, "The times [of all earthquakes in this list] are expressed in Pacific Standard Time." Townley and Allen (1939, p. 293) also included those two reports in their catalog, and the Arizona portion of their catalog is prefaced by the statement, "The times are Pacific Standard." Nevertheless, if the stated times in the original Phoenix reports were given in something other than PST, it is conceivable that Lawson (1908) never corrected those times to PST and that Townley and Allen (1939) simply copied the times from Lawson (1908), believing them to be in PST. Circumstantial evidence suggests this is the case.

Table 3
Intensity and Felt Data for the 18 April 1906 Triggered Event at 16:30 in the Imperial Valley, California

City	County	State	MMI, Felt (F), or Not Felt (NF)
Brawley	Imperial	CA	VII–VIII (preferred: VIII)
Calexico	Imperial	CA	V
El Centro	Imperial	CA	V
Heber	Imperial	CA	F
Holtville	Imperial	CA	VI
Imperial	Imperial	CA	VI
Imperial Junction*	Imperial	CA	F
Silsbee	Imperial	CA	F
Los Angeles	Los Angeles	CA	III
San Juan Capistrano	Orange	CA	F
Santa Ana	Orange	CA	IV–V (preferred: IV)
Coachella	Riverside	CA	IV?
Hemet	Riverside	CA	F
Riverside	Riverside	CA	F
San Jacinto	Riverside	CA	IV?
Temecula	Riverside	CA	F
San Bernardino	San Bernardino	CA	IV
Alpine	San Diego	CA	F
Ballast Point	San Diego	CA	F
Coronado	San Diego	CA	IV
Cuyamaca	San Diego	CA	F
Julian	San Diego	CA	IV?
Lakeside	San Diego	CA	F
La Mesa	San Diego	CA	F
National City	San Diego	CA	IV
Ramona	San Diego	CA	F
San Diego	San Diego	CA	IV–V (preferred: IV)
Yuma	Yuma	AZ	IV–V (preferred: IV)
Cocopah	—	Baja California (Mexico)	F
Tijuana	—	Baja California (Mexico)	F

*Now the town of Niland, California.

Standard time and time zones were instituted in the United States and Canada by the railroads on 18 November 1883, but they were not established in U.S. law until the Standard Time Act of 1918, enacted on 19 March 1918. (The Standard Time Act of 1918 also established the practice of Daylight Saving Time [DST] in the United States; DST was not in practice before then.) DuBois *et al.* (1982) stated that from 1883 until 1910, each municipality in Arizona chose whether to follow local time (i.e., time according to the position of the sun at any particular locality) or standard railroad time. In one of his books on the railroad history of Arizona, Myrick (1980, p. 565) discussed a particular train schedule in 1904, in which "trains left Phoenix '8:30 a.m. City Time' and Tempe '8:30 a.m. Slow Time.'" Later, when discussing occurrences in 1910, Myrick (1980, p. 761) explained that "Phoenix city time" was half an hour earlier than Mountain Standard Time and half an hour later than PST. Because Phoenix city time differed from standard time in 1904 and also in 1910, we infer that Phoenix remained off

Table 4

Intensity and Felt Data for the 19 April 1906 Triggered Event at 12:31 near Santa Monica Bay, California

City	County	State	MMI, Felt (F), or Not Felt (NF)
Avalon	Los Angeles	CA	III
Hollywood	Los Angeles	CA	IV–V (preferred: IV)
Long Beach	Los Angeles	CA	IV
Los Angeles	Los Angeles	CA	IV
Monrovia	Los Angeles	CA	F
Ocean Park	Los Angeles	CA	V?
Pasadena	Los Angeles	CA	F
San Pedro	Los Angeles	CA	V
Santa Monica	Los Angeles	CA	IV–V (preferred: V)
Sawtelle	Los Angeles	CA	V
Soldiers Home*	Los Angeles	CA	V?
Venice	Los Angeles	CA	VI
Whittier	Los Angeles	CA	F
Santa Ana	Orange	CA	III–IV (preferred: IV)
Riverside	Riverside	CA	III
Ontario	San Bernardino	CA	III
San Bernardino	San Bernardino	CA	III
Ventura	Ventura	CA	IV

*Now Veterans Administration land, west of Westwood.

Table 5

Intensity and Felt Data for the 19 April 1906 Triggered Event at 20:15 near Fernley, Lyon County, Nevada

City	County	State	MMI, Felt (F), or Not Felt (NF)
Carson Dam	Churchill	NV	F
Fallon	Churchill	NV	NF
Hazen	Churchill	NV	IV–V (MMI V used for analysis)
Fernley	Lyon	NV	V
Browns Station	Pershing	NV	IV?
Lovelock	Pershing	NV	NF
Olinghouse	Washoe	NV	IV
Reno	Washoe	NV	NF
Steamboat Springs	Washoe	NV	Uncertain*
Wadsworth	Washoe	NV	IV

*May have been a different event.

Table 6

Intensity and Felt Data for the 23 April 1906, 01:10 Aftershock

City	County	State	MMI, Felt (F), or Not Felt (NF)
Chico	Butte	CA	III
Crescent City	Del Norte	CA	IV?
Georgetown	El Dorado	CA	Uncertain*
Arcata	Humboldt	CA	V
Blocksburg	Humboldt	CA	F
Cape Mendocino	Humboldt	CA	V
Eureka	Humboldt	CA	V
Ferndale	Humboldt	CA	V
Fieldbrook	Humboldt	CA	F
Hydesville	Humboldt	CA	F
Orick	Humboldt	CA	V
Trinidad Head	Humboldt	CA	F
San Rafael	Marin	CA	Uncertain*
Point Arena lighthouse	Mendocino	CA	III?
Grass Valley	Nevada	CA	III
La Porte	Plumas	CA	III
Quincy	Plumas	CA	III
Kennett	Shasta	CA	F
Redding	Shasta	CA	IV
Dunsmuir	Siskiyou	CA	IV–V (preferred: IV)
Fort Jones	Siskiyou	CA	F
Hornbrook	Siskiyou	CA	F
Sisson[†]	Siskiyou	CA	IV
Yreka	Siskiyou	CA	IV
Red Bluff	Tehama	CA	IV
Burnt Ranch	Trinity	CA	F
Hayfork	Trinity	CA	F
New River	Trinity	CA	F
Weaverville	Trinity	CA	IV
Challenge	Yuba	CA	F
Glendale	Douglas	OR	F
Ashland	Jackson	OR	III
Medford	Jackson	OR	IV
Grants Pass	Josephine	OR	F
Merlin	Josephine	OR	F
Eugene	Lane	OR	Uncertain, but probably NF
Portland	Multnomah	OR	Uncertain, but probably NF

*May have been a different event.

[†] Now the town of Mt. Shasta, California.

of standard time (and presumably on local time) continuously during those years. In Phoenix, at longitude 112° W, local time would be 32 min ahead of PST, which is local time along the 120th meridian. (Local time changes 4 min per degree of longitude.) This is consistent with Myrick's (1980) explanation, although it is not clear whether Phoenix was 32 or 30 min ahead of PST.

An account published in a Phoenix newspaper (the *Arizona Gazette*) gave the time of the earthquake as 05:48 (again, see table 2 in Meltzner and Wald [2002]). Presumably, the time stated in this local newspaper report would not have been corrected to PST (there would have been no reason to do so), yet the time is the same as that of the earlier report in Lawson (1908) and in Townley and Allen (1939). The implication is that the time stated in all reports for this event is in Phoenix local time, not in PST. If this is the case (and assuming Phoenix was 32 min ahead of PST), the earthquake would have been felt in Phoenix some time between 05:16 and 05:27 PST.

The question arises as to whether the event felt in Phoenix was the San Francisco mainshock or a separate, possibly triggered, event. One argument that it was a separate event is that Phoenix (and all of Arizona, for that matter) was well beyond the felt limit of the mainshock (Lawson, 1908). The mainshock was reported felt as far southeast as San Jacinto, but it was apparently not felt in Las Vegas, Needles, or the Imperial Valley (Fig. 1a). The strongest argument that it was a separate event, however, comes from the various descriptions of high-frequency ground motion. The *Arizona Gazette* (20 April 1906, early edition, p. 1) describes the earthquake in Phoenix as a "distinct shaking of the earth," with several people having felt it "distinctly." This description is not consistent with the long-period motion that would be expected in the outskirts of the felt region of a great earthquake; rather, it suggests that the earthquake was a small-to-moderate local event. (In contrast, many reports of the mainshock in Nevada [in the outskirts of the felt region] describe effects of long-period motion such as [1] long, gentle swaying, without any sharp or jerky movements; [2] the swaying of hanging objects, without vibrations having been felt; [3] the sloshing or splashing of water surfaces [in irrigation ditches], without vibrations having been felt; or [4] a dizzying or nauseating sensation [Lawson, 1908; *Nevada State Journal* (Reno), 18 April 1906 "Extra," p. 1]).

In addition to the reports from Phoenix, there was one report from Salome, 140 km west of Phoenix, in La Paz County (see table 2 in Meltzner and Wald [2002]). The earthquake was said to have been "distinctly noted" in Salome. Mr. Pratt, the man giving the report, claimed to have been about 40 miles from Salome, in the mountains, at the time of the earthquake; he and a friend were staying in a cabin. The friend, who was inside at the time, said that the cabin "shook quite noticeably." Mr. Pratt was outdoors and "plainly felt the quaking of the earth." Although their location cannot be determined precisely, both their report and the description from Salome are more consistent with the short-period motion associated with a local event than with the long-period motion expected for a very large but distant event. The time of the shaking was not given precisely; it is only stated to have occurred in the morning. Most likely, this is the earthquake that was felt in Phoenix, although we cannot rule out the possibility of two separate events. If it was one event, it must have been large enough to be felt "distinctly" in two towns 140 km apart ($M \sim 4.0$?); if there were two events, the one nearer Salome must have been large enough to be felt outdoors (MMI IV–V) at Mr. Pratt's location ($M \sim 3.5$–4.0?).

Because of the temporal proximity of the Phoenix reports and the San Francisco mainshock, it may be informative to determine the travel times of the seismic waves from San Francisco to Phoenix. Phoenix is located 1050 km ($\Delta = 9.44°$) from the 1906 epicenter of Bolt (1968), just south of San Francisco (Fig. 1a). According to the Jeffreys–Bullen (1967) travel times, the predicted initial arrival times for various phases at a distance of $\Delta = 9.5°$ is *P* waves, 2 min 17 sec; *S* waves, 4 min 4 sec; Love waves, ~4.4 min; and Rayleigh waves, ~4.6 min. Using the mainshock origin time of 05:12:21 PST of Bolt (1968), we would expect the *P*-wave arrival in Phoenix at 05:14:38, the *S*-wave arrival at 05:16:25, and the initial surface waves to arrive at about 05:16:45 PST. If the earthquake felt in Phoenix was *not* the San Francisco mainshock, the Arizona event would have occurred during the time when the seismic waves from San Francisco were passing through Phoenix.

Our preferred interpretation of the Arizona reports is that there was a single event, with $M \sim 4.0$ and with an epicenter somewhere between Phoenix and Salome. Although our calculation for the travel times of seismic waves from the San Francisco mainshock assumed a Phoenix location for the triggered event, it is also applicable (as an approximation) for a triggered event source nearer Salome. The various phases of seismic waves from San Francisco would have arrived at a source near Salome roughly 15–30 sec prior to reaching Phoenix; likewise, a triggered event near Salome would have started roughly 15–35 sec before shaking was felt in Phoenix. Of course, attempting to determine the arrival times to the precision of a second is in this case a pointless task, as the uncertainty in the observers' reported times is at best a few minutes; additionally, the mainshock radiated seismic energy for nearly 2 min (Wald *et al.*, 1993). Wherever the Arizona triggered event was located, we propose that it was dynamically triggered by the traveling waves of the San Francisco mainshock. At a distance of $\Delta = 8.2°$–$9.4°$ (910–1050 km, the epicentral distances of Salome and Phoenix, respectively), the surface waves would have the largest amplitudes and therefore would be most likely to dynamically trigger an earthquake; nevertheless, limitations in our data preclude any conclusion to that effect. If there were two separate events in Arizona (our alternative interpretation), the event between 05:16 and 05:27 PST would have occurred during the passage of the seismic waves from San Francisco and, accordingly, we would propose that it was triggered dynamically.

The phenomenon of remote earthquake triggering *during* shaking from a mainshock has been documented in California in the cases of the 1992 M_W 7.3 Landers earthquake and the 1999 M_W 7.1 Hector Mine earthquake. Following the Landers earthquake, triggered activity began in Long Valley caldera (eastern California) and at the Geysers (northwestern California) 30–40 sec after the *S*-wave arrivals from the Landers earthquake and during the passage of the large-amplitude Love and Rayleigh surface wave trains (Hill *et al.*, 1993). The Hector Mine earthquake triggered an M 4.7 event near the southern end of the Salton Sea (in southern California) within 30 sec of the *P*-wave arrival at that location, and the triggered event was followed by its own M 4.4 aftershock within about 10 min (Hough and Kanamori, 2002). Elsewhere, the M_W 7.4 August 1999 Izmit, Turkey, earthquake triggered smaller earthquakes in Greece immediately after the passage of the largest-amplitude surface waves (Brodsky *et al.*, 2000). And most recently, the November 2002 M_W 7.9 Denali fault, Alaska, earthquake triggered seismicity in a number of places in western North America (including Yellowstone caldera in Wyoming; Long Valley caldera, the Geysers, and the Coso geothermal field in California; Mount Rainier in Washington; the Intermountain Seismic Belt in Utah, and the Katmai volcanic cluster in southwestern Alaska), with the triggered seismicity beginning in each place during the *S*-wave coda or the early phases of the surface wave arrivals (Hill *et al.*, 2002; Husen *et al.*, 2002; Johnston *et al.*, 2002; Moran *et al.*, 2002; Pankow *et al.*, 2002).

18 April 1906 Santa Cruz Area Aftershock

This aftershock occurred only hours after the mainshock, at a time when aftershocks were occurring at a very high frequency. That there was a relatively large aftershock at about 14:28 on the afternoon of 18 April 1906 is inferred from a surge of widely spaced earthquake reports (see tables 1 and 5 in Meltzner and Wald, [2002]) between 14:20 and 14:30; a number of these reports describe the earthquake as being one of the stronger aftershocks up to that point. Nevertheless, there are reports of two or more closely timed events from some of those locations, and in some cases it is not clear which reports describe which event. Although our preferred interpretation is that there was a single large event at around 14:28, with several smaller events a few minutes before and after (hereafter, the single-event hypothesis), the data support an alternative interpretation: there may have been two large aftershocks, one near San Francisco at 14:25 and one near Santa Cruz at 14:28 (the double-event hypothesis).

In Meltzner and Wald (2002) and here, using the method of Bakun and Wentworth (1997) (as qualified earlier) to determine the best magnitude and location, we assume the single-event hypothesis. At each location, we use the intensity from the strongest event between 14:20 and 14:30 as the representative intensity for that location. If indeed there was only one large event, the solution is appropriate. If instead there were two large events, the true intensities would be lower near Santa Cruz for the 14:25 event and lower near San Francisco for the 14:28 event; the solution would overestimate the size of each event. Either way, the magnitude suggested by the solution is a maximum for the size of the event(s).

A list of the intensities used (where they could be determined) and all other points where this aftershock was felt is given in Table 2. The solution of the algorithm for this event is shown in Figure 2. The solid gray 95%, 80%, and 50% confidence-level contours constrain the location. Because of the relatively few observation points, the location is not well constrained; nevertheless, the intensity center (white star) is very close to the SAF. Our preferred location (gray star) in this case is simply the point along the SAF with the lowest rms error; it is just roughly between the towns of Aptos and Morgan Hill, in the Santa Cruz Mountains. M_I at our preferred location is 4.9; incorporating the uncertainty in the magnitude for five observation points at 95% confidence (Table 1), our magnitude for this event is M_I 4.9 ($-0.6/+0.5$). As stated earlier, this magnitude is an upper bound. Excluding triggered events, this was the largest aftershock within 48 hr of the San Francisco mainshock; observe that no known aftershock within the first 2 days exceeded M 5.0 (M 5.4 at 95% confidence).

18 April 1906 Imperial Valley, California, Triggered Events

On the afternoon of 18 April 1906, a series of earthquakes began in the Imperial Valley in southern California. (For a regional map showing many of the locations to be discussed in this section, see Fig. 1b; for the original reports, see table 2 in Meltzner and Wald [2002]). Initially, the earthquakes must have been small, as only a few localities reported them: Brawley and Imperial Junction (now Niland) reported earthquakes beginning at 13:30, and Imperial reported its first "distinct" earthquake at 15:00. In other locations, these earthquakes were either not felt or simply not recorded.

Then, at 16:30 on 18 April 1906, 11.3 hr after the 05:12 mainshock, the Imperial Valley swarm culminated with a large earthquake that was felt over much of southern California and into Mexico and Arizona. This earthquake has already been the subject of several studies: Toppozada *et al.* (1978) estimated $M_I = 6.0$ based mainly on the size of the total felt area, but Toppozada and Parke (1982) revised that figure downward to $M_I = 5.8$ based on the areas shaken at MMI V and greater; Abe (1988) estimated a surface wave magnitude based on Milne instrument data of $M_S = 6.2$; and Ellsworth (1990) assigned this event a summary magnitude of M 6.2. In more recent work, Toppozada *et al.* (2000) and Toppozada and Branum (2002) adopted the higher M of 6.2. For the location, Toppozada *et al.* (1978) estimated it to be at 32.5° N, 115.5° W, in the Mexicali Valley south of the international border, but Toppozada and Parke (1982) moved the epicenter north across the border to 32.9° N, 115.5° W; Abe (1988) used the more southerly location of Toppozada *et al.* (1978), but all other papers published since then have assumed the more northerly location of Toppozada and Parke (1982). In this study, we reinterpret old felt reports, assess newly found felt reports, and apply the method of Bakun and Wentworth (1997) (as qualified earlier) to the intensity data set. (For the original felt reports for this event, see table 6 in Meltzner and Wald [2002].)

A list of the assigned intensities and all points where this aftershock was felt is given in Table 3, and the solution of the algorithm is shown in Figure 3. Note that, in some cases, the intensities differ slightly from those of Toppozada and Parke (1982). The highest intensity is in Brawley (MMI VIII), and the intensity drops off rapidly to the south. The intensity also appears to drop off to the north of Brawley, but because of a lack of intensity data immediately north of Brawley, we cannot be certain where one would draw isoseismal curves. The intensity center is northwest of the Imperial Valley, but it is biased by the distal reports to the northwest and lack of reports in the desert to the northeast and in Mexico to the south.

Our preferred location is in the Brawley Seismic Zone southeast of the Salton Sea, because we feel that it is the most likely location within the solution's 50% confidence-level contour. Note that an M 4.7 triggered event occurred in that vicinity following the 1999 M_W 7.1 Hector Mine earthquake (Hough and Kanamori, 2002). Still, other locations in the Imperial Valley should be considered. The trace of the Brawley fault associated with the 1979 rupture (U.S. Geological Survey, 1982, Plate 1; Real, 1982) and the Imperial fault north of El Centro are both plausible locations; however, the rapid southward decrease in intensity precludes a more southerly source location. (In the 1979 earthquake, which involved rupture on the Brawley fault and the Imperial fault south to the international border, the intensity was uniformly MMI VII from Brawley to Calexico; see Reagor *et al.* [1982] and Nason [1982].) Alternatively, slip along one of the northeast-trending cross faults southeast of the Salton Sea could be responsible; candidates include the fault involved in the strongest aftershock of the 1979 event (Johnson and Hutton, 1982) and the fault involved in the 1981 Westmorland earthquake (Nicholson *et al.*, 1986). The Superstition Hills, Elmore Ranch, and Coyote Creek faults are less likely sources, as an $M \sim 6.1$ event on one of those faults would not be expected to produce the MMI VIII observed in Brawley in 1906. (The 1987 M_W 6.2 Elmore Ranch earthquake on the Lone Tree, Elmore Ranch, and Kane Spring faults produced MMI V in Brawley [J. Dewey, personal comm., 1997], the 1987 M_W 6.6 Superstition Hills earthquake on the Superstition Hills and Wienert faults produced MMI VI in Brawley [J. Dewey, personal comm., 1997], and the 1968 M_W 6.5 Borrego Mountain earthquake on the Coyote Creek fault produced MMI VI in Brawley [Seismological Field Survey, NOAA, 1972].) Paleoseismic evidence precludes an earthquake with surface rupture on the Superstition Mountain fault any time after A.D. 1637 (Gurrola and Rockwell, 1996). We also rule out a location on the SAF near or northwest of Bombay Beach because Bombay Beach is approximately halfway between Brawley and Coachella, but the intensities are much higher in Brawley and to the south than they are in Coachella and to the north. (Observe that the amplification of intensity due to the underlying sediments in the Imperial Valley should not be any greater than it is in Coachella, which sits on similar materials.)

Fortuitously, M_I does not vary much over the potential source region. At our preferred location, M_I is 6.1, and at the other possible locations, M_I ranges from 6.1 to 6.2 (Fig. 3). The statistical uncertainty in the magnitude for 15 observation points at 95% confidence (Table 1) is $-0.4/+0.3$; hence, our magnitude for this event is 6.1–6.2 ($-0.4/+0.3$), or, roughly, M_I 6.1 ± 0.4. This magnitude is consistent with those published previously (see earlier discussion), although our preferred source region is to the north: the location is more consistent with the epicenter of Toppozada and Parke (1982). As expected, reports confirm that the Imperial Valley earthquake was followed by its own sequence of aftershocks, although the aftershocks cannot be located any more precisely than the Imperial Valley mainshock.

18 April 1906 Pomona Valley, California, Triggered Events

Late on the evening of 18 April 1906, a small swarm of earthquakes occurred near San Dimas in the Pomona Valley of southern California. Three "light" earthquakes were reported in Glendora: one at 20:45, one at 21:10, and the last at 22:30. The second event was either located further east than the others or it was larger, as it was also reported in Lordsburg (now La Verne) and in Chino. In Lordsburg (La Verne) the second event was described as severe, and in Chino it was described as slight. In addition, a diary kept by Mr. Robert B. Waterman lists an event at 20:50 on 19 April 1906; this may be a misdated account of one of the aforementioned 18 April events. At the time, Mr. Waterman was camping several miles north of Azusa. (See table 2 in Meltzner and Wald [2002] for the original reports and for a discussion on Mr. Waterman's exact location.) Irrespective of Mr. Waterman's report, the intensity distribution for the 21:10 event is similar to the intensity distributions of at least two modern events: an M 2.7 event 2 miles south of San Dimas on 8 January 2001 and an M 3.1 event 5 miles north-northeast of La Verne on 24 September 2000. (Intensity data for the modern events is from the U.S. Geological Survey; see also Wald *et al.* [1999].) We estimate the magnitude of the largest Pomona Valley triggered event to be $M \sim 3$ and the others to be slightly smaller.

19 April 1906 Southern Oregon Triggered Events

Lawson (1908, Vol. I, p. 163) discussed an earthquake swarm that occurred near Paisley, Oregon, in the early morning hours of 19 April 1906. According to Lawson, "At Paisley no shock was noticed on April 18, but on Thursday, April 19, about $1^h\,30^m$ A.M., a tremor was felt, strong enough to generally awaken people, and during the next hour and a half three more shocks were felt. Considerable excitement was caused, some people going out-of-doors and one rather delicate woman being made sick. . . . " A report in the *Lake County Examiner* (26 April 1906, p. 1), published in nearby Lakeview, Oregon, was vague in regard to the times of the events but confirms that multiple "distinct" earthquakes were felt in Paisley. The description of the 01:30 event is consistent with MMI IV–V at Paisley; the smallest earthquake capable of producing such an intensity is approximately M 3.5. Madin and Mabey (1996) mapped an active fault near Paisley. If that fault were responsible, the magnitude of the 01:30 event may have been as small as M 3.5; otherwise, if the epicenter were farther away, the magnitude would have been higher. Owing to the remoteness of the area, a precise location for this event cannot be determined.

19 April 1906 Santa Monica Bay, California, Triggered Event

At 12:31 PST on 19 April 1906, 31.3 hr after the San Francisco mainshock, a moderate earthquake struck the Los Angeles region. The event was felt with MMI III+ from Santa Catalina Island to San Bernardino to Ventura, and it was most strongly felt on the west side of Los Angeles. (Venice had the strongest reported intensity at MMI VI.) The intensities and locations where the earthquake was felt are listed in Table 4, and the solution for this event is shown in Figure 4; for the original reports, see tables 2 and 7 in Meltzner and Wald (2002). Both the intensity center and our preferred location are in Santa Monica Bay; our preferred location is near the Palos Verdes fault. M_I at our preferred location is 5.0; incorporating the statistical uncertainty in the magnitude for 15 observations at 95% confidence (Table 1), our magnitude for this event is M_I 5.0 ($-0.4/+0.3$).

19 April 1906 Reno, Nevada, Triggered Event

Shortly after 14:00 PST on 19 April 1906, a small earthquake was reported in Reno and in two towns east of Reno. (For the original reports, see table 2 in Meltzner and Wald [2002]). In Reno and in Olinghouse (40 km east-northeast of Reno) the intensity was MMI III; in Hazen, 70 km east of Reno, it was MMI II. It was apparently not felt in a number of towns farther east that reported an earthquake later that day (see next paragraph). Comparisons with intensity data from modern events (again, from U.S. Geological Survey; see Wald *et al.* [1999]) suggests that a magnitude of *M* 3.25–3.5 would be consistent with the observations, with a location between Reno and Hazen, nearer to Reno.

19 April 1906 Western Nevada Triggered Event (Near Fernley, Lyon County)

Shortly after 20:00 PST on 19 April 1906, a second earthquake was felt across a wider portion of western Nevada. It was apparently *not* felt in Reno, but it was felt at points farther east and farther north than was the event at around 14:00. Intensities were in the MMI IV–V range over a wide area. The intensities and locations where the earthquake was felt are listed in Table 5; for the original reports, see tables 2 and 8 in Meltzner and Wald (2002). Although the method of Bakun and Wentworth (1997) is calibrated for California and not for the Basin and Range province, we applied their method to the intensity data for this event to provide an estimate of the magnitude and location. The true magnitude for the western Nevada event may be less than that predicted by the California-based algorithm, owing to the lower attenuation in the Basin and Range province (W. Bakun, personal comm., 2001). The solution is shown in Figure 5.

Note that several points where the earthquake is reported to have been unfelt are indicated on Figure 5. These points are shown merely for reference; we did not utilize them in solving for the best-fit magnitude or location, as the algorithm was not designed to consider such points. Instead, we will use the "not felt" points to visually constrain the location; we discard the intensity center in preference for a location more central to the stronger intensities (Fig. 5). Our preferred source location is near a north-northeast-trending, east-dipping normal fault northeast of Fernley, Nevada (see dePolo *et al.* [1997]). Another fault in the vicinity is the Pyramid Lake fault, which runs immediately west of Fernley (again, see dePolo *et al.* [1997]). If the method used is applicable for the Basin and Range province, the magnitude for this earthquake is M_I 4.9 ($-0.6/+0.5$) (five observations at 95% confidence; see Table 1).

19–20 April 1906 Azusa, California, Triggered Event(s)

As mentioned earlier, we located a diary kept by Mr. Robert B. Waterman, which mentions that an earthquake was felt at 20:50 on 19 April 1906. At the time, Mr. Waterman was camping several miles north of Azusa. (See table 2 in Meltzner and Wald [2002] for the original report and for a discussion on Mr. Waterman's exact location.) As we speculated, this may be a misdated account of one of the 18 April events in the Pomona Valley, although, of course, it could also be a separate event on 19 April. In addition, the diary lists an event at 00:30 on the morning of 20 April 1906 (again, see table 2 in Meltzner and Wald [2002] for the original report). This event was not reported anywhere else, so it is presumed to be small, possibly $M \sim 3$. The 20 April event, and the 19 April event if indeed Mr. Waterman's report was correctly dated, may have been related to the 18 April events in the Pomona Valley.

Later Significant Aftershocks (Through December 1907)

After the first 48 hr, triggered activity beyond the aftershock zone died off, although a few small events continued to be felt in some of the areas that had experienced triggered events during the first two days (see table 2 in Meltzner and Wald [2002]); these are probably aftershocks of the initial triggered events. Within the aftershock zone, the largest events took place near the ends of the 1906 rupture; remarkably few significant aftershocks occurred along the mainshock rupture itself. One of the largest aftershocks of the sequence occurred on 23 April 1906, off the Humboldt County coast, north of the mainshock rupture. It was the first noteworthy ($M \geq 5.5$) aftershock or triggered event to occur since those of 18 and 19 April.

23 April 1906 North-Coast Aftershock

An earthquake was felt over a widespread area of northern California and southern Oregon shortly after 01:00 on the morning of 23 April 1906, 5 days after the mainshock. The strongest shaking occurred along the Humboldt County coast, where the intensity was uniformly MMI V; it was felt as far east as the Sierran foothills, where MMI III effects were reported. The intensities and locations where the earthquake was felt are listed in Table 6, and the intensity distribution is shown in Figure 6; for the original reports, see tables 1 and 9 in Meltzner and Wald (2002).

Figure 6 also shows the solution of the algorithm. The intensity center is in western Trinity County, about 75 km northeast of the SAF, and the magnitude at that point is M_I 6.0. Several concerns, however, bring the validity of the solution into question. First, the region around the intensity center lacks earthquakes of *M* 5 or greater in historical times. (Specifically, no earthquakes of $M \geq 5$ have occurred anywhere within the 80% confidence-level contour indicated in

Fig. 6 since at least 1900, according to the catalog of the Council of the National Seismic System.) Second, if the source location had been in western Trinity County, the intensity distribution would be strongly asymmetrical: intensities were uniformly MMI V to the west of the hypothetical source location, whereas they were uniformly MMI IV at a nearly equal distance to the east. Third, the only part of the SAF within the 95% confidence contour is that portion in the immediate vicinity of Shelter Cove, and even that location is improbable, as the intensities in Mendocino County appear to have been too low. (At Point Arena, the intensity was MMI III; in Ukiah and in Mendocino, the event was not mentioned in the local weekly newspapers, suggesting that the earthquake was not felt strongly enough in those towns to be newsworthy.) And fourth, in a study of many north-coast California earthquakes, Bakun (2000) observed that a maximum intensity of MMI V or VI is generally indicative of either an *M* 5 earthquake onshore or near the coast, or an *M* 6 or 7 event located 100 km or farther offshore; an *M* 6 onshore would be expected to generate intensities of MMI VII or higher.

As mentioned earlier, the method of Bakun and Wentworth (1997) is useful for most onshore and near-coast offshore events, but Bakun (2000) established that the confidence contours for location generally fail to usefully constrain the source regions for earthquakes located more than a few tens of kilometers offshore. The inherent difficulty lies in ascertaining whether the solution is valid—that is, whether the confidence contours usefully constrain the source regions—for any particular event (with an unknown location). In the case of the 23 April 1906 aftershock, the concerns and inconsistencies noted earlier lead us to suspect that the location is not reliably constrained by the confidence contours. Bakun (2000) suggested that, for events with maximum MMI V or VI, an *M* 6 or 7 earthquake located 100 km or farther offshore can be distinguished from an *M* 5 event onshore or near the coast by MMI IV and V at sites hundreds of kilometers from the site of maximum reported intensity. In the case of an onshore or near-shore *M* 5 earthquake, one would expect a small area of MMI V–VI near the epicenter, with the earthquake being felt over a comparatively small area; in the case of an *M* 6 or 7 event far offshore, the area over which MMI V–VI effects were reported would be roughly similar, but one would expect the total felt area to be much broader. To that end, we will now compare the intensity distribution from the 23 April 1906 event with those of modern events of known source parameters.

Intensity data for nineteenth- and twentieth-century north-coast events have been compiled by Bakun (1999b); locations and magnitudes for those events were tabulated in Bakun (2000). Of the events considered by Bakun (1999b, 2000), we have selected five for comparison here, and their source parameters are listed in Table 7. Both the 1941 (Fig. 7b) and 1987 (Fig. 7d) events were near-shore events; in each event, MMI VI+ was felt over a small to moderately-sized area, but neither event was felt as far north or as far inland as was the 23 April 1906 event. Comparison of the 23 April 1906 event with the 1987 and 1941 events suggests that the 1906 event was farther offshore and larger in magnitude than these events; the 1906 event may also have been farther north. The 1934 (Fig. 7a), 1956 (Fig. 7c), and 1994 (Fig. 7e) events were all 100 km or more offshore. The 1934 and 1956 events had a maximum reported intensity of MMI V and were felt over a coastal region similar to that over which the 23 April 1906 event was felt, but in general they were not felt as strongly or as far inland as was the 1906 event; the 1906 event may have been slightly larger than the 1934 and 1956 events. The 1906 event also appears to have been farther south than the 1934 event.

Of the five nineteenth- and twentieth-century north-coast events considered, the 1 September 1994 event's intensity distribution is the most similar to that of the 23 April 1906 event. For the 1994 event, there was a single location with MMI VI; otherwise, the largest reported intensity was MMI V. The 1994 event was reported felt slightly farther north, slightly farther south, and slightly farther inland, but it is not clear whether, at 1 o'clock in the morning and in the days following the 1906 mainshock, shaking of MMI III would be reported in the San Francisco Bay area (SFBA) or in small communities in Oregon or northeastern California. A comparison of the 23 April 1906 event with the 1994 event suggests that the 1906 event was slightly smaller. As an aside, Bakun (2000) performed an analysis (using the method of Bakun and Wentworth [1997]) of the 1994 north-coast event; for that event, the epicenter was outside the 95% confidence-level contour. If the source locations of the 23 April 1906 and 1 September 1994 events are near one another, as is suggested, it should not be surprising that the confidence-level contours also fail to constrain the 23 April 1906 location.

Based on the comparisons discussed earlier and on the suggestions of Bakun (2000), we tentatively estimate the magnitude to be between *M* 6.5 and 7, and we estimate the location to be between longitudes 125.7° and 125.0° W and between latitudes 40.7° and 41.05° N. The region (or box) so constrained (Fig. 6) should not be construed to carry any formal level of confidence (the level of confidence cannot be determined in any meaningful fashion); rather, the box is merely the locus of our preferred locations.

It is also helpful to compare our results with those of other investigations. Abe (1988) used amplitude data from Milne instruments to estimate a surface wave magnitude for this event of $M_S = 6.4$; he did this assuming the location of Toppozada *et al.* (1978), 41° N, 124° W. Although the location estimated by Toppozada *et al.* (1978) and used by Abe (1988) is grossly imprecise, the magnitude Abe (1988) determined would not be very sensitive to a small change in location: had Abe instead assumed an epicenter of 41.0° N, 125.7° W, his magnitude would not have been higher than M_S 6.5. Note that Toppozada *et al.* (2000) and Toppozada and Branum (2002) moved the event farther west, to 41.0° N, 124.5° W. In light of Abe's (1988) results, we will use his

Table 7
Selected Twentieth-Century California North-Coast Earthquakes[*]

Date (UTC)	Latitude (°N)	Longitude (°W)	No. MMI[†]	Max MMI (#)[‡]	M_W[§]	Preferred M[ǁ]
06 July 1934	41.25	125.75	17	V (2)		6.5 ± 0.4
03 October 1941	40.40	124.80	76	VII (1)		6.4 ± 0.4
11 October 1956	40.67	125.77	34	V (11)		6.0 ± 0.4
31 July 1987	40.42	124.41	48	VI (8)	6.0	6.0 ± 0.2
01 September 1994	40.40	125.68	132	VI (1)	7.0	7.0 ± 0.2

[*] Abridged from Bakun (2000).

[†] No. MMI is the number of MMI data points used in the study.

[‡] Max MMI (#) is the maximum MMI and the number of sites with that MMI.

[§] M_W is moment magnitude (Hanks and Kanamori, 1979).

[ǁ] Preferred M is the magnitude preferred by Bakun (2000).

magnitude as a minimum and the magnitude of the 1 September 1994 event as a maximum; hence, our preferred magnitude is between M 6.4 and 7, or, put another way, it is M 6.7 ± 0.3. For the location, we will disregard the more easterly locations (which we do not consider to be robust) and we will retain our box, bounded by 125.7° and 125.0° W, 40.7° and 41.05° N. The uncertainties for the location and the magnitude are subjective in this case and do not carry any statistical level of confidence. Nonetheless, note (from Table 1) that an uncertainty of ± 0.3 for 19 observations using the method of Bakun and Wentworth (1997, 1999) would roughly correlate to 90%–95% confidence.

Finally, we feel it appropriate to comment on one lingering inconsistency. According to Bakun (2000), if the epicenter of an offshore north-coast event is known or can be independently constrained, then M_I at that source location should agree with the instrumental magnitude, even if the method fails in and of itself to usefully constrain the source location. For the 23 April 1906 event, we constrained the source region independently of the method of Bakun and Wentworth (1997), so we would expect M_I in that source region to agree with our estimated magnitude. This is not the case. One reason for the inconsistency might be that the majority of the observations come from inland locations, with fewer observations coming from coastal sites (Fig. 6); this is largely due to a lack of reports from Mendocino County. To test this hypothesis, we ran the algorithm using data sets in which each of the six observations from Humboldt and Del Norte Counties (Table 6) were counted twice, three times, and four times. When those data points were counted twice, the range of M_I over the preferred source region (the box) dropped from M_I 6.9–7.5 to M_I 6.7–7.3; when the observations were counted three times, M_I over the preferred source region dropped to M_I 6.5–7.1; and when the observations were counted four times, M_I dropped to M_I 6.4–7.0. This lowering of M_I over the preferred source region suggests that our hypothesis is correct: namely, that the M_I contours are biased by a lack of reports in parts of the coastal region (as well as a lack of reports offshore) coupled with an abundance of reports inland.

25 April 1906 San Francisco Bay Area Aftershock

At around 15:17 PST on 25 April 1906, an earthquake occurred in the SFBA. It was felt most strongly (MMI IV–V) in the areas immediately surrounding San Francisco Bay, and it was also reported from a few inland locations. The intensities and locations where the earthquake was felt are listed in Table 8, and the solution for this event is shown in Figure 8; for the original reports, see tables 1 and 10 in Meltzner and Wald (2002). The intensity center is located offshore, although the offshore location is probably an artifact of a lack of data that would constrain the source location from an offshore direction. Our preferred location is in or near San Francisco Bay, amidst the strongest intensities, although, with few observations for this event, we cannot distinguish between a location west of the bay (e.g., on the SAF or farther west) and a location east of the bay (e.g., on the Hayward fault). M_I in that vicinity ranges from 5.0 (for an SAF location) to 4.8 (for a Hayward fault location). The statistical uncertainty in the magnitude for eight observations at 95% confidence (interpolating from Table 1) is about $(-0.5/+0.4)$; hence, our summary magnitude for this event is M_I 4.9 $(-0.6/+0.5)$.

17 May 1906 San Juan Bautista Aftershock

The largest aftershock to occur south of the Humboldt County region took place at around 20:21 on the evening of 17 May 1906. It was felt over a wide area from San Luis Obispo to Napa and as far inland as Woodland (Yolo County) and Oakdale (Stanislaus County). The strongest intensities (MMI V+) were felt from San Jose to Salinas, with Los Gatos topping the list at MMI VI. The intensities and felt locations (and one location where it is inferred to have not been felt) are listed in Table 9, and the solution for this event is shown in Figure 9; for the original reports, see tables 1 and 11 in Meltzner and Wald (2002). Once again, the intensity center is located offshore, although that is probably an artifact of a lack of offshore data that would constrain the source location from that direction. Our preferred location is the point on the SAF with the lowest rms error (Fig. 9);

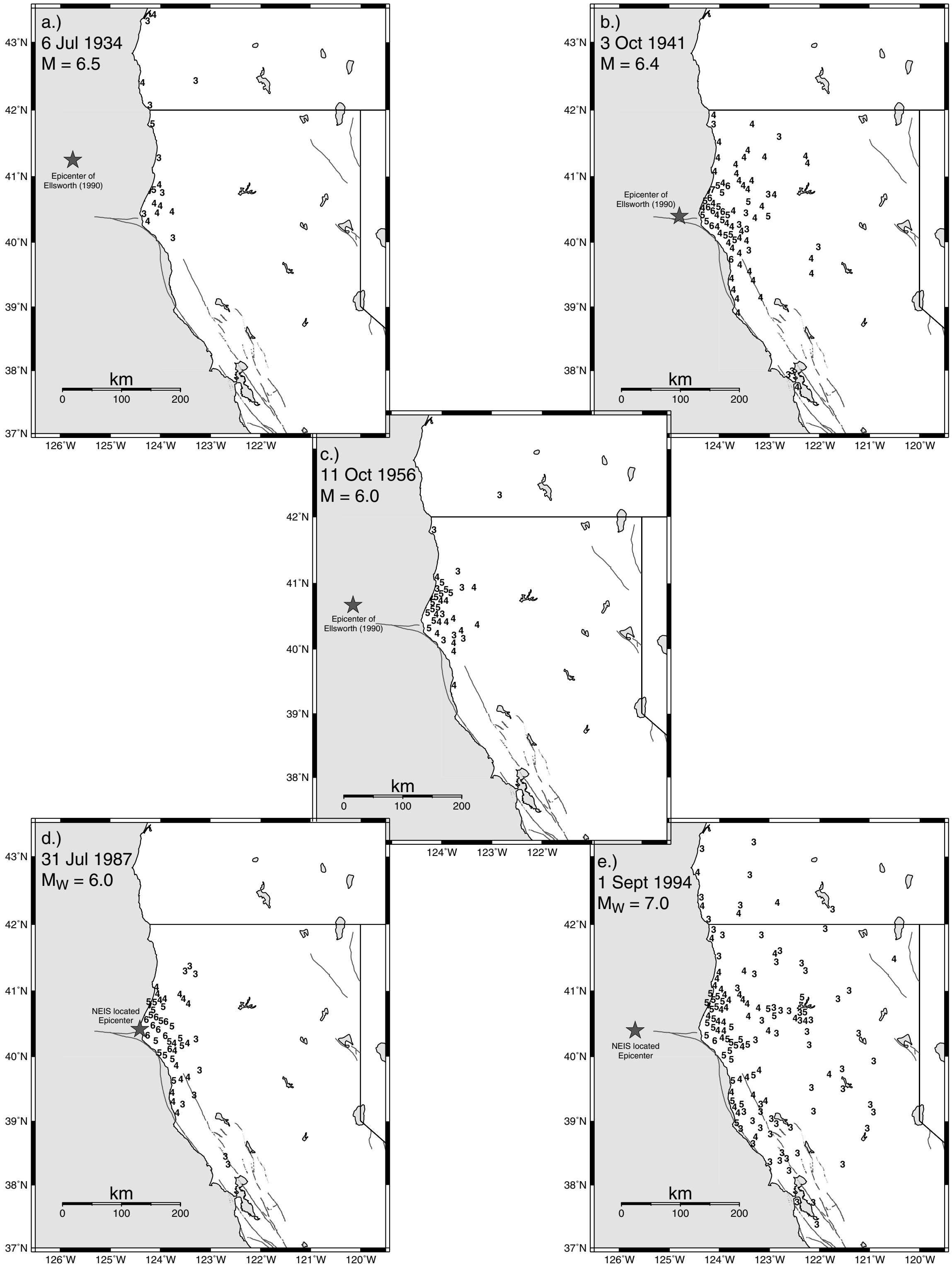

Figure 7. Intensity distributions for selected twentieth-century California north-coast earthquakes, shown for comparison with the 23 April 1906 event. Numbers indicate MMI values at their respective locations, although some numbers have been moved as much as ~5 km for the sake of legibility. The epicenters are designated by stars. See Table 7 for more information. (a) 6 July 1934 event (M 6.5); (b) 3 October 1941 event (M 6.4); (c) 11 October 1956 event (M 6.0); (d) 31 July 1987 event (M_W 6.0); (e) 1 September 1994 event (M_W 7.0).

Table 8
Intensity and Felt Data for the 25 April 1906, 15:17 Aftershock

City	County	State	MMI, Felt (F), or Not Felt (NF)
Alameda (pier)	Alameda	CA	F
Berkeley	Alameda	CA	IV–V (preferred: V)
Niles*	Alameda	CA	F
Oakland	Alameda	CA	IV–V (preferred: IV)
Antioch	Contra Costa	CA	F
Martinez	Contra Costa	CA	IV–V (preferred: V)
Point Bonita	Marin	CA	F
Napa	Napa	CA	F
Napa Redwoods	Napa	CA	Uncertain†
Yountville	Napa	CA	F
Sacramento	Sacramento	CA	II
Mile Rocks	San Francisco	CA	F
San Francisco	San Francisco	CA	V
Stockton	San Joaquin	CA	II
Mount Hamilton	Santa Clara	CA	F
San Jose	Santa Clara	CA	IV
Vallejo	Solano	CA	IV

*Now the area of Niles District.
†May have been a different event.

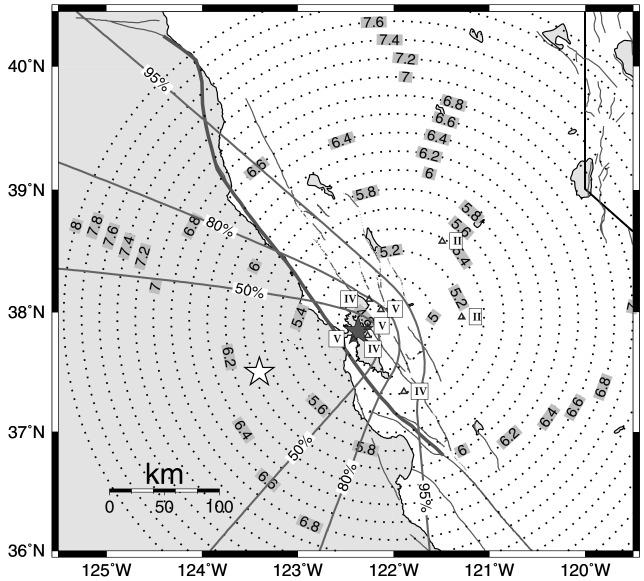

Figure 8. Map of the 25 April 1906 aftershock. See Figure 2 for explanation.

Table 9
Intensity and Felt Data for the 17 May 1906, 20:21 Aftershock

City	County	State	MMI, Felt (F), or Not Felt (NF)
Alameda (pier)	Alameda	CA	F
Berkeley	Alameda	CA	F
Livermore	Alameda	CA	IV
Oakland	Alameda	CA	IV
Crockett	Contra Costa	CA	III
Bolinas	Marin	CA	F
Point Bonita	Marin	CA	F
Potter Valley	Mendocino	CA	Uncertain*
Corral de Tierra	Monterey	CA	F
Gonzales	Monterey	CA	F
King City	Monterey	CA	IV
Monterey	Monterey	CA	F
Point Piños	Monterey	CA	F
Salinas	Monterey	CA	V?
Napa	Napa	CA	II
Panoche	San Benito	CA	F
Mile Rocks	San Francisco	CA	F?
San Francisco	San Francisco	CA	IV?
Southampton Shoal	San Francisco	CA	F
Yerba Buena	San Francisco	CA	F
Stockton	San Joaquin	CA	II
San Luis Obispo	San Luis Obispo	CA	III–IV (preferred: III)
Menlo Park	San Mateo	CA	IV?
Campbell	Santa Clara	CA	F
Los Gatos	Santa Clara	CA	VI
Mount Hamilton	Santa Clara	CA	F
San Jose	Santa Clara	CA	V
Sunnyvale	Santa Clara	CA	IV
Boulder Creek	Santa Cruz	CA	V
Santa Cruz	Santa Cruz	CA	IV–V (preferred: V)
Watsonville	Santa Cruz	CA	F
Vallejo	Solano	CA	F
Modesto	Stanislaus	CA	III
Oakdale	Stanislaus	CA	F
Woodland	Yolo	CA	III
Marysville	Yuba	CA	Uncertain, but probably NF

*May have been a different event.

interestingly, that point nearly corresponds with the southeastern termination of the 1906 mainshock rupture, near San Juan Bautista. Alternative locations include points along the southernmost portion of the mainshock rupture, points along the creeping segment of the SAF southeast of San Juan Bautista, and points along faults west of the SAF, within appropriate confidence-level contours. The M_I at our preferred location is 5.6; incorporating the statistical uncertainty in the magnitude for 17 observations at 95% confidence (interpolating from Table 1), our magnitude for this event is M_I 5.6 ($-0.4/+0.3$). A comparison to the intensity distributions of similarly sized modern events in the vicinity (i.e., 9 April 1961, *M* 5.6; 14 September 1963, *M* 5.4; 26 January 1986, *M* 5.5; 18 April 1990, *M* 5.4; and 12 August 1998, *M* 5.4; intensity data from the National Geophysical Data Center earthquake intensity database, 1638–1985 [2002], and from J. Dewey, personal comm. [2002]) suggests that *M* ~5.6 on or west of the SAF is reasonable for the 17 May 1906 event, but *M* ~5.4 or 5.5 (which would be within our uncertainty) might fit the observations better.

6 July 1906 Priest Valley Aftershock

Shortly before 23:00 on 6 July 1906, an earthquake was felt in central California, along the coast from San Luis Obispo to Santa Cruz and in the San Joaquin Valley from Hanford (Kings County) to Los Banos (Merced County). The strongest intensity (MMI V) was reported in Coalinga. It does not appear to have been felt in Fresno or Visalia. The

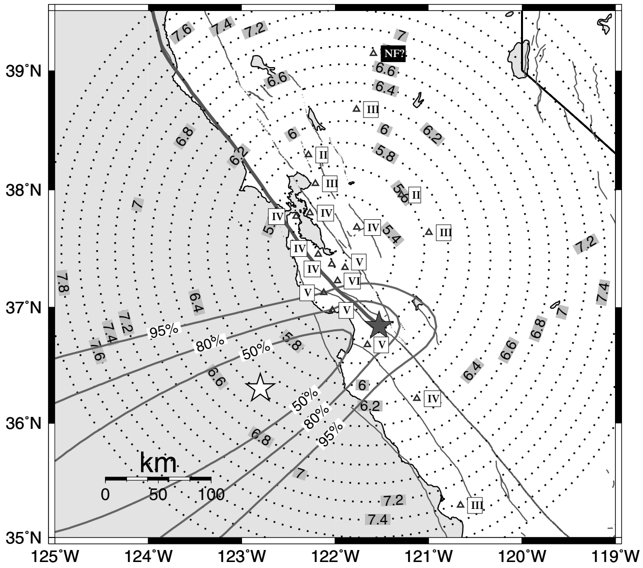

Figure 9. Map of the 17 May 1906 aftershock. See Figure 2 for explanation.

intensities, and locations where it is known to have been felt or where it is inferred to have not been felt, are listed in Table 10; the solution for this event is shown in Figure 10. (For the original reports, see tables 1 and 12 in Meltzner and Wald [2002].) The intensity center and our preferred location are along the creeping section of the SAF, east of King City and northwest of Priest Valley. M_I at our preferred location is 4.9; incorporating the statistical uncertainty in the magnitude for nine observations at 95% confidence (interpolating from Table 1), our magnitude for this event is M_I 4.9 ($-0.5/+0.4$). Although earthquakes of $M > 4$ are rare along this stretch of the fault, a similar event ($M \sim 5.25$) appears to have occurred in the same location in January 1855, less than 17 years after the previous large earthquake along the San Francisco–to–San Juan Bautista section of the SAF in 1838 (Toppozada and Borchardt, 1998).

Table 10
Intensity and Felt Data for the 6 July 1906, 22:55 Aftershock

City	County	State	MMI, Felt (F), or Not Felt (NF)
Coalinga	Fresno	CA	V
Fresno	Fresno	CA	Uncertain, but probably NF
Hanford	Kings	CA	II
Lemoore	Kings	CA	III?
Los Banos	Merced	CA	III?
Volta	Merced	CA	F
King City	Monterey	CA	IV?
Salinas	Monterey	CA	F
San Lucas	Monterey	CA	IV?
San Luis Obispo	San Luis Obispo	CA	III
Mount Hamilton	Santa Clara	CA	F
Santa Cruz	Santa Cruz	CA	III
Watsonville	Santa Cruz	CA	III
Visalia	Tulare	CA	Uncertain, but probably NF

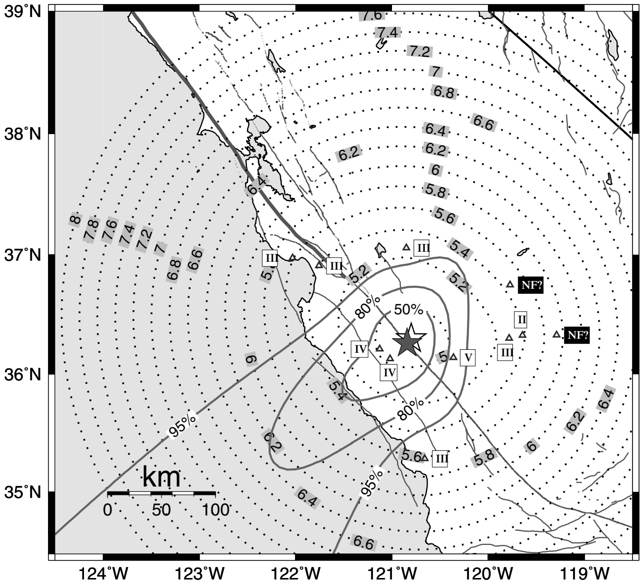

Figure 10. Map of the 6 July 1906 aftershock. See Figure 2 for explanation.

6 December 1906 Cambria Aftershock

At 22:40 on 6 December 1906, an earthquake was felt along coastal central California, from Surf (Santa Barbara County) north to at least Point Piedras Blancas (northern San Luis Obispo County). It was probably also felt well into Monterey County, but because of the sparse population between Piedras Blancas and the Monterey Peninsula, the northern limit of the felt area is very poorly constrained. Although it was reported from a number of locations in San Luis Obispo and Santa Barbara Counties (see Townley and Allen [1939] and table 1 in Meltzner and Wald [2002]), few of those reports were accompanied by any description. From the original reports, we assigned MMI VI (?) at Point Piedras Blancas based on cracking at the lighthouse tower there, MMI V at Cambria based upon articles being "shaken from shelves," MMI IV (?) at Santa Maria based upon the statement that it was "severe" there but no damage was reported, and MMI III (?) at Surf based only on a statement that it was felt there, but that it was the farthest point southeast that it was felt. An additional report from Paso Robles (which was not included in Meltzner and Wald [2002]) has been located: the *Paso Robles Record* of 8 December 1906 (p. 3) states that "two severe shocks of earthquake were felt here Thursday evening [6 December] about 11 o'clock." This statement would support MMI ≥ IV at Paso Robles, but it would be a stretch to assign a particular intensity value based solely on that description.

At San Luis Obispo, MMI IV or V could be assigned, depending upon which descriptions are given the greatest weight and credibility: MMI IV would be appropriate based upon two independent reports that called it “slight” and a statement that “many did not feel it at all, while others were of the opinion that the end of the world had come” (note that this earthquake happened at night, when some people may have already been asleep), whereas MMI V might be valid based upon cracked plaster at the city hall and one description of the earthquake lasting more than 30 sec. (We are skeptical about the reported 30-sec duration in San Luis Obispo. Untrained observers sometimes overestimate the duration of shaking, in some cases by a significant amount. Note as a case in point that the 19 April 1906 Santa Monica Bay triggered event was described as lasting 32 sec in Santa Monica, but only 3–4 sec in Long Beach and about 3 sec in downtown Los Angeles; it is hard to believe that such a marked difference in the duration of perceptible shaking could have occurred over such short a distance. Other examples exist in Meltzner and Wald [2002].)

Toppozada *et al.* (2000) and Toppozada and Branum (2002) placed the event about 10 km offshore from Cambria, at 35.5° N, 121.2° W. They estimate an “area magnitude” of 5.7 for the event, based on empirical relationships between magnitude and the total areas shaken at or above MMI V, VI, and VII. Their location is certainly reasonable, and we adopt it as our preferred location. (Our data do not provide a better constraint on the location.) Using the method adapted from Bakun and Wentworth (1997, 1999) and assuming MMI VI at Piedras Blancas, V at Cambria, IV at San Luis Obispo, IV at Santa Maria, and III at Surf, M_{I} at our preferred location is 5.3 ($-0.6/+0.5$). This is our preferred magnitude. If, however, we assume the intensity at San Luis Obispo to be MMI V, then M_{I} at our preferred location is 5.4 ($-0.6/+0.5$). Finally, if we assume that the intensity at Paso Robles is MMI V (and we again assume the intensity at San Luis Obispo is MMI V), then M_{I} at our preferred location is still only 5.4 ($-0.5/+0.4$). Note that in all of these cases, our magnitude is less than that of Toppozada *et al.* (2000) and Toppozada and Branum (2002), but their magnitude is within our uncertainty. Unfortunately, there are no modern events in that vicinity that could be used to improve the constraints on the magnitude.

5 June 1907 Fremont Aftershock

Another aftershock occurred in the SFBA shortly after midnight on the morning of 5 June 1907. It was felt from Sonoma to Los Gatos and as far inland as Tuolumne County. The intensities, and locations where it is known to have been felt or where it is reported or inferred to have not been felt, are listed in Table 11; the solution for this event is shown in Figure 11. (For the original reports, see tables 1 and 13 in Meltzner and Wald [2002].) The intensity center and our preferred location are along the Hayward fault in Fremont. M_{I} at our preferred location is 5.0; incorporating the statistical uncertainty in the magnitude for 11 observations at 95% confidence (interpolating from Table 1), our magnitude for this event is M_{I} 5.0 ($-0.4/+0.3$). Note that our Fremont location for this event agrees with a statement in Townley

Table 11
Intensity and Felt Data for the 5 June 1907, 00:27 Aftershock

City	County	State	MMI, Felt (F), or Not Felt (NF)
Alameda	Alameda	CA	V
Berkeley	Alameda	CA	IV
Dimond	Alameda	CA	F
Livermore	Alameda	CA	IV
Mills College	Alameda	CA	F
Oakland	Alameda	CA	F
Martinez	Contra Costa	CA	IV
Fresno	Fresno	CA	NF
Bakersfield	Kern	CA	NF
Kentfield	Marin	CA	F
Napa	Napa	CA	III?
San Francisco	San Francisco	CA	IV–V (preferred: IV)
Stockton	San Joaquin	CA	III
San Luis Obispo	San Luis Obispo	CA	Uncertain, but probably NF
Half Moon Bay	San Mateo	CA	Uncertain*
Menlo Park	San Mateo	CA	F
Redwood City	San Mateo	CA	F
San Gregorio	San Mateo	CA	Uncertain*
Alma	Santa Clara	CA	F
Campbell	Santa Clara	CA	F
Los Gatos	Santa Clara	CA	IV
Mountain View	Santa Clara	CA	F
Mount Hamilton	Santa Clara	CA	F
Palo Alto	Santa Clara	CA	F
San Jose	Santa Clara	CA	IV–V (preferred: V)
Santa Clara	Santa Clara	CA	F
Boulder Creek	Santa Cruz	CA	F
Peachland	Sonoma	CA	F
Sonoma	Sonoma	CA	III?
Jamestown	Tuolumne	CA	III?

*May have been a different event.

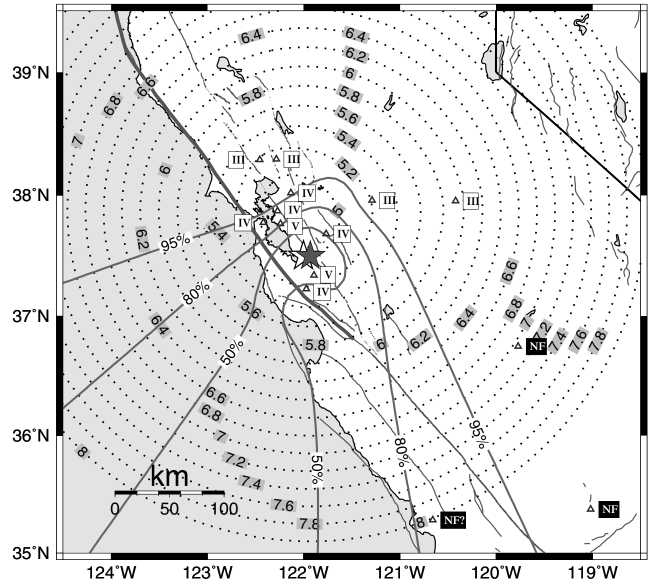

Figure 11. Map of the 5 June 1907 aftershock. See Figure 2 for explanation.

and Allen (1939, p. 145) that the seismogram for this event obtained at the University of California, Berkeley, had "an interval *L–P* of six seconds, corresponding to a distance of origin of about thirty miles"; our location is about 31 miles (50 km) from the university.

8 August 1907 Punta Gorda Aftershocks

On the early morning of 8 August 1907, two moderate earthquakes (along with several smaller ones) occurred in the Humboldt County vicinity. The two largest events occurred at 04:44 and 06:05. Based on the majority of the descriptions, these two earthquakes seem to be similar. (For the original reports, see tables 1 and 14 in Meltzner and Wald [2002].) Three reports identified differences between the two: in Eureka, the second event was heavier, according to one report; in Eureka, the first one was longer, according to another report; and in Upper Mattole, the first was the hardest, according to a third report. However, other reports from the same towns did not identify these contrasts and made no distinction between the two events. The lack of concurring reports suggests that the differences may have been only in some individuals' perceptions, although, alternatively, the reported contrasts may reflect that the first event was closer to Upper Mattole and that the second event was closer to Eureka. In this article, we assume that the two events were similar in size and source location and that the intensities at each location were the same for both events. Even if the two events were slightly different in location and/or in magnitude, our solution is still a useful approximation for both events.

The intensities and felt locations are listed in Table 12; the solution for these events is shown in Figure 12. The intensity center and our preferred location are located near Punta Gorda along the Humboldt County coast. Punta Gorda is near the inferred northern termination of the 1906 mainshock rupture, and several faults exist in this area (Prentice *et al.*, 1999); any one of these faults is a plausible source. M_I at our preferred location is 5.1; incorporating the statistical uncertainty in the magnitude for six observations at 95% confidence (interpolating from Table 1), our magnitude for each of these events is M_I 5.1 ($-0.5/+0.4$).

11 August 1907 Shelter Cove Aftershock

Shortly after 04:00 on the morning of 11 August 1907, 3 days after the double shock in Humboldt County (just discussed), a larger earthquake occurred in the same general region. The intensities, and locations where the 11 August event is reported to have been felt or not felt, are listed in Table 13; Figure 13 shows the intensity distribution. (For the original reports, see tables 1 and 15 in Meltzner and Wald [2002]). In some respects, the intensity distribution of the 11 August 1907 event is similar to that of the 23 April 1906 event (Fig. 6), although the 11 August 1907 event was not felt in Oregon or northernmost California, and the total felt area for the 11 August 1907 event was smaller.

Table 12
Intensity and Felt Data for the 8 August 1907 Aftershocks at 04:44 and 06:05

City	County	State	MMI, Felt (F), or Not Felt (NF)
Arcata	Humboldt	CA	F
Blocksburg	Humboldt	CA	F
Blue Lake	Humboldt	CA	F
Eureka	Humboldt	CA	IV?
Falk	Humboldt	CA	F
Ferndale	Humboldt	CA	IV
Garberville	Humboldt	CA	IV?
Grizzly Bluff	Humboldt	CA	IV?
Pepperwood	Humboldt	CA	V
Upper Mattole	Humboldt	CA	V
Branscomb	Mendocino	CA	F
Ruth	Trinity	CA	Uncertain*

*May have been a different event.

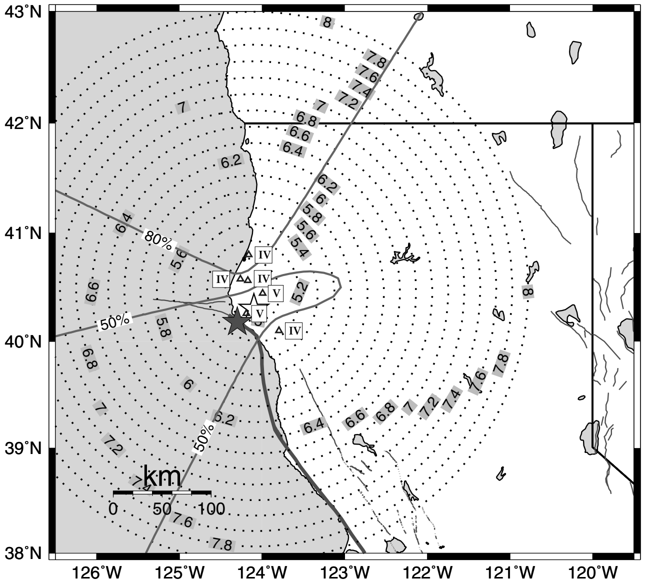

Figure 12. Map of the 8 August 1907 aftershocks, which are assumed to be similar. See Figure 2 for explanation. Note that the 95% confidence-level contour is off the map; the entire area shown is within the 95% confidence contour.

The solution for this event is shown in Figure 13. Like the 23 April 1906 event, the intensity center for this event is inland; this time, it is in southern Trinity County. The 95% confidence-level contour for location includes an 80-km stretch of the SAF off the Humboldt and Mendocino County coast. Although (as with the 23 April 1906 event) we reject an inland source region, this time we prefer a location on or near the SAF within the 95% confidence contour: specifically, near Shelter Cove.

There are several reasons why we believe an SAF location is plausible for this event, but not for the 23 April 1906 event. First, the smaller felt area of the 11 August 1907 event suggests that the magnitude was smaller and that the

Table 13
Intensity and Felt Data for the 11 August 1907, 04:19 Aftershock

City	County	State	MMI, Felt (F), or Not Felt (NF)
Chico	Butte	CA	IV
Oroville	Butte	CA	III?
Colusa	Colusa	CA	NF
Crescent City	Del Norte	CA	NF
Willows	Glenn	CA	III
Arcata	Humboldt	CA	F
Blocksburg	Humboldt	CA	V?
Briceland	Humboldt	CA	F
Cape Mendocino	Humboldt	CA	F
Eureka	Humboldt	CA	IV
Falk	Humboldt	CA	F
Ferndale	Humboldt	CA	V
Fortuna	Humboldt	CA	V
Garberville	Humboldt	CA	F
Ryan Slough	Humboldt	CA	F
Branscomb	Mendocino	CA	F
Covelo	Mendocino	CA	V?
Fort Bragg	Mendocino	CA	F
Laytonville	Mendocino	CA	F
Mendocino	Mendocino	CA	IV
Willits	Mendocino	CA	F
French Corral	Nevada	CA	F
Grass Valley	Nevada	CA	IV
Nevada City	Nevada	CA	IV
North San Juan	Nevada	CA	F
Shady Creek gravel mine	Nevada	CA	F
La Porte	Plumas	CA	F
San Francisco	San Francisco	CA	II
Baird	Shasta	CA	V
Redding	Shasta	CA	IV
Sisson*	Siskiyou	CA	IV
Corning	Tehama	CA	IV
Red Bluff	Tehama	CA	IV
Island Mountain	Trinity	CA	F
Ruth	Trinity	CA	F
Weaverville	Trinity	CA	IV?

*Now the town of Mt. Shasta, California.

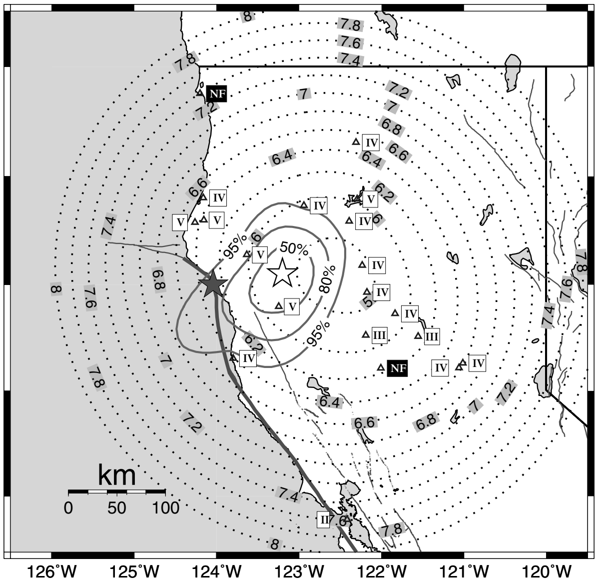

Figure 13. Map of the 11 August 1907 aftershock. See Figure 2 for explanation.

location was closer to shore. Second, the intensities in Mendocino County appear to have been higher for the 11 August 1907 event, suggesting that the Mendocino County coast or southern Humboldt County coast are at least possible source locations. (The northern Mendocino County coast is sparsely populated, and MMI VI+ there could easily have gone unreported in the county newspapers.) Third, the "not felt" report from Crescent City, coupled with a lack of felt reports from anywhere north of Eureka, Arcata, or southern Siskiyou County, precludes a location on or north of the Mendocino fracture zone (MFZ). And fourth, the most tectonically feasible offshore source location south of the MFZ is the SAF. (A location west or southwest of the preferred location is possible but considered less likely.)

The M_I at our preferred location is 6.3; incorporating the statistical uncertainty in the magnitude for 18 observations at 95% confidence (interpolating from Table 1), our magnitude for this event is M_I 6.3 ($-0.4/+0.3$). Abe (1988) used Milne instrument data to estimate M_S 5.0 for this event, but he only used components from stations at Victoria and Toronto (K. Abe, personal comm., 2001). Abe's (1988) magnitude conflicts with the numerous teleseismic recordings mentioned by Townley and Allen (1939), from as far as Tiflis (Tbilisi), Georgian Republic. No Milne data could be located from Tiflis; however, the Milne instrument amplitude at Shide, Isle of Wight, is listed as 0.5 mm in Shide Circular no. 17, issued by the British Association for the Advancement of Science (available in the supplementary CD-ROM volume to Lee *et al.*, 2003 and at their web site). Toppozada and Branum (2002) applied Abe's (1988) formula to this amplitude and derived M_S ~6.4 for this event, with a tentative location at 40.5° N, 125.5° W. Toppozada and Branum's (2002) magnitude and our M_I 6.3 ($-0.4/+0.3$) are consistent with the earthquake being felt as far away as San Francisco and Nevada City. If our value for M_I is correct, the 11 August 1907 event was the second-largest aftershock of the sequence, through at least December 1907 (the end of our study period). Its source location was near that of the 8 August 1907 aftershocks, suggesting that the 8 August events were foreshocks to the 11 August event.

On a related note, Bakun (2000) analyzed an earthquake that occurred in October 1909 along California's north coast. He located the earthquake onshore, near Cape Mendocino, based on intensities of MMI VIII at three nearby towns. Bakun's M_I value is 6.7 ($-0.4/+0.3$) and the Gutenberg–Richter magnitude ($M_{G\text{-}R}$) is 6+ for the 1909 event, although Abe (1988) estimated only M_S 5.8. Bakun (2000) surmised that the high M_I value for 1909 might be anomalous, and he suggested two possible explanations for it: that the 1909 source was located in the midcrust (deeper than normal) or that it was a high-stress-drop event. Bakun's doubts notwithstanding, his M_I value may be valid. Comparing the intensity distributions of the 1909 event and the 11 August 1907 Shelter Cove event, both events appear to be consistent with onshore or near-coast locations, and the 1909 event appears to be larger and approximately 50 km farther north. If the 1909 event was larger than the M_I 6.3 Shelter Cove event on 11 August 1907, then M_I 6.7 is certainly reasonable for 1909. In a more rigorous approach, Toppozada and Branum (2002) estimated an area magnitude of 6.6 for the 1909 event, based on empirical relationships between magnitude and the total areas shaken at or above MMI V, VI, and VII; this also supports Bakun's (2000) M_I value of 6.7. It remains puzzling, however, that Abe's values for M_S are significantly lower than M_I for both the 1907 and 1909 events. Although we prefer the higher M_I values, we cannot rule out midcrustal or high-stress-drop sources for either event.

Discussion

Size of Aftershocks and Triggered Events

Looking at the first 20 months of the aftershock sequence, some general remarks can be made. In the 20-month period following the M_W 7.8 mainshock, two aftershocks and an additional triggered event had a magnitude of M 6.0 or above, and a total of four aftershocks and triggered events had a magnitude of M 5.5 or above. The largest events, in order of decreasing size, were the M ~6.7 north-coast aftershock of 23 April 1906, the M ~6.3 Shelter Cove aftershock of 11 August 1907, the M ~6.1 Imperial Valley triggered event of 18 April 1906, and the M ~5.6 San Juan Bautista aftershock of 17 May 1906. The largest aftershocks and triggered events ($M \geq 4.9$) in our study period (through December 1907) are shown in Figure 14 and are summarized in Table 14. Work by Bakun (2000) suggested that there was at least one large late aftershock: an M ~6.7 event near Cape Mendocino on 28 October 1909 (PST).

An important issue to address is the completeness threshold for our study. We attempted to identify the larger events based on co-temporal reports of earthquakes from locations spaced tens to hundreds of kilometers apart. The biggest question pertains to how large an aftershock could have occurred that might not have been identified in this study. The smallest aftershock we characterized had a magnitude of M 4.9, but other similarly sized or even larger events may have been missed. There are several reasons for this. For one, a moderate earthquake in a sparsely populated region might have been reported in only a few towns, possibly none of which being near the epicenter; in that case, the earthquake might have been mistaken for a smaller event, and, consequently, we may have failed to analyze it. For another, some of the newspapers attempted to suppress all news regarding earthquakes in California (Lawson, 1908). In our observation, this was the practice of a number of newspapers in the SFBA and in Sonoma and Solano Counties. Elsewhere, the fact that most newspapers reported even small events suggests that the reporting of a larger aftershock would not have been suppressed. Another reason might be that, during the first few days of the aftershock sequence, the sheer number of aftershocks made it difficult to distinguish between two closely timed events in different locations and one larger regional event.

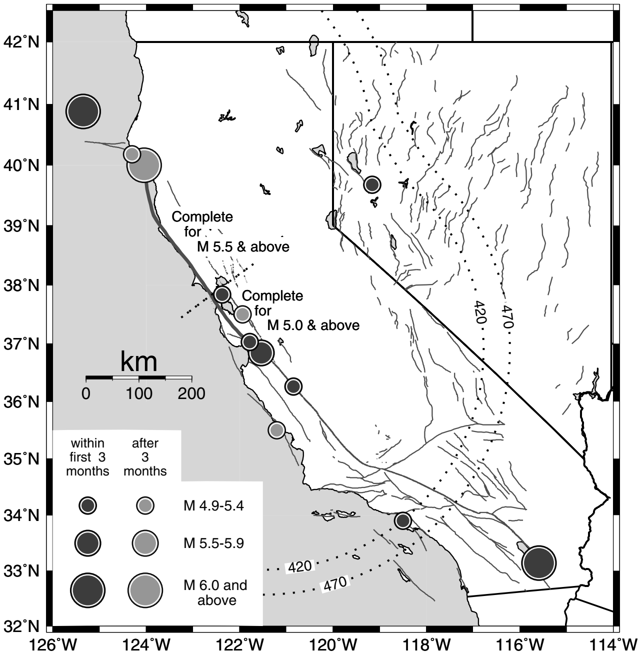

Figure 14. Summary map, showing the locations of the largest ($M \geq 4.9$) aftershocks and triggered events of the 1906 San Francisco earthquake, through December 1907. (Regions beyond the aftershock zone, where triggered events potentially may have occurred, were only studied for the first few days following the mainshock.) Note that, in the SFBA and to the south, the record is probably complete for $M \geq 5.0$, but north of the SFBA, the record may only be complete down to M 5.5. (Far offshore, events of even higher magnitudes could be missing.) Distance contours of 420 and 470 km (the equivalent of one rupture length, given its uncertainties) from the 1906 mainshock rupture are shown as dotted lines. See Table 14 for more information.

Because a significant number of M 4.9–5.0 aftershocks were identified in the SFBA and to the south, and because all other events in that region appear to have had smaller intensity distributions than those identified, it is believed that all $M \geq 5.0$ events in the SFBA and to the south were characterized. Events of $M \geq 5.0$ would presumably have been felt and reported at distances from the SFBA (up to 50 km away or more). Hence, even if reports of earthquakes were suppressed within the SFBA, we infer that we could identify a $M \geq 5.0$ SFBA event from abundant felt reports in the periphery of the SFBA, in conjunction with the relatively complete record at Berkeley and a fairly reliable newspaper source in Livermore. In that case, we further infer that our

Table 14

$M \geq 4.9$ Aftershocks and Triggered Events* (Through Dec 1907)

Date	Time (PST)	Magnitude[†]	Source Location	Latitude (°N)	Longitude (°W)
18 April 1906	14:28	4.9 ($-0.6/+0.5$)	Near Santa Cruz	37.03	121.78
18 April 1906	16:30	6.1 ± 0.4	Imperial Valley	33.14	115.59
19 April 1906	12:31	5.0 ($-0.4/+0.3$)	Santa Monica Bay	33.90	118.50
19 April 1906	20:15	4.9 ($-0.6/+0.5$)[‡]	Near Fernley, Nevada	39.68	119.16
23 April 1906	01:10	6.7 ± 0.3[§]	100 km West of Eureka	40.88	125.35
25 April 1906	15:17	4.9 ($-0.6/+0.5$)	San Francisco Bay area	37.84?	122.37?
17 May 1906	20:21	5.6 ($-0.4/+0.3$)	San Juan Bautista	36.84	121.53
06 July 1906	22:55	4.9 ($-0.5/+0.4$)	Northwest of Priest Valley	36.26	120.84
06 December 1906	22:40	5.3 ($-0.6/+0.5$)	Near Cambria	35.5	121.2
05 June 1907	00:27	5.0 ($-0.4/+0.3$)	Fremont	37.50	121.93
08 August 1907	04:44	5.1 ($-0.5/+0.4$)	Punta Gorda	40.18	124.30
08 August 1907	06:05	5.1 ($-0.5/+0.4$)	Punta Gorda	40.18	124.30
11 August 1907	04:19	6.3 ($-0.4/+0.3$)	Shelter Cove	40.00	124.04

*This list should be considered complete only for $M \geq 5.5$ events, although it is possible that even larger aftershocks located far offshore may be missing.

[†] Uncertainties in magnitude are at 95% confidence, unless otherwise indicated.

[‡] Our method is not calibrated for the Basin and Range province, and this magnitude estimate may be too high.

[§] The uncertainty in magnitude for this event is purely subjective and does not carry any statistical level of confidence.

list of $M \geq 5.0$ events is not missing any event due to suppression of earthquake reports. To the north of the SFBA, a pair of M 5.1 events was located near Punta Gorda, but it is possible that a similarly sized event in Mendocino or Sonoma County may have been overlooked. Although it is difficult to ascertain the completeness of our list north of the SFBA, a conservative estimate is that we have identified all $M \geq 5.5$ events near the fault north of the SFBA; we may be complete for earthquakes down to $M \sim 5.1$. Away from the 1906 rupture to the north, south, and east, we speculate that our catalog is complete for $M \geq 5.5$, as we feel that such events would stand out in the catalog of Townley and Allen (1939), but far offshore it may be incomplete at higher magnitudes. In regard to aftershocks within the first few days, the identification of an M 4.9 event near Santa Cruz on 18 April 1906 suggests that our completeness threshold of M 5.0 for the SFBA and to the south is also valid for the first few days: many other aftershocks were reported in the first few days, but none appear to be larger than the event near Santa Cruz. To the north, the largest events within the first few days appear to be an event in Mendocino County at around 10:00 on 18 April 1906 and an event in Humboldt County in the early morning hours of 20 April 1906 (Meltzner and Wald [2002], their table 1), but neither event appears to have a magnitude as large as M 5.5; so again, our completeness threshold for that region also applies for the first few days.

Finally, we must consider the possibility of a significant aftershock within the first few minutes. As an analog, the M_W 6.7 Northridge earthquake was followed 1 min later by an M 6 aftershock (Hough and Jones, 1997). Indeed, many accounts of the San Francisco mainshock describe two maxima or surges in the shaking, separated by a very brief lull (Lawson, 1908, Vol. I, pp. 374–376), which suggests that there may have been two separate events. Bolt (1968) argued that the observations, as well as instrumental records, are most consistent with a foreshock preceding the mainshock. There appears to be no evidence to support the hypothesis that there was a large aftershock within the first few minutes of the mainshock; still, it is important to remember that interpretation of the instrumental recordings is challenging (Wald *et al.*, 1993) and that the felt reports cannot preclude with certainty such an aftershock. Except for earthquakes that may have occurred far offshore, we believe that our catalog is complete for all aftershocks of $M \geq 5.5$ for the duration of the study period.

Spatial Distribution

One striking characteristic of the aftershock sequence is that the largest aftershocks (including triggered events) occurred either at the ends of the 1906 mainshock rupture or off the mainshock rupture entirely. This agrees well with the findings of Mendoza and Hartzell (1988), who made similar observations looking at aftershock patterns and mainshock faulting associated with a number of earthquakes in California and Idaho between 1966 and 1986. This characteristic is also consistent with the conclusions of Liu *et al.* (1999, 2003), that most of the aftershocks of the 1992 Landers earthquake are not candidates for rerupture of the mainshock faults, and of Rubin and Gillard (2000), who showed that aftershocks of microearthquakes on the central SAF tend not to occur within a distance approximately equal to the radius of the first rupture. The 17 May 1906 aftershock was located at or near the southern end of the mainshock rupture, the 8 August and 11 August 1907 events (and the October 1909 event) were located at or near the northern end, and most of the other events either were more consistent with a location on a parallel fault than on the SAF (e.g., the Fremont aftershock of 5 June 1907 on the Hayward fault) or were located tens to hundreds of kilometers from the mainshock rupture. The 18 April 1906 Santa Cruz area aftershock, which had an estimated *M* of 4.9, was one of the largest documented aftershocks along or near the mainshock rupture (excluding its endpoints). The 25 April 1906 aftershock may have been an *M* 5.0 aftershock on or near the SAF near San Francisco, but the intensity data could be explained just as well by an *M* 4.8 event on or near the Hayward fault.

Interestingly, at least one aftershock (*M* 4.9, 6 July 1906) appears to have occurred on the creeping section of the SAF southeast of San Juan Bautista. Although this section of the fault has experienced only creep and microearthquake activity in modern times, Toppozada and Borchardt (1998) identified a series of earthquakes that occurred along the creeping section between 1853 and 1855, 15–17 years after the 1838 earthquake on the SAF north of San Juan Bautista. One of those earthquakes, an *M* ~5.25 event in January 1855, appears to have occurred in the same location as the 6 July 1906 event. Although the timescales are different (months versus years after a major earthquake), the occurrence of these moderate events in the creeping section suggests that coseismic slip along the SAF north of San Juan Bautista may load the creeping section faster than stress can be released by creep alone, which in turn may produce these relatively rare moderate-sized earthquakes.

Triggered Events

Earthquakes were triggered as far away as western Arizona, between 800 and 940 km southeast of San Juan Bautista, the southeastern limit of the mainshock rupture. The event in western Arizona occurred during the passage of the seismic wave train from the mainshock and is inferred to have been dynamically triggered. An abundance of seismic activity in several areas of southern California, which apparently began in the hours following the San Francisco mainshock and began to die off about a day later, is also inferred to have been triggered, as it is exceedingly improbable that all of the earthquakes coincided by chance alone. For similar reasons, the earthquakes in southern central Oregon and in western Nevada on 18–19 April 1906 are inferred to have been triggered. The earthquake triggering clearly extended into the Basin and Range tectonic province, as the triggered events in Arizona, Nevada, and Oregon all occurred within that province. Figure 15 shows the spatial distribution of significant aftershocks and triggered events within the first 48 hr, and these events are summarized in Table 15. Several triggered events approached or exceeded *M* 5.0, and one event exceeded *M* 6.0.

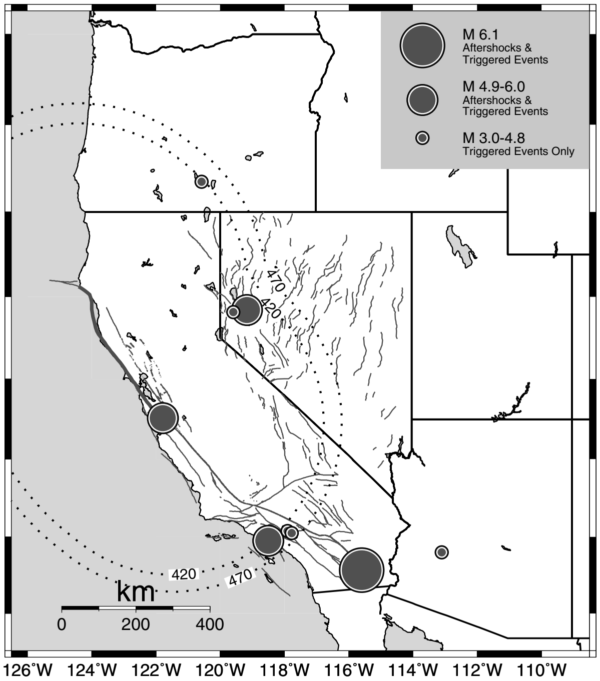

Figure 15. Summary map, showing the locations of *M* ≥4.9 aftershocks and *all* reported triggered events of the 1906 San Francisco earthquake, within the first 48 hr. Distance contours of 420 and 470 km (the equivalent of one rupture length, given its uncertainties) from the 1906 mainshock rupture are shown as dotted lines. Note that while a distance equal to one rupture length is conventionally used to distinguish aftershocks from triggered events, it is not clear that such a convention is applicable in this case, given the long rupture length. A few events near the periphery of the aftershock zone in the Basin and Range province were considered to be triggered events. See Table 15 and the text for more information.

It is notable that much of the well-documented evidence for triggered seismicity comes from volcanic and geothermal areas, but many of the reported triggered events from 1906 did not occur in such regions. It is also notable that some of the triggered events (e.g., those in western Arizona and near Paisley, Oregon) appear to be larger than any earthquakes in their respective vicinities in modern times, that is, in the last few decades. Following the 2002 Denali fault earthquake, one of the triggered events recorded in Utah was larger than any event within a 15-km radius within the 3-year study period preceding it (Pankow *et al.*, 2002; K. Pankow, personal comm., 2002).

Beyond the first 48 hr, earthquakes continued to be felt in the Imperial Valley, as would be expected following an *M* 6.1 earthquake, and one other earthquake was reported in Paisley, Oregon, on 29 April 1906. In addition, several earthquakes were felt in San Jacinto (Riverside County) during the week following the 18 April mainshock, but it is not clear if these events were triggered by either the San Francisco or Imperial Valley earthquakes.

Comparison to Modern Aftershock Sequences

The magnitudes of aftershocks generally follow a Gutenberg–Richter relation, with each unit decrease in main-

Table 15

Significant Aftershocks and Triggered Events within 48 hr

Date	Time (PST)	Magnitude	Source Location	Latitude (°N)	Longitude (°W)
18 April 1906	05:16	~4	West of Phoenix, AZ	33.6*	113.1*
18 April 1906	14:28	4.9 (−0.6/+0.5)	Near Santa Cruz	37.03	121.78
18 April 1906	16:30	6.1 ± 0.4	Imperial Valley†	33.14	115.59
18 April 1906	21:10	~3	Pomona Valley†	34.10*	117.77*
19 April 1906	01:30	≥3.5	Near Paisley, OR†	42.70*	120.57*
19 April 1906	12:31	5.0 (−0.4/+0.3)	Santa Monica Bay	33.90	118.50
19 April 1906	14:02	~3.25 to 3.5	East of Reno, NV	39.63*	119.59*
19 April 1906	20:15	4.9 (−0.6/+0.5)‡	Near Fernley, NV	39.68	119.16
20 April 1906	00:30	~3	North of Azusa§	34.16*	117.90*

Includes aftershocks of M ≥4.9 and *all* triggered events in the first 48 hr.

*Source location based on observations from three or fewer locations.

†The event listed is the largest of a swarm or cluster of events that occurred at this location.

‡Our method is not calibrated for the Basin and Range province, and this magnitude estimate may be too high.

§This event may have been preceded by a similar-sized event at 20:50 on 19 April in the same general location.

shock magnitude leading to a tenfold decrease in the total number of aftershocks (Reasenberg and Jones, 1989). Without calculating Gutenberg–Richter a- or b-values or the p-value in Omori's law for the 1906 aftershock sequence, some robust observations are apparent upon comparison with typical or average California aftershock sequences. (Calculating a-, b-, or p-values may not be very meaningful, considering that there are only four events with magnitudes above the completeness threshold.) Reasenberg and Jones (1989, 1994) have developed a stochastic parametric model for determination of aftershock probabilities and expectations, based on the generic values $a = -1.67$, $b = 0.91$, and $p = 1.08$. These generic values are based on observations of historic California aftershock sequences, for which the mainshock magnitude is M ≥5.0. It is unclear, however, how applicable these aftershock expectations are to the aftershock sequence of an M_W ~7.8 SAF mainshock, since the expectations are calculated based on observed behavior of aftershocks following smaller mainshocks on shorter and more heterogeneous faults.

Using the California generic model (CGM) (Reasenberg and Jones, 1989, 1994), for the 20-month period following the 1906 San Francisco mainshock, 2.7 aftershocks of M ≥6.5 should be expected (at the 95% confidence range, between 0 and 6 such aftershocks would be expected), 7.6 aftershocks of M ≥6.0 should be expected (at 95% confidence, 3–13 such aftershocks would be expected), and 21.6 aftershocks of M ≥5.5 should be expected (at 95% confidence, 13–31 such aftershocks would be expected). From this study, however, we observe a far less productive aftershock sequence: only one aftershock had M ≥6.5, only three events (including the Imperial Valley triggered event) had M ≥6.0, and only four events had M ≥5.5. If, for the sake of argument, we assume that the magnitude for each earthquake in our study was the highest allowable within the 95% confidence limit, we would still have only seven events of M ≥5.5 (this assumes that the Cambria earthquake of 6 December 1906, which was estimated to be of M_I 5.3 [−0.6/+0.5], is actually M 5.8 and that the two Punta Gorda earthquakes of 8 August 1907, which were estimated to be of M_I 5.1 [−0.5/+0.4], are actually M 5.5). Even if we identified only half of the M ≥5.5 aftershocks, and an equivalent number occurred far offshore and were not identified in our efforts, there still would have been 14 or fewer aftershocks of M ≥5.5; this is more than one standard deviation below the total number expected within the first 20 months of the aftershock sequence, based on the CGM. (It has recently been discovered [P. Reasenberg, personal comm., 2002] that an error in the determination of generic California a-, b-, and p-values by Reasenberg and Jones [1989, 1994] may bias the CGM such that it predicts an aftershock rate that is slightly higher than the "average"; work is currently being done to remedy this bias, but it is not anticipated that this bias will significantly affect our conclusions.) Similar low productivity has been observed for the aftershock sequence of the 1857 Fort Tejon earthquake (Meltzner and Wald, 1999).

The relatively anemic aftershock sequences following the last two great SAF earthquakes suggest that the CGM cannot be extrapolated usefully up to M_W ~7.8 mainshocks, that the rate of aftershocks is governed by the local magnitude of the mainshock rather than by the moment magnitude (local magnitude saturates and is commonly much lower than moment magnitude for events larger than M_W ~7), or that SAF earthquakes and their aftershock sequences behave differently than most California earthquakes. If the latter case is true, it would support the hypotheses that earthquakes on faults with large cumulative offsets (and consequential low heterogeneity) have relatively few aftershocks because of a smoother residual stress field after the mainshock and that mainshocks on faults with large cumulative offsets are less likely to leave large patches with little or no slip after the main rupture to produce large aftershocks (Jones, 1997).

Finally, we draw a comparison between the 1857 and

1906 earthquakes on the SAF and the 2002 earthquakes on the Denali fault in Alaska: like the two SAF events, both the 23 October 2002 M_W 6.7 Nenana Mountain earthquake and the 3 November 2002 M_W 7.9 Denali Park earthquake are being followed by extremely low rates of aftershocks (Anderson *et al.*, 2002). The Denali fault is an analog to the SAF in terms of total length, cumulative slip, and other factors, so the similarities between the four events, including one as small as M_W 6.7, suggest that the shortcomings of the CGM for the 1857 and 1906 earthquakes may be due more to the uniqueness in California of the SAF than to the size of the mainshocks. More work needs to be done to resolve these questions.

The 1906 aftershock sequence also appears to be characterized by slower-than-average decay. Hough and Jones (1997) noted that out of 13 selected southern California mainshock–aftershock sequences for which the mainshock and the largest aftershock were both over M 5.5, 8 mainshocks were followed by their largest aftershock within 1 hr, and all were followed by their largest aftershock within 10 hr; in contrast, the 1968 Borrego Mountain earthquake (which was not included in the selected 13) and its largest aftershock were separated by more than 1 year. Following the 1906 earthquake, the first $M \geq 5.5$ aftershock or triggered event did not occur until 11.3 hr after the mainshock, and the two largest aftershocks (both $M \sim 6.7$) occurred 5 days and 3.5 years, respectively, after the mainshock. Ellsworth *et al.* (1981) used the record of felt aftershocks at Berkeley to argue that the 1906 aftershock rate decays in accordance with Omori's law (proportional to t^{-p}, $p \approx 1$) until about 1910 and that it appears to reach a constant value by about 1915. A closer look at their data, however (see their fig. A1), reveals that the aftershock sequence was characterized by slower-than-average decay ($p \approx 0.8$), which is in agreement with our results.

Comparison to 1857

Many similarities exist between the aftershock sequences of the 1906 (M_W 7.8) and the 1857 (M_W 7.9) earthquakes on the SAF. Although there is considerable uncertainty in the locations and magnitudes of 1857 aftershocks as a result of the ambiguous nature of some of the data, all of the largest aftershocks in both cases appear to have occurred off the SAF (see Figs. 1 and 14). The largest aftershocks of the 1857 earthquake included two significant events during the first 8 days of the sequence, with magnitudes $M \sim 6.25$ and $M \sim 6.7$, near the southern half of the rupture; later aftershocks included an $M \sim 6$ event near San Bernardino in December 1858 and an $M \sim 6.3$ event near the Parkfield segment in April 1860 (Meltzner and Wald, 1999). This is comparable to the results for 1906. As mentioned earlier, both aftershock sequences were relatively unproductive (i.e., there were fewer aftershocks than expected) compared to typical or average California aftershock sequences. Finally, both sequences were characterized by slower-than-average decay, with the largest aftershocks ($M \sim 6.7$ in both cases) coming 5 days (or 3.5 years) and 7 days after the mainshocks in 1906 and in 1857, respectively.

Conclusions

The analysis of historical documents has provided abundant useful information in regard to the aftershocks and triggered events of the most recent great earthquake on the SAF, the 1906 San Francisco earthquake. The two largest aftershocks both had $M \sim 6.7$; one occurred roughly 100 km west of Eureka on 23 April 1906, and the other took place near Cape Mendocino on 28 October 1909. Other significant aftershocks included an $M \sim 5.6$ event near San Juan Bautista on 17 May 1906 and an $M \sim 6.3$ event near Shelter Cove on 11 August 1907. An $M \sim 4.9$ aftershock appears to have occurred on the creeping segment of the SAF (southeast of the mainshock rupture) on 6 July 1906, suggesting that the 1906 earthquake may have loaded the creeping section faster than the fault could relieve stress by creep alone. The 1906 San Francisco earthquake dynamically triggered a small earthquake in western Arizona, 800–940 km from the rupture zone and 910–1050 km from the epicenter, minutes after the origin time of the mainshock. The 1906 earthquake also triggered events in southern California (including separate events in or near the Imperial Valley, the Pomona Valley, and Santa Monica Bay), in western Nevada, and in southern central Oregon, all within 2 days of the mainshock. Of these triggered events, the largest were an $M \sim 6.1$ earthquake near Brawley and an $M \sim 5.0$ event under or near Santa Monica Bay, 11.3 and 31.3 hr after the San Francisco mainshock, respectively.

In general, the largest aftershocks occurred at or near the ends of the 1906 rupture or away from the rupture entirely; very few significant aftershocks occurred along the mainshock rupture itself. The total number of large aftershocks was less than predicted by a generic model based on typical (or average) California mainshock–aftershock statistics; this may suggest that earthquakes on long, smooth faults such as the San Andreas are more efficient at releasing stress than are earthquakes on shorter, more heterogeneous faults. The 1906 sequence also appears to have decayed more slowly than average California sequences. The aftershock sequence of the 1906 earthquake is similar in many respects to the aftershock sequence of the latest large event on the southern SAF, the M_W 7.9 Fort Tejon earthquake in 1857.

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