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The 2007 *M*5.4 Alum Rock, California, earthquake: Implications for future earthquakes on the central and southern Calaveras Fault

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[1] The similarity of seismograms recorded by two seismic stations demonstrate that the 31 October 2007 moment magnitude *M*5.4 Alum Rock earthquake is a repeat of a 1955 M_L5.5 earthquake. Both occurred on Oppenheimer et al.'s (1990) Zone V "stuck patch" on the central Calaveras fault, providing new support for their model of Calaveras fault earthquake activity. We suggest that Zone V fails only in a family of recurring *M* ~ 5.4–5.5 earthquakes. The 1955 and 2007 earthquakes are the penultimate and ultimate Zone V events. Earthquakes in 1891 and 1864 are possible earlier Zone V events. The next Zone V event is not expected in the next few decades, assuming a time-dependent recurrence model: the mean forecast date is 2064 (2035–2104, 95% confidence range). We further suggest that Zones I, II, III, and IV fail in recurring *M* ~ 5.1–5.3, *M* ~ 5.6–5.8, *M* ~ 6.1–6.3, and *M* ~ 4.9–5.0 earthquakes, respectively. If our earthquake recurrence model is correct, the next Zone I event is overdue and could occur anytime, and *M*5–6 earthquakes should not occur on Zones II, III, and IV before 2014, 2012, and 2026, respectively. We cannot rule out the possibility that Zone VI, which lies at the southern end of the Mission Seismic Trend, where the southern Hayward and central Calaveras faults appear to connect at depth, fails aseismically or in large events on the southern Hayward fault, such as last occurred in 1868, or in large events on the adjoining northern Calaveras fault segment.

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1. Introduction

[2] With the exception of the 1989 moment magnitude *M*6.9 Loma Prieta earthquake and its associated preshocks and aftershocks, many of the earthquakes widely felt in the south San Francisco Bay region in the past 100 years have occurred on the Calaveras fault [*Bakun*, 2008]. The felt earthquakes and the slip apparent along the Calaveras fault trace have attracted scientists and tourists alike. U. S. Geological Survey (USGS) fault trace maps [e.g., *Radbruch-Hall*, 1974] guide visitors to offset curbs, fences, cracks in pavement, and damaged homes that extend in a straight line through the streets of Hollister. It is not uncommon for tourists and scientists to meet on the trace of the Calaveras fault. The first questions posed to the scientists are usually, "Does this steady movement (fault creep) release the energy and prevent felt earthquakes?" and "When is the next big one?"

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[3] *Oppenheimer et al.* [1990] provided a model with which they attempted to answer these questions. They noted that the spatial pattern of microearthquakes occurring before the larger main shocks on the Calaveras fault was similar to the pattern of aftershocks and that the main shock hypocenters were at 8–9 km depth near the base of the zone of microearthquakes (Figures 1 and 2). They also noted that the areas of coseismic slip for the 1979 *M*5.7 Coyote Lake and 1984 *M*6.2 Morgan Hill earthquakes coincided with fault areas that were otherwise aseismic (Figure 2e). From these observations, they proposed a model: persistent aseismic fault areas near the base of the seismogenic zone represent "stuck" patches on the fault surface that slip only during moderate earthquakes. The surrounding matrix of fault slips frequently through creep and microearthquakes. *Oppenheimer et al.* [1990] identified six stuck patches, numbered I–VI from south to north, where past and future *M*5–6 main shocks occur (Figure 1). They proposed a post-1910 rupture history for each: Zone I, an M_L5.2 earthquake in 1949; Zone II, the *M*5.7 1979 Coyote Lake earthquake; Zone III, *M*6.2 earthquakes in 1911 and 1984; Zone IV, an M_L4.9 event in 1943 and an *M*5.0 event in 1988; Zone V, a M_L5.5 earthquake in 1955; Zone VI, no post-1910 *M*5–6 earth-

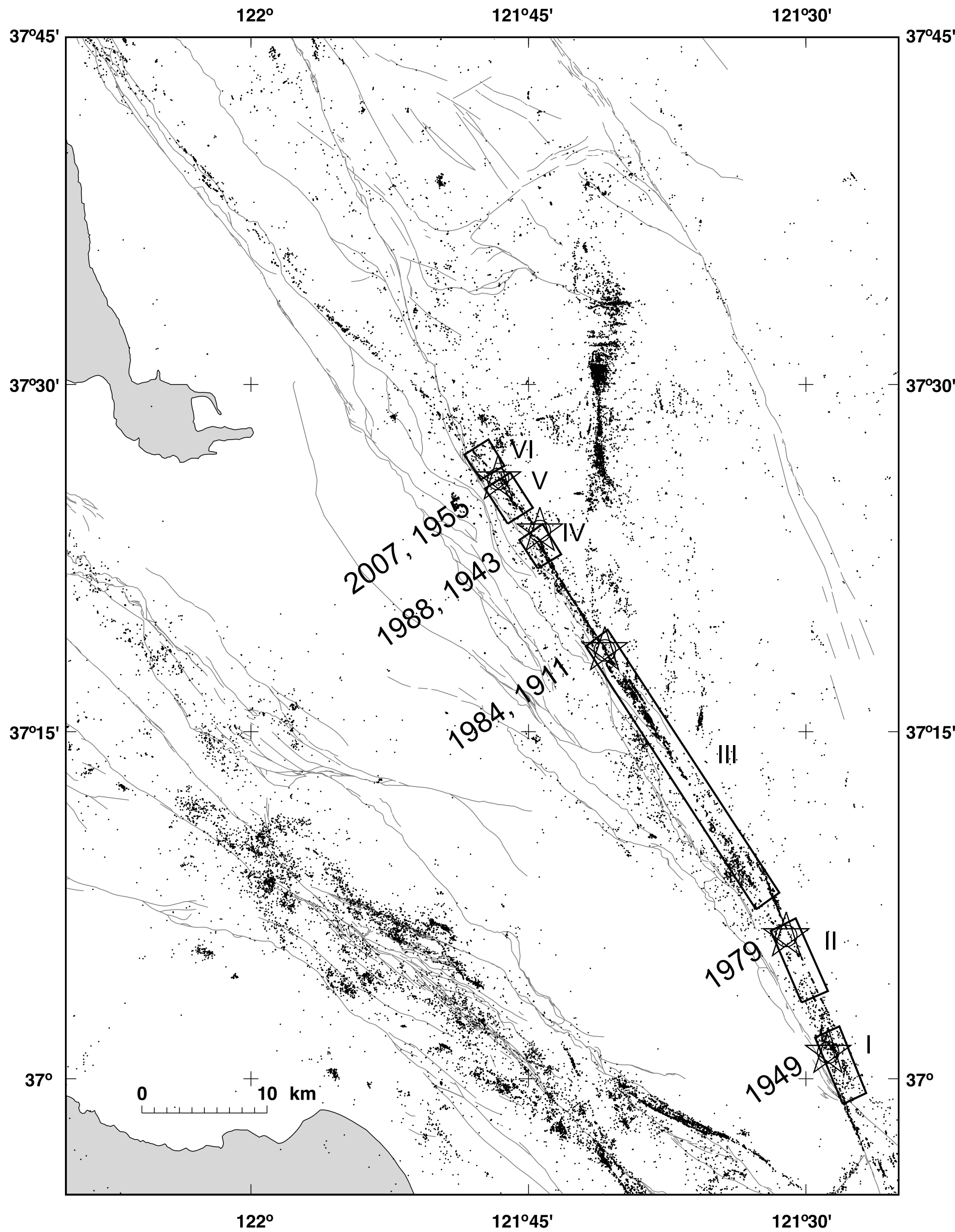

Figure 1. Seismicity in the south San Francisco Bay region, California, recorded by the USGS Northern California Seismic Network (NCSN) between 1984 and 2003 relocated using the double-difference technique [*Waldhauser Schaff*, 2008]. *Oppenheimer et al.*'s [1990, Figure 1] Zones I–VI along the Calaveras fault are shown. Epicenters of moderate earthquakes in Zones I–VI since 1910 are indicated by stars and dates.

quakes that might have occurred on this zone could be identified. They suggested that Zones I and VI were the most likely sites for the next $M > 5$ Calaveras fault earthquakes and that the potential for Zone V was low.

[4] On 31 October 2007 an *M*5.4 earthquake occurred on the Calaveras fault 8 km northeast of Alum Rock. The 2007 Alum Rock earthquake is the largest earthquake in the San Francisco Bay region since the 1989 Loma Prieta earthquake and the first significant earthquake on the Calaveras fault since *Oppenheimer et al.* [1990] proposed their model of Calaveras fault earthquake activity. (The *M*5.0 Calaveras fault event on 13 June 1988 located 5 km to the south in Zone IV has also been called the "Alum Rock" earthquake; we will hereafter refer to this and other Zone IV events as "1988-type Alum Rock" earthquakes.) The purpose of this report is to document the support that the 2007 Alum Rock earthquake provides for *Oppenheimer et al.*'s [1990] model, extend the rupture history for Zones I–VI to pre-1910 earthquakes, and quantify forecasts for future felt earthquakes on the Calaveras fault.

2. The 2007 Alum Rock Earthquake

[5] Although little damage resulted, the 31 October 2007 (030454 UTC) Alum Rock earthquake was recorded by

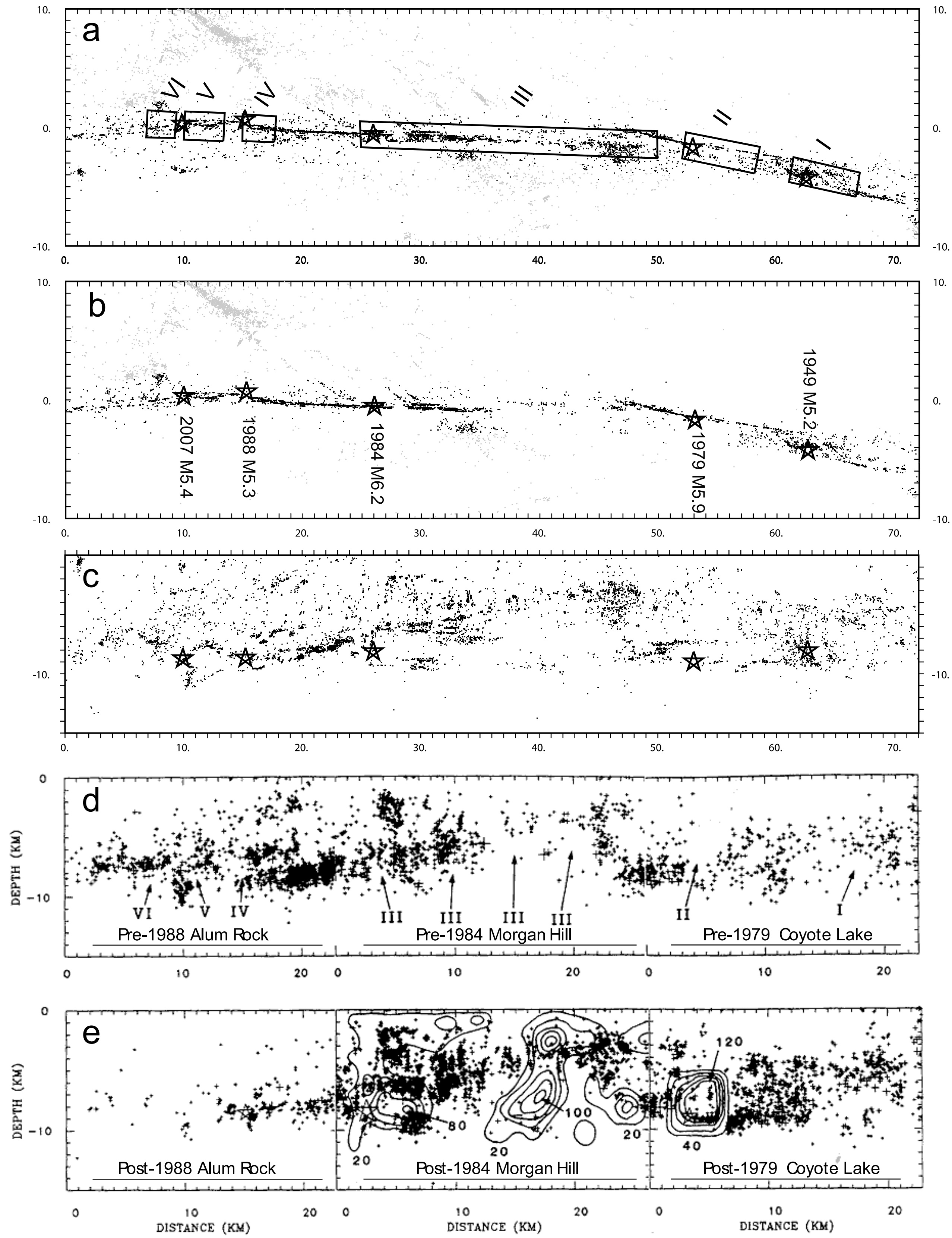
a
VI
V
IV
III
II
I
b
2007 M5.4
1988 M5.3
1984 M6.2
1979 M5.9
1949 M5.2
c
d
DEPTH (KM)
Pre-1988 Alum Rock
Pre-1984 Morgan Hill
Pre-1979 Coyote Lake
e
Post-1988 Alum Rock
Post-1984 Morgan Hill
Post-1979 Coyote Lake
DISTANCE (KM)

Figure 2

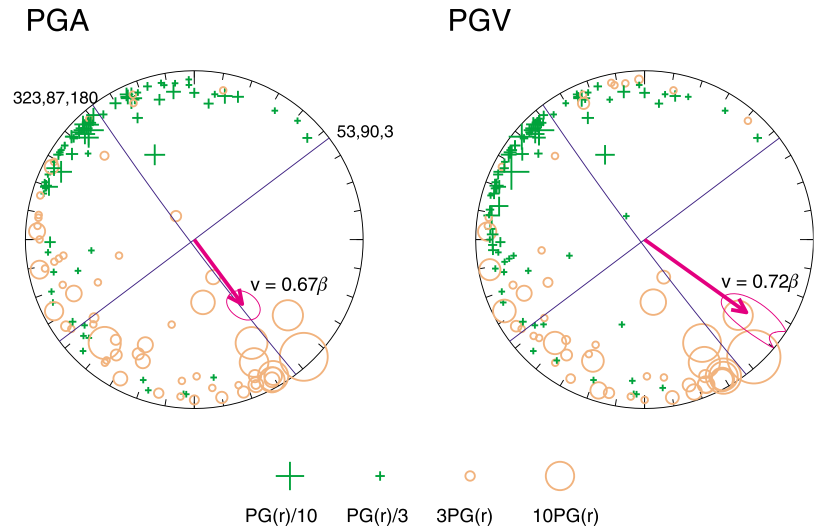

Figure 3. Symbols indicating the amplitude of the residual peak ground accelerations (PGA) and velocities (PGV) plotted on upper hemisphere stereonets at the azimuths and vertical takeoff angles of the *S* waves. Orange circles indicate amplified ground motions; green crosses indicate deamplified ground motions. The thick magenta lines show the rupture direction. Because we restrict the station distance to within 70 km of the earthquake, most takeoff angles are vertically upward. However, the takeoff angles to the more distant stations can be slightly downward. The lines with arrow heads represent upward rupture direction. The longer the line, the more horizontal the rupture direction. The thin magenta lines around the rupture directions enclose the 2σ uncertainty areas and extend into the lower hemisphere for PGV. The rupture velocity "v" is shown in terms of the shear velocity β. The blue lines show the nearly vertical nodal planes of the pure strike-slip moment tensor solution [*Hellweg et al.*, 2008]. The strike, dip, and rake are shown adjacent to each nodal plane. The PGA and PGV directivities are strong and clearly identify the NW-SE striking nodal plane (i.e., the Calaveras fault) as the fault plane. The PGA solution, with the slower rupture velocity, appears more appropriate, largely because it is more closely aligned with the nodal plane.

more than 200 digital accelerographs deployed since the Loma Prieta event. Both the first-motion focal mechanism (Northern California Earthquake Data Center) and the regional moment tensor solution (Figure 3) for the 2007 Alum Rock earthquake [*Hellweg et al.*, 2008] (Northern California Earthquake Data Center) indicate predominant right-lateral strike-slip motion on a northwest striking vertical fault consistent with rupture of the Calaveras fault. The earthquake nucleated slightly to the northwest of Zone V at a depth of 10.0 km when located using Hypoinverse [*Klein*, 2002] and the same velocity models used by *Oppenheimer et al.* [1990]. When located with a double-difference location method (Hardebeck, personnel communication, 2007), the hypocenter depth is 8.6 km (Figure 2c).

[6] To gain insight into whether the earthquake ruptured into or away from Zone V, we used the method of *Seekins and Boatwright* [2010] to estimate directivity by analyzing peak ground acceleration (PGA) and velocity (PGV) data within 70 km of the earthquake recorded on strong motion instrumentation operated by partners of the California Integrated Seismic Network (Figure 3). The PGA and PGV directivities are strong and clearly identify the NW-SE striking nodal plane (that is, the Calaveras fault) as the rupture plane. The PGA solution has a rupture velocity of 0.66β, where β is the shear velocity, with an updip component. The PGV solution has a rupture velocity of 0.82β with a downdip component. The PGA solution with the slower rupture velocity appears more appropriate, largely because it is more closely aligned with the nodal plane.

[7] The results of the directivity analysis and the *Wells and Coppersmith*'s [1994] relationship between *M* and subsurface rupture length indicate that the 2007 Alum Rock earthquake ruptured about 6 km to the southeast of its hypocenter. The 6 km long section of fault southeast of the hypocenter coincides with *Oppenheimer et al.*'s [1990] Zone V.

Figure 2. Map views and cross-section views of the Calaveras fault looking from southwest toward the northeast. (a) Map view showing double-difference [*Waldhauser Schaff*, 2008] relocated seismicity from 1984 to 2003 (Figure 1); events within 2 km of a generalized, simple 3-D Calaveras fault surface are highlighted in black (surface is not shown in the figure). (b) Map view showing double-difference seismicity below 5 km depth, with epicenters of most recent moderate earthquake in Zones I–V shown as stars. (c) Cross-section view of double-difference earthquakes within 2 km of a generalized Calaveras fault surface. (d) Composite of the three panels from Figures 4a, 4c, and 4e in *Oppenheimer et al.* [1990], showing NCSN seismicity for various time periods. (e) Composite of the three panels from Figures 4b, 4d, and 4f in *Oppenheimer et al.* [1990].

[8] *Oppenheimer et al.* [1990] concluded from S-P arrival time data at two seismic stations that if the 5 September 1955 M_L5.5 earthquake occurred on the Calaveras fault, it ruptured Zone V. If so, the 2007 *M*5.4 Alum Rock earthquake is a repeat of the 1955 earthquake. To confirm whether the 1955 and 2007 events both ruptured Zone V, we scanned Wood-Anderson seismograms of the 1955 earthquake recorded at University of California-Berkeley Seismological Laboratory seismic stations Mount Hamilton (MHC) and Berkeley (BRK). After deconvolving the instrument response of the 2007 event recordings at MHC and BRK and convolving in the Wood-Anderson response [*Bakun et al.*, 1978], the synthetic Wood-Anderson seismograms for the 2007 earthquake can be compared with the Wood-Anderson seismograms for the 1955 earthquake. The first 180 s of the 1955 seismogram are too faint for meaningful comparison with the synthetic seismograms of the 2007 earthquake (Figure 4). After 180 s, the 1955 and 2007 seismograms at MHC and BRK are nearly identical at frequencies greater than about 2 Hz. Assuming the "λ/4 Rule" of *Geller Mueller* [1980], the centroids of these two events lie within a few hundred meters of each other and confirm that the two magnitude 5.4–5.5 earthquakes ruptured Zone V.

[9] Although the waveform comparison clearly demonstrates that the 1955 and 2007 earthquakes ruptured the same section of the Calaveras fault, it is instructive to see if the relocation of the 1955 earthquake is close to the 2007 hypocenter. We obtained the 1955 earthquake phase data from the Northern California Earthquake Data Center and used Hypoinverse [*Klein*, 2002] to relocate the earthquake with the same velocity model as used to locate the earthquakes shown in Figures 1 and 2. The sparse distribution of five stations that recorded the earthquake (Figure 5) made it necessary to reject any distance or residual weighting of the phase data in determining the solution in order to ensure a sufficient number of phase arrivals to locate the event. Note that three of the five stations (FRE, PAC, and USF) ceased operation long before 2007, and therefore, no travel time corrections can be applied for these stations. The 1955 hypocenter has a focal depth of 8.7 km and locates 1.1 km from the 10 km deep non-double-difference solution of the 2007 Alum Rock main shock epicenter. The horizontal and vertical standard errors are 2.5 and 4.8 km, respectively, and enclose the estimated hypocenters of both the 1955 and 2007 earthquakes. The small location uncertainty obtained for the 1955 earthquake is surprising, given that the number and distribution of seismic stations is far poorer than that of the 2007 earthquake. Given the 1 km separation and velocities at hypocentral depths, the timing of the 1955 phase data seems accurate to about ±0.2 s.

3. Families of Recurring Earthquakes

[10] Families of recurring earthquakes have been identified on faults in diverse tectonic regimes [e.g., *Okada et al.*, 2003]. One of the best-studied families is the sequence of *M*5.5–6.5 Parkfield, California earthquakes that occurred on the San Andreas fault in 1881, 1901, 1922, 1934, 1966, and 2004 [*Bakun et al.*, 2005]. Although details are limited for the earlier events, available evidence suggests that all of these events occurred on the same section of fault. Additional early events in 1860, 1877, 1882, 1885, and 1908 in the Parkfield region and northward along the San Andreas fault [*Toppozada et al.*, 2002; *Toppozada Branum*, 2006] have been cited as casting doubt on the regularity of the Parkfield sequence proposed by *Bakun et al.* [2005].

[11] Smaller recurring microearthquakes also occur at Parkfield. Magnitudes for families of these smaller events rarely vary by more than 0.1 from the family average [*Nadeau Johnson*, 1998]. *Ellsworth* [1995] summarized studies of repetitive failure of the same fault surface patch in nearly identical earthquakes for moderate (magnitude, 4–5) and microearthquakes (magnitude, 1–2) in California and found that magnitudes range over about 0.5 *M* units. In this study, we assume that recurring earthquakes on the Calaveras fault share the characteristics of these families of recurring earthquakes reported elsewhere in California.

[12] *Bakun* [2008] provides quantitative estimates of intensity center locations and magnitudes for pre-1911 earthquakes in the region using the method of *Bakun Wentworth* [1997]. There is very limited intensity data for almost all of these pre-1911 events, and the earthquake locations are highly uncertain, as shown by *Bakun*'s [2008] confidence contours for location. We will show that the analysis of *Oppenheimer et al.* [1990] can be extended back in time for each of the five zones. Because of the large epicentral and magnitude uncertainty for many of the pre-1911 earthquakes, there are multiple scenarios for extending *Oppenheimer et al.*'s [1990] model back through the historical record, and there is no objective basis to select one preferred scenario (see Table 1). Except for Zone II, in the following discussion, we confine our potential scenarios to those historical earthquakes where *Bakun*'s [2008] standard error in location and magnitude encompasses the *M* and location of *Oppenheimer et al.*'s [1990] zones of repeating earthquakes.

[13] We note that, contrary to the *Oppenheimer et al.* [1990] model of repeating moderate size earthquakes, trenching studies at San Ysidro Creek in Zone I raise the possibility of three large, surface rupturing earthquakes between 2000 and 4000 years ago with right-lateral offsets of 2–2.5 m [*Kelson et al.*, 1998, 1999; *Kelson*, 2001]. If caused by a single event, offsets of this size would be consistent with *M* ~ 7 earthquakes [*Wells Coppersmith*, 1994]. It is not clear to us how to reconcile the idea of frequent (*T* ~ 50–100 years) moderate earthquakes on the Calaveras suggested by its recent activity, with occasional (*T* ~ 2000–3000 years) large earthquakes, although such large events might nucleate to the south and rupture northward into the parts of the Calaveras covered by Zones I–IV.

3.1. Zone V (Alum Rock)

[14] The 1955 and 2007 events define the family of *M* ~ 5.4–5.5 Zone V earthquakes. *Bakun* [2008] lists four possible pre-1955 Zone V earthquakes (Table 1): 26 February 1864, 5 March 1864, 21 May 1864, and 2 January 1891. For our purposes, the three 1864 earthquakes are indistinguishable as candidate *M* ~ 5.4–5.5 Alum Rock earthquakes. The 1955 and 2007 events occurred 52 years apart, and it is reasonable that the 1891 event, which occurred 64 years before the 1955 event, was the pen-penultimate Alum Rock earthquake. The 1864 events occurred 91 years before 1955 or about twice the time between the 1955 and 2007 events.

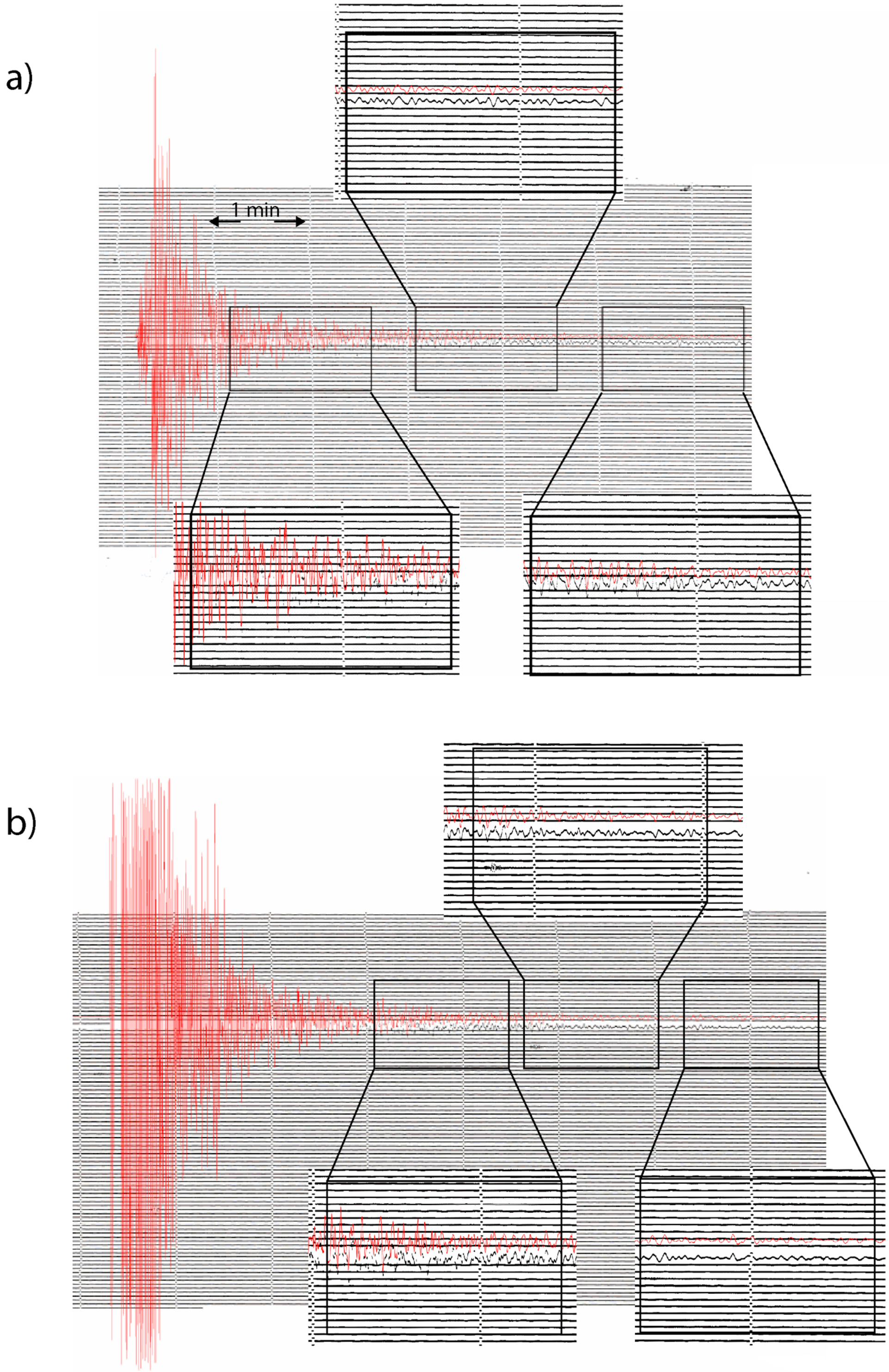

Figure 4. Comparison of the waveforms from the 2007 and 1955 Alum Rock events. Scanned images of helicorder recordings are in gray. (a) The 1955 UC Berkeley Wood Anderson seismographs for the EW channel at station BRK (Berkeley) at an epicentral distance of 65 km and (b) NS channel at MHC (Mount Hamilton) at an epicentral distance of 15 km. The red seismograms are synthetic Wood-Anderson records from the 2007 earthquake derived from the broadband channel for BRK and acceleration channel for MHC because its broadband sensor clipped. The 1955 record is too faint for comparison until the first enlarged frame on each seismogram. After that time, the two waveforms are essentially identical. The orthogonal channels for BRK and MHC recordings of the 1955 and 2007 earthquakes are also similar but are not shown.

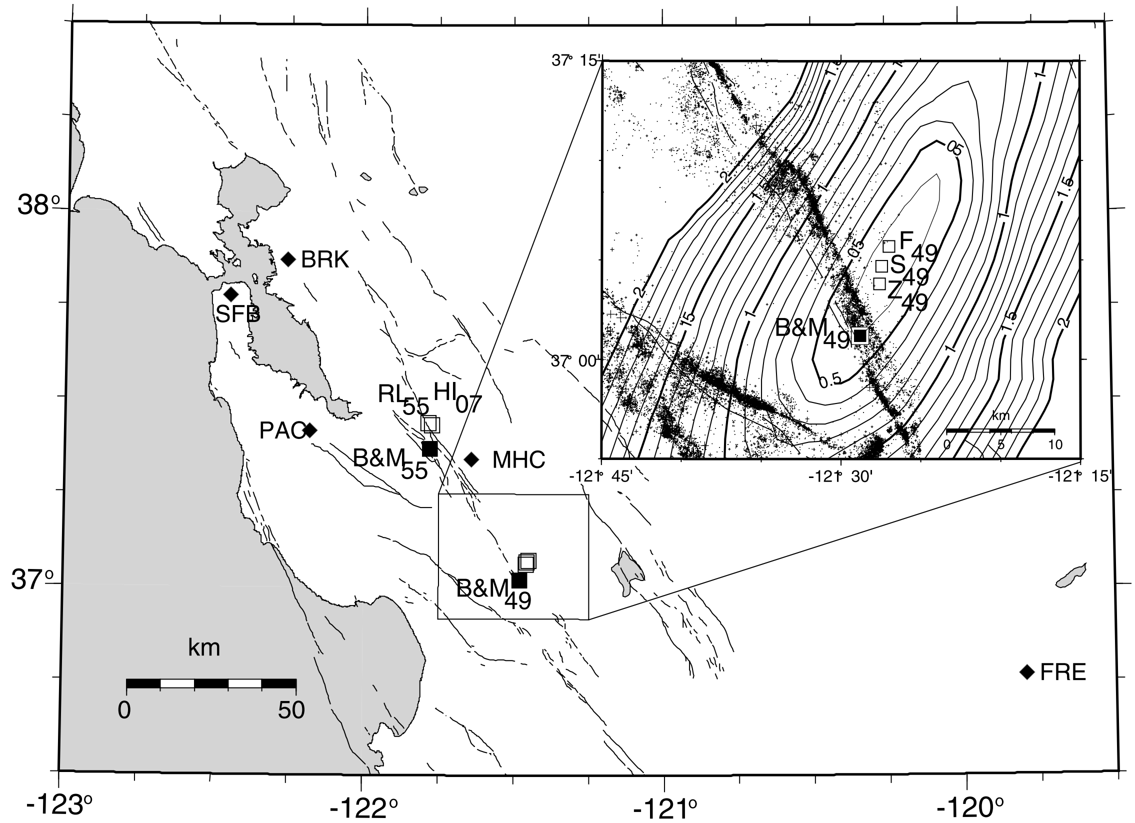

Figure 5. Map of stations (solid diamonds) that recorded the 9 March 1949 M_L5.2 and 5 September 1955 M_L5.5 earthquakes and epicenters (squares) of the 1949, 1955, and 31 October 2007 M_w 5.4 earthquakes ("49," "55," and "07," respectively). (See Appendix A for a discussion of the 1949 event.) *Bolt and Miller*'s [1975] locations are denoted with solid squares labeled B&M. RL_{55} and HI_{07} denote relocation and non-double-difference Hypoinverse [*Klein*, 2002] locations of the 1955 and 2007 earthquakes, respectively. Inset: epicenters (small dots) from 1969 to 2009 and RMS contours for solutions of the 1949 earthquake fixed on a 1 km grid at a depth of 8.5 km with S data. Z49, S49, and F49 denote the relocations of the 1949 earthquake with a fixed depth of 8.5 km, no depth constraint and no S readings, and no depth constraint, respectively.

It is reasonable then to assume that one of the 1864 events was the pen-pen-penultimate Zone V event.

3.2. Zone I (East of Gilroy)

[15] The 9 March 1949 M_L5.2 earthquake is the only instrumentally located $M > 5$ earthquake that plausibly locates in Zone I (Appendix A). *Bakun* [2008] lists only one possible *M*5.1–5.3 pre-1949 Zone I event: the 17 September 1888 earthquake. The earthquake catalog is, however, incomplete before 1905 for $M < 5.5$ earthquakes [*Bakun*, 1999], and several small earthquakes occurred in the period 1890–1910 near the southern and central Calaveras fault [*Townley Allen*, 1939]. Intensity data are not sufficient to locate these events, but M_I and a range of M can be estimated for assumed source locations. If on Zone I, the 1 sigma range in M for the earthquake on 15 January 1890 is 5.1–5.9, the earthquake on 11 December 1901 has a 1 sigma range in M of 5.2–5.8 for a location on Zone I. Thus, the 1888, 1890, and 1901 events are all viable penultimate Zone I earthquakes.

3.3. Zone II (Coyote Lake)

[16] Surface slip and aftershocks for the *M*5.7 1979 Coyote Lake earthquake were observed along the Calaveras fault from Coyote Lake to near San Felipe Lake where the Calaveras fault crosses California Highway 152 [*Reasenberg Ellsworth*, 1982]. *McClellan Hay* [1990] reported triggered right-lateral slip on the Calaveras fault at Highway 152 near San Felipe Lake at the time of the 1989 Loma Prieta earthquake. Fresh northwest striking cracks observed at Highway 152 after the 1984 Morgan Hill earthquake were interpreted as triggered slip [*Galehouse Brown*, 1987; *Harms et al.*, 1987]. The Calaveras fault near Highway 152 apparently is a zone of frequent triggered slip, and it would be surprising if the penultimate Zone II earthquake also did not trigger slip there. *Bakun* [2008] lists seven possible *M*5.7 pre-1979 Zone II events: earthquakes on 26 February 1864, 5 March 1864, 21 May 1864, 24 May 1865, 26 March 1866, 2 January 1891, and 6 July 1899.

[17] Fissures were reported on the Pacheco Pass road near San Felipe for the 20 June 1897 M_I6.3 earthquake [*Toppozada et al.*, 1981]. These fissures can be attributed to

Table 1. Calaveras Fault Earthquake Recurrence Scenarios[a]

Zone	Date	M	M 1σ (2σ) Range
I	17 September 1888	5.2	4.9–5.5
	15 January 1890[b]	5.5	5.1–5.9
	11 December 1901[b]	5.5	5.2–5.8
	9 March 1949	M_L5.2	5.1–5.3
II	26 February 1864	5.6	5.0–6.1
	5 March 1864	5.5	5.3–5.7
	21 May 1864	5.9	5.6–6.2
	24 May 1865	5.9	5.6–6.2
	26 March 1866	5.5	5.3–5.7
	2 January 1891	5.8	5.5–6.0
	20 June 1897	M_I6.3	6.0–6.4 (5.7–6.6)
	6 July 1899	5.8	5.6–6.0
	6 August 1979	5.7	5.6–5.8
III	26 November 1858	6.3	6.1–6.5
	24 May 1865	5.9	5.6–6.2
	20 June 1897	6.3	6.1–6.4
	11 June 1903	6.2	6.0–6.4
	3 August 1903	6.3	6.1–6.5
	1 July 1911	M_I6.2	6.0–6.3
	24 April 1984	6.2	6.1–6.3
IV	5 March 1864	5.3	5.1–5.5
	15 January 1890[b]	5.0	4.6–5.4
	11 December 1901[b]	5.0	4.7–5.3
	26 October 1943	M_L4.9	5.0–5.1
	13 June 1988	5.0	4.9–5.1
V	26 February 1864	5.6	5.4–5.8
	5 March 1864	5.3	5.1–5.5
	21 May 1864	5.6	5.3–5.9
	2 January 1891	M_I5.7	5.5–5.9
	5 September 1955	M_L5.5	5.4–5.6
	31 October 2007	5.4	5.3–5.5
VI	26 November 1858	6.1	5.9–6.3
	26 February 1864	5.6	5.4–5.8
	5 March 1864	5.3	5.1–5.5
	21 May 1864	5.5	5.2–5.8
	17 February 1870	5.9	6.1–6.3
	2 January 1891	5.6	5.4–5.8
	11 June 1903	6.0	5.8–6.2
	3 August 1903	6.1	5.9–6.3

[a]Except for the 1897 event scenario on Zone II, we consider only those pre-1911 events for which the zone location lies within *Bakun*'s [2008] 1σ uncertainty region and for which the M of the recent events on the zone are within *Bakun*'s [2008] 1σ uncertainty in M.

[b]*Townley Allen* [1939] list many $M < 5.5$ earthquakes near Mount Hamilton and San Jose. These data are sufficient to estimate M if a location is assumed.

triggered slip, and the intensity data for the 1897 earthquake are consistent with a location on Zone II [*Bakun*, 2008]. If the 1897 event occurred on Zone II, the 95% confidence range from Bakun's analysis is $5.7 \leq M \leq 6.6$. That is, if the constraint on M is relaxed from 1 sigma to 2 sigma, the 1897 earthquake is also a viable penultimate Zone II event, as suggested by *Oppenheimer et al.* [1990].

3.4. Zone III (Morgan Hill)

[18] The interevent time T between the M6.2 1911 and 1984 Morgan Hill Zone III earthquakes is 73 years. The 1911 event is somewhat anomalous in that it occurred soon after the great 1906 San Francisco earthquake, punctuating a long period of seismic quiescence in the San Francisco Bay region that followed this M7.8 event [*Harris Simpson*, 1998; *Doser et al.*, 2009]. *Bakun* [2008] lists five potential pre-1911 Zone III events: 26 November 1858, 24 May 1865, 20 June 1897, 11 June 1903, and 3 August 1903.

3.5. Zone IV (1988-Type Alum Rock)

[19] The similarity of seismograms led *Oppenheimer et al.* [1990] to conclude that the 1943 M_L4.9 and 1988 M5.0 earthquakes both occurred on Zone IV. *Bakun* [2008] lists only one possible $M \sim 4.9$–5.0 pre-1943 Zone IV event: the 5 March 1864 earthquake.

[20] As noted above, the earthquake catalog is incomplete before 1905 for $M < 5.5$ earthquakes, but several small earthquakes occurred in the period 1890–1910 near the southern and central Calaveras fault [*Townley Allen*, 1939]. Intensity data are not sufficient to locate these events, but we again estimate M_I and a range of M for assumed source locations. If on Zone IV, the 1 sigma range in M for an earthquake on 15 January 1890 is 4.6–5.4. If on Zone IV, the 1 sigma range in M for an earthquake on 11 December 1901 is 4.7–5.3. The 1890 and 1901 events are both viable pen-penultimate Zone IV earthquakes.

3.6. Zone VI (South of Calaveras Reservoir)

[21] The instrumental record suggests no candidate M5 Zone VI earthquakes since 1910. *Bakun* [2008] lists eight potential pre-1911 Zone VI events: 26 November 1858, 26 February 1864, 5 March 1864, 21 May 1864, 17 February 1870, 2 January 1891, 11 June 1903, and 3 August 1903. There is no particular reason to argue that any of them did occur there. That is, there is no evidence that any M5–6 earthquake has occurred on Zone VI since 1850.

[22] Zone VI is located in the vicinity of the intersection of the Central Calaveras, Northern Calaveras, and the southern part of the Hayward fault at depth. The trend of small earthquake epicenters that connect the southern Hayward fault and the central Calaveras fault at depth has been called the Mission Seismic Trend by *Manaker et al.* [2005]. Zone VI, as originally defined, could lie on the northern Calaveras fault, on the southern Hayward at depth, or in a zone of complex deformation surrounding the kinematically unstable joining of these three faults. The region to the north of the 2007 Alum Rock hypocenter and Zone V contains concentrations of distributed seismicity not easily attributed to individual structures (Figure 1), suggesting that the intersections of these three faults may be a complex zone of distributed deformation spanning a distance of 7–10 km along strike.

[23] Zone VI may be different from the Zones I–V to the south in that it may only undergo aseismic deformation. It is also possible that Zone VI fails seismically, but the loading rate is low and the repeat time is greater than about 100 years. Perhaps Zone VI fails in conjunction with large earthquakes on the northern Calaveras or Hayward faults. If Zone VI slips in association with large Hayward fault earthquakes such as the 1868 event, then the Zone VI "family of recurring earthquakes" would include events at the times of the eleven surface rupturing M6–7 events on the Hayward Fault reported from paleoseismic studies in Fremont [*Lienkaemper Williams*, 2007]. Alternatively, Zone VI might fail in conjunction with surface rupturing events on the Northern Calaveras fault, such as those recorded at Leyden Creek [*Kelson et al.*, 1993, 1996; *Simpson et al.*, 1999; *William Lettis & Associates, Inc.*, 2005]. If the ruptures of large events on either fault stop just north of Zone VI,

Zone VI might be a good candidate location for a significant aftershock.

[24] *Oppenheimer et al.* [1990, p. 8493] suggested that Zones I and VI were the most likely sites for the next $M > 5$ Calaveras fault earthquakes and that the potential for Zone V was low. This qualitative estimation was based on the lengths of time that had elapsed since the last event on the various zones and the larger magnitude of the more recent 1955 event on Zone V compared to the 1949 event on Zone I. Given the hypothesis that *M*5–6 earthquakes occurring on the Calaveras repeatedly rupture the same set of locked patches (in Zones I–VI) in nearly identical events and assuming that the occurrence of events on each zone follow a time-dependent distribution, we will attempt to derive a quantitative estimate of the potential for future events. Other hypotheses and assumptions are certainly possible, but given our present knowledge of the behavior of the Calaveras fault, these seem to offer a straightforward approach toward quantitative and testable forecasts such as those presented in section 4. (Appendix B considers the possible effects of nearby large earthquakes on other faults.)

4. Earthquake Forecast for Calaveras Fault Zones (I–V)

[25] Observation of families of recurring earthquakes on Calaveras fault segments implies that future events can be forecast. Further, if earthquake occurrence is quasiperiodic, then earthquake probability is time dependent. Time dependence emerges from the concept of elastic rebound, where time is required to recharge stresses released in the last large earthquake. Under a time-dependent process, the probability of an earthquake occurring is lowest just after the last large earthquake and then increases over the duration of the mean recurrence interval. This theoretical concept has been accepted as a component of earthquake forecasting in California [e.g., *Working Group on California Earthquake Probabilities* (*WGCEP*), 2003, 2008], and appears consistent with the paleoseismic record on the adjacent Hayward fault [*Parsons*, 2008a].

[26] While adopted for use in formal earthquake forecasts, the time-dependent model remains unproven and has been challenged on a number of fronts. For example, inferences from the south San Andreas paleoseismic record indicate temporal and spatial earthquake clustering [e.g., *Weldon et al.*, 2004, and references therein]. Renewal as an effective forecast model was questioned altogether by *Kagan Jackson* [1999], who noted a global tendency of large earthquakes occurring closely in space and time rather than periodically. An examination of the Parkfield segment of the San Andreas fault by *Murray Segall* [2002] indicated behavior inconsistent with time predictability because of the long gap since the previous earthquake in 1966. The eventual 2004 $M = 6.0$ earthquake was not consistent with slip predictability either, because the elapsed time since 1966 should have produced a larger ($M = 6.6$–6.9 [*Murray Segall*, 2002]) earthquake. A key purpose of this paper is to provide a testable time-dependent earthquake forecast of the Calaveras fault, which may enable us to assess the validity of the method.

[27] A time-dependent earthquake probability calculation sums a probability density function that distributes around some mean interevent time (μ), with the width of the distributions representing inherent variability (α) on recurrence. Optimally, we would have enough recorded earthquake intervals to unequivocally define the shape of recurrence distributions on faults. However, doing that requires at least ~25–50 intervals to gain the necessary resolution [e.g., *Matthews et al.*, 2002]. For zones along the Calaveras fault, we can only associate earthquakes with particular zones with any confidence during the period between 1911 and present, which restricts the number of intervals for most zones to no more than 3. If we are willing to specify general functional forms of recurrence distributions in advance, then it is possible to overcome the limited sampling problem with Monte Carlo techniques [*Parsons*, 2008b]. Here we use Brownian passage time (inverse Gaussian) distributions [*Kagan Knopoff*, 1987; *Matthews et al.*, 2002] to represent time dependence [after *WGCEP*, 2003, 2008] as

$$f(t,\mu,\alpha) = \sqrt{\frac{\mu}{2\pi\alpha^2 t^3}}\exp\left(-\frac{(t-\mu)^2}{2\mu\alpha^2 t}\right), \qquad (1)$$

where μ is recurrence interval, α is coefficient of variation, and t is time. The Brownian passage time distribution is nearly indistinguishable from the also commonly applied lognormal distribution for earthquake recurrence. Time independence is represented by exponential distributions (Poisson process) as

$$f(t) = \lambda e^{-\lambda t}, \quad \text{for } t > 0, \qquad (2)$$

where t is time and λ is the mean rate (1/mean recurrence).

[28] To find the most likely recurrence parameters, a series of distributions that covers all reasonable mean recurrence intervals is developed (1–500 years). Time-dependent distributions are characterized by two parameters (equation (1)) and are thus also constructed across coefficient of variation values between 0.01 and 0.99 for each mean recurrence interval. Time-independent distributions are described by just a rate parameter. Groups of earthquake dates are randomly drawn millions of times from each possible recurrence distribution and assembled into sequences. With this method, sequence means are identified directly from the parameters of parent distributions rather than from taking arithmetic means of sequences. This process overcomes the sampling bias problem of skewed distributions and is more effective than bootstrapping over the dating uncertainty intervals, which repeats and stacks means from insufficient samples [*Parsons*, 2008b].

[29] Every recurrence distribution is randomly sampled 5 million times for intervals between Calaveras fault earthquakes for Zones I–V. Those sequences that have one earthquake occurring in order during each observed event year and no earthquakes in the intervals between events are tallied, and a ranking of matches versus mean recurrence and coefficient of variation to the observed record is produced (Figure 6). Further, sequences are only tallied if no simulated event times occur in the open intervals between the first post-1911 event and the latest possible historic earthquake that could have happened on each segment from the analysis of *Bakun* [2008]. Similarly, sequences are only tallied if no simulated event times happened in the open intervals between the last observed earthquake year for each zone and the present.

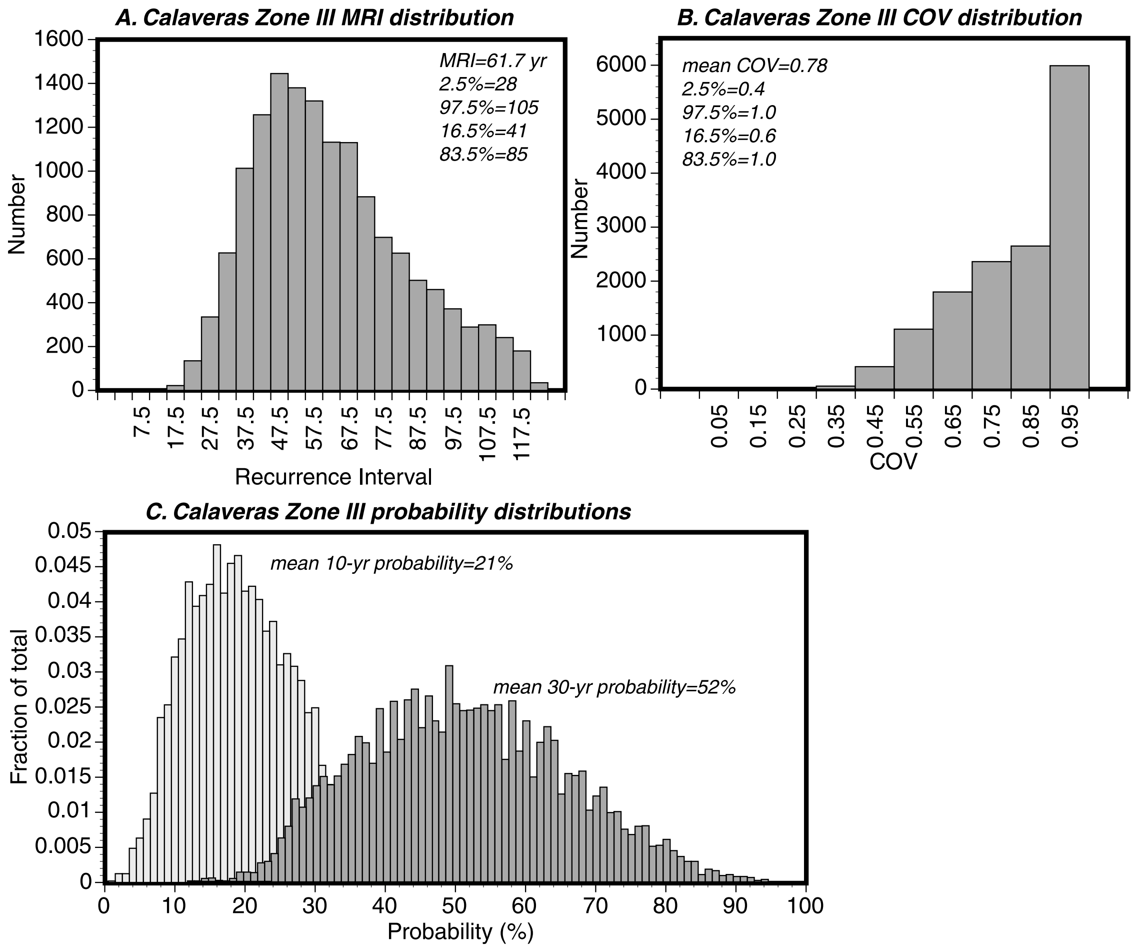

Figure 6. (a) Distribution of possible recurrence intervals for Calaveras fault Zone III assuming a Brownian passage time stress renewal process. By counting through the distribution, we can determine confidence intervals on recurrence. (b) The distribution of coefficients of variation (COV). For all Calaveras zones, we find high COV values, implying that the renewal process on the Calaveras fault is relatively aperiodic. (c) The distributions of 10-year and 30-year probabilities. From these distributions, mean values, and uncertainty estimates related to recurrence interval and COV parameter ranges can be expressed (Table 2).

[30] Monte Carlo analysis of Zones I–V along the Calaveras fault reveals broad arrays of allowable recurrence times for each zone (Figure 6). Mean recurrence times are quite similar across the zones and range from 57 to 73 years (Table 2). We find high coefficients of variation (0.8–0.9) for all zones. This suggests that if the renewal model we apply is correct, then recurrence along the Calaveras fault is relatively aperiodic. Calculated mean recurrence intervals using time-independent distributions tend to be longer (63–149 years; Table 2) because of the stronger skew between mode and mean for exponential distributions [*Parsons*, 2008b].

[31] We calculated 10-year and 30-year probability values for Calaveras fault Zones I–V using the distribution parameters from Table 2 and integrating equations (1) and (2), which generated distributions of possible answers (Figure 6c). The distributions allow us to determine the sensitivity of probability calculations to uncertainty in recurrence interval parameters. We report the mean values and confidence bounds taken from distributions in Table 3. In the time-dependent model, we also forecast most likely intervals within which Calaveras fault earthquakes are expected to occur, based on the times of the last earthquakes by zone and our analysis of recurrence intervals. We have thus made testable assumptions about the time-dependent process (Brownian passage time) and the existence of characteristic, recurring earthquakes on five Calaveras fault segments. Our calculations suggest that an event is expected in Zone I at any time (Table 3 and Figure 7). Further, if our time-dependent model is correct, then we should not expect to see $M \sim 5$ earthquakes occurring in Zone II before 2014, Zone III before 2012, Zone IV before 2026, nor Zone V before 2035. Conversely, if a $M \sim 5$ earthquake should strike in Zones II–V prior to those expected dates, then our model is invalid at 95% confidence.

5. Conclusions

[32] The 31 October 2007 *M*5.4 Alum Rock earthquake provides new support for *Oppenheimer et al.*'s [1990]

Table 2. Recurrence Interval Parameters for BPT and Exponential Distributions[a]

Time-dependent recurrence	Zone I (year)	Zone II (year)	Zone III (year)	Zone IV (year)	Zone V (year)
Mean	72	73	62	70	57
67% confidence	46–102	49–99	41–85	48–91	38–76
95% confidence	29−115	35−113	28−105	38−109	28−97
COV	Zone I	Zone II	Zone III	Zone IV	Zone V
Mean	0.9	0.8	0.8	0.9	0.9
Time-independent recurrence	Zone I (year)	Zone II (year)	Zone III (year)	Zone IV (year)	Zone V (year)
Mean	149	116	98	136	63
67% confidence	110–204	71–120	58–100	84–146	47–66
95% confidence	46–409	40–276	31–242	40–324	33–117

[a]Determined from Monte Carlo analysis of post-1911 earthquake occurrence on 5 Calaveras fault zone segments. Confidence bounds were calculated by counting through the distributions to determine ranges containing 67% and 95% of values.

model of earthquake activity on central and southern segments of the Calaveras fault. The epicenter is located on the Calaveras fault near the northwest end of *Oppenheimer et al.*'s [1990] Zone V. Peak ground acceleration and peak ground velocity data indicate strong directivity along the Calaveras fault toward the southeast. The typical subsurface rupture length for *M*5.4 strike-slip fault ruptures is about 6 km. Thus, we infer that the 2007 Alum Rock rupture extended about 6 km southeast of the epicenter along the Calaveras fault, coincident with *Oppenheimer et al.*'s [1990] Zone V.

[33] *Oppenheimer et al.* [1990] had concluded that if the 5 September 1955 M_L5.5 earthquake occurred on the Calaveras fault, it had ruptured Zone V. Waveforms of the 2007 *M*5.4 Alum Rock earthquake do, in fact, replicate the waveforms of the M_L5.5 1955 earthquake. We suggest that Zone V fails in *M* ~ 5.4–5.5 earthquakes and that the 2007 and 1955 earthquakes are the ultimate and penultimate events in a family of recurring Zone V earthquakes. No other *M*5 events occurred on Zone V in the post-1910 instrumental record. Analyses of macroseismic data suggest several possible earlier *M* ~ 5.4–5.5 Zone V events. The

Table 3. Earthquake Probability Values for Five Calaveras Fault Zones[a]

Time-Dependent Probability	Zone I (%)	Zone II (%)	Zone III (%)	Zone IV (%)	Zone V (%)
			2010–2020		
Mean	20	18	21	17	9
Median	17	16	19	16	6
67% confidence	12–26	5–23	12–29	10−23	1−16
95% confidence	10−36	3−29	8−36	7−28	1−25
			2010−2040		
Mean	49	44	52	45	42
Median	45	42	50	44	41
67% confidence	33−63	31−56	36−65	33−56	25−58
95% confidence	29−77	26−64	28−75	26−62	16−68
Forecast Dates	Zone I (year)	Zone II (year)	Zone III (year)	Zone IV (year)	Zone V (year)
Mean	2021	2052	2046	2058	2064
67% confidence	1995–2051	2028–2078	2025–2069	2036–2079	2045–2083
95% confidence	1978–2064	2014–2092	2012–2089	2026–2097	2035–2104
Time-Independent Probability	Zone I (%)	Zone II (%)	Zone III (%)	Zone IV (%)	Zone V (%)
			2010–2020		
Mean	7	8	10	7	15
67% confidence	5–9	8–13	10–16	7–11	14–19
95% confidence	2–20	4–22	4–28	3–22	8–26
			2010–2040		
Mean	18	23	26	20	38
67% confidence	14–24	22–35	26–40	19–30	37–47
95% confidence	7–48	10–53	12–62	9–53	23–60

[a]Time-dependent and time-independent probabilities calculated from distribution parameters given in Table 2. Values for 10-year and 30-year periods beginning in 2010 are given. Most likely dates for earthquake occurrence are also given based on the last earthquake times in each zone and recurrence values given in Table 2. Confidence bounds were calculated by counting through the distributions to determine ranges containing 67% and 95% of values.

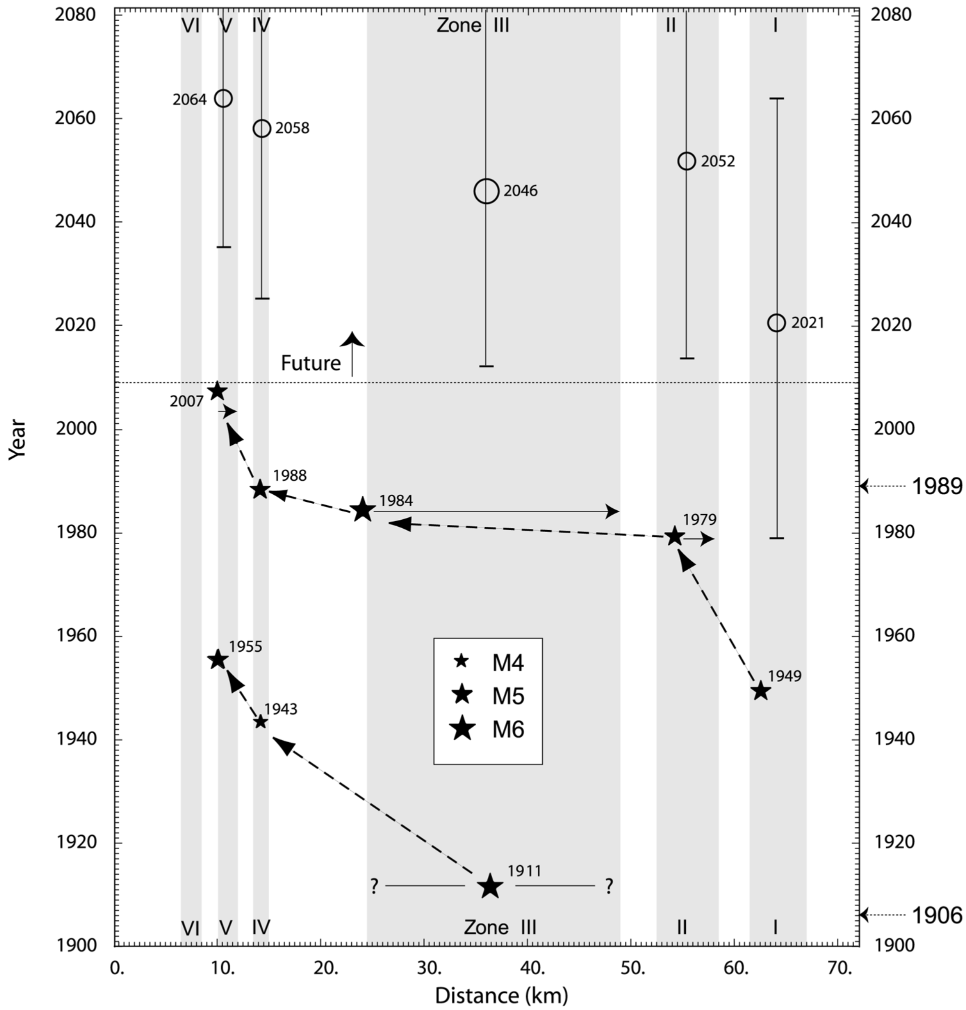

Figure 7. Calaveras fault earthquakes since 1900. Distance range corresponds to that shown in Figures 1 and 2. Instrumentally-recorded events are shown as black filled stars and forecast events as open circles with vertical lines indicating the 95% confidence interval in time (Table 3). Gray areas indicate the extent of *Oppenheimer et al.*'s [1990] Zones I–VI. Black arrows pointing to the right adjacent to some events indicate the directivity of the rupture where known. Diagonal arrows with dashed lines indicate an apparent progression of events from south to north [compare *Du Aydin*, 1993]. Events before about 1960 have uncertainties in location of 10 km or more, except for the 1943 and 1955 events where waveform comparisons with recent events allow for more precise locations.

2 January 1891 earthquake is a candidate pen-penultimate Zone V event, and there are three events in 1864 that might be a pen-pen-penultimate Zone V event. Using a time-dependent earthquake probability calculation for the instrumental (post-1910) record, the mean forecast date for the next $M \sim 5.4$–5.5 Zone V event is 2064, and the 95% confidence range is 2035–2104.

[34] We suggest further that Zones I–VI all fail in characteristic families of recurring earthquakes (Figure 7): Zone II in recurring $M \sim 5.6$–5.8 events, Zone III in recurring $M \sim 6.1$–6.3 events, and Zone IV in recurring $M \sim 4.9$–5.0 events. (Zones I and VI are not easily characterized and are summarized below.) *M*5 and larger earthquakes on the central and southern Calaveras fault segments occur only in these zones; other fault segments fail only in small events and in aseismic slip. If infrequent *M*7 events rupture the central and southern Calaveras fault segments, those hypothetical events originate elsewhere and rupture into the central and southern Calaveras fault segments.

[35] The mean forecast dates (95% time interval range) for Zones II, III, and IV are 2052 (2014–2092), 2046 (2012–2089), and 2058 (2026–2097), respectively. If *M*5–6 events occur in Zones II–V before the start of the 95% interval, then our model (families of recurring earthquakes on each zone and a Brownian passage time renewal process) is invalid at the 95% confidence level. If our model is correct, we should not expect *M*5–6 events on Zone II before 2014, on Zone III before 2012, on Zone IV before 2026, or on Zone V before 2035.

[36] The 9 March 1949 $M_L 5.2$ event is the only instrumentally located Zone I event [*Bolt Miller*, 1975], but our attempts to relocate this earthquake indicate that it may also have occurred off the Calaveras fault a few kilometers to the northwest (Appendix A). Although possible pre-1911 Zone I

events have been identified, No *M*5 Zone I events occurred in the 1911–1949 period. If on the Calaveras fault, our forecast calculation suggests that the next $M \sim 5.1–5.3$ Zone I event is overdue and could occur at any time.

[37] Zone VI poses special problems. No *M*5–6 event has occurred on Zone VI since 1910. Although any of several possible 1850–1911 events might have occurred on Zone VI, there is no reason to conclude that any did occur there. Zone VI lies within a trend of small earthquake epicenters, sometimes called the Mission Seismic Trend, where the southern Hayward fault and the central Calaveras fault apparently are connected at depth. We cannot rule out the possibility that Zone VI is fundamentally different. Perhaps it only fails aseismically or only in association with infrequent large northern Calaveras fault segment events. Perhaps Zone VI only fails in association with large events on the southern Hayward fault, such as last occurred in 1868.

Appendix A: The 1949 Earthquake (Zone I)?

[38] An M_L5.2 earthquake occurred on 9 March 1949 that *Bolt Miller* [1975] located on the Calaveras fault. The earthquake was recorded by only seven seismic stations in California and Nevada. No depth is reported by Bolt and Miller, as the location was determined with graphical methods in an era before the development of computers. To confirm whether the earthquake occurred on the Calaveras fault, we relocate it using Hypoinverse [*Klein*, 2002].

[39] The 1949 earthquake phase data (Northern California Earthquake Data Center) contains multiple and conflicting P arrival time readings for the same stations. Analysts at the seismographic stations of the University of California-Berkeley apparently picked P and S arrivals on different seismographs operating at a single site (e.g., Benioff and Wood Anderson seismographs at MHC) as well as on both horizontal channels of an instrument. To gain insight into the reliability of these conflicting observations, we first fixed the location of the 1949 earthquake at the location reported by *Bolt Miller* [1975] and assigned a focal depth of 8.5 km, typical of hypocentral depths of $M > 5$ earthquakes on the Calaveras fault (Figures 2c–2e). We then chose the P arrival time at each station that had the lowest travel time residual. We suspect the variability in reported P arrival times is evidence of poor clock accuracy on individual channels. In particular, the P residuals estimated at Mineral (MIN) range from 14 to 52 s, exceeding the travel time uncertainty expected for velocity model inaccuracy.

[40] Having established a set of preferred P and S phase data, we relocate the 1949 earthquake with the same approach used above for the 1955 earthquake (Figure 5). We computed a focal depth of 12.7 and 11.2 km with and without S readings, respectively. These off-fault epicenters are 6–8 km north northeast of *Bolt and Miller*'s [1975] location on the Calaveras fault ("S_{49}" and "F_{49}" in Figure 5). Since depths of well-located earthquakes along the Calaveras fault in this region do not exceed 10 km, we fixed the depth to 8.5 km, but the epicenter still locates off the fault ("Z_{49}" in Figure 5). To gain additional insight into the epicentral uncertainty, we computed the root mean square (RMS) of the uncertainty on a 1 km grid fixing the depth at 8.5 km and foregoing the use of any distance or residual weighting of phase data. Solutions within the 0.4 s RMS contour allow the location to be on the Calaveras fault (Figure 5), but it is not the minimum misfit solution. Similar location results were obtained by varying the Vp/Vs ratio and eliminating S phase data.

[41] Our analysis of the 1955 Alum Rock earthquake suggests that the clocks at all five stations were accurate to within a few tenths of seconds on 5 September 1955. In contrast, the inconsistent P arrival times for the 1949 earthquake and its large location uncertainties suggest that the clock accuracy on 9 March 1949 may be too poor to obtain a reliable location using P arrival times. Given that there is essentially no seismicity since 1969 east of the Calaveras fault within the 0.4 s RMS contour shown in Figure 5, we suspect that clock errors are causing the 1949 earthquake to mislocate to the east of the fault. It is not possible to demonstrate that the 1949 earthquake ruptured the aseismic patch of Zone I shown in Figures 1 and 2, but the data permit such an interpretation. We therefore assume that the 1949 earthquake did occur on the Calaveras fault near or a few kilometers north northwest of the Bolt and Miller location.

Appendix B: Possible Effects of the 1868, 1906, and 1989 Earthquakes on the Calaveras Fault

[42] In identifying potential families of repeating earthquakes and in forecasting future events, we have not considered the possible effect that large earthquakes in the region might have had in advancing or retarding occurrence times of Calaveras events. For example, the 1906 *M*7.8 earthquake had a profound effect on seismicity in the San Francisco Bay region [*Bakun*, 1999]. In the 70 years before 1906, there were 17 $M \geq 6$ events in the region, but in the following 103 years, there have been only five. This post–1906 seismic quiescence has been attributed to a stress shadow cast on San Francisco Bay region faults, which were relaxed by the coseismic stress changes from the 1906 event [e.g., *Jaumé Sykes*, 1996]. Modeling suggests that viscoelastic relaxation in the lower crust and mantle can, depending on geometry, further relax neighboring faults over a period of years and decades [*Kenner Segall*, 2000; *Parsons*, 2002; *Pollitz et al.*, 2004], although even with viscoelastic effects most models suggest that a stress shadow should have ended by now. We note that *Felzer Brodsky* [2005] raise questions about the validity of the stress shadow hypothesis.

[43] Large earthquakes have been observed to affect the loading rate and the timing of subsequent nearby repeating small earthquakes [*Ellsworth*, 1995]. We note that the time between the 1891 and 1955 Alum Rock events on Zone V, 64 years, is longer than the time between 1858 (or 1864) and 1891 events and longer than the 52 years between the 1955 and 2007 events. The intervals are consistent with the 1906 earthquake, delaying the 1955 Alum Rock earthquake by about a decade. If this suggested timing delay on Zone V due to 1906 is appropriate for Zone II, then the 1979 Coyote Lake earthquake would have occurred later than expected. That is, the 82 years between 1897 and 1979 may be longer than the average time between Zone II events.

[44] The 1911 event, one of the five $M > 6$ events in the Bay region since 1906, does pose a puzzle, falling only 5 years after 1906 on a segment of the Calaveras fault that

coseismically was significantly relaxed [*Simpson*, 2003; *Pollitz et al.*, 2004]. Several explanations that have been offered for this paradox are summarized by *Doser et al.* [2009], including dynamic triggering and rate-and-state nonlinear failure behavior. Although there is good agreement on the estimated effect of the 1906 coseismic relaxation at the site of the 1911 earthquake, there is considerable question as to the rate of the loading that is restressing the fault to pre-1906 levels. Elastic models that do not take account of the large amount of aseismic slip on the Calaveras fault yield recovery times ranging from several years to several decades, depending on model assumptions and location along the fault [*Simpson*, 2003]. Viscoelastic models that do not account for aseismic slip tend to yield recovery times ranging from decades to a century [*Parsons*, 2002; *Pollitz et al.*, 2004]. *Hori Kaneda* [2001] offer a simple model that incorporates aseismic slip on the Calaveras fault and use it to amplify the tectonic loading rate on the stuck patches, so that stress could recover to pre-1906 levels within several years, in time for the 1911 hypocenter to be out of the stress shadow. However, *Doser et al.* [2009] suggest that creep rates at Hollister after 1906 were retarded until 1923, although Hollister is about 50 km southeast of Zone III where the 1911 event occurred.

[45] The moment of the 1989 *M*6.9 Loma Prieta earthquake was ~30 times smaller than that of the 1906 event and presumably would have had a smaller effect on the Calaveras fault. There were, however, notable changes in regional seismicity and creep rates on the Calaveras fault after the 1989 earthquake [*Reasenberg*, 1997], but most did not persist for more than a few years. Quantitative estimates of the recovery time on the Calaveras fault after 1989 using simple elastic models range from 2 to 4 years [*Simpson*, 2003].

[46] The 1868 *M*6.8–7.0 Hayward fault earthquake could also have had an effect on subsequent Calaveras fault seismicity, especially on Zone VI. If the 1868 rupture on the southern Hayward fault extended southward along the Mission Seismic trend, it might have included Zone VI or perhaps triggered aftershocks on Zone VI. However, the location and extent of the 1868 rupture are uncertain, making estimation of its effects on the Calaveras fault Zones even more uncertain.

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