Bulletin of the Seismological Society of America, Vol. 68, No. 6, pp. 1731–1749, December 1978

CENTRAL CALIFORNIA FORESHOCKS OF THE GREAT 1857 EARTHQUAKE

By Kerry E. Sieh

ABSTRACT

Analysis of contemporary accounts indicates that several small to moderate central California earthquakes preceded the great 1857 earthquake by 1 to 9 hr. The earliest events apparently were felt only in the San Francisco area or the Sacramento and Sierran Foothills region. Two later and much more widely felt foreshocks were experienced within the region bounded by San Francisco, Visalia, Fort Tejon, and Santa Barbara. A comparison with felt areas and intensity distributions of modern events of known source and magnitude indicates that these later two shocks were $5 \leqq M \leqslant 6$ and probably originated at some point within an area of radius $\approx$60 km that includes the southeastern 100 km of the historically creeping segment of the San Andreas fault. The northwestern terminus of the 1857 rupture is probably located along this segment.

If the location of these foreshocks is indicative of the epicenter of the main event, then the several-hundred-kilometer main-event rupture propagated principally in a unilateral fashion toward the southeast. This implies that, like many great earthquakes, the 1857 rupture originated on a fault segment historically characterized by moderate activity and propagated into an historically quiet segment.

There is a strong possibility that the foreshock activity represents a moderate Parkfield-Cholame sequence similar to those of 1901, 1922, 1934, and 1966. To the extent that such premonitory activity is characteristic of the failure of the 1857 segment of the fault, studies of the creeping segment of the fault may be relevant to the prediction of large earthquakes in central and southern California.

Introduction

One intriguing aspect of many contemporary accounts of the great California earthquake of January 9, 1857 is the mention of shocks felt during the several hours prior to the main earthquake. If indeed these were foreshocks, their location might indicate the epicentral region of the main shock (Kelleher and Savino, 1975; Dewey, 1976). Knowledge of the approximate epicenter of the main shock would enable calculation of more realistic models of strong ground motion for the earthquake and for similar future events (R. Butler and H. Kanamori, personal communication). Predicted long-period motions in Los Angeles, for example, are more severe if the 1857 rupture is modeled to begin near its northwestern terminus and propagate southeastward toward the city than if it is modeled to begin east of Los Angeles near San Bernardino and propagate to the northwest.

Documentation of foreshocks to the main 1857 event is also important in the context of earthquake prediction, especially if such precursory activity commonly precedes 1857-like events.

In this paper the evidence for precursory events is critically analyzed and interpreted. The data base is drawn from many contemporary accounts, all of which are published on microfiche in Agnew and Sieh (this volume). In this paper I refer to these accounts by number, as listed in their Table 1.

Timekeeping in California in 1857

The seismic activity of the night and early morning prior to the main shock (~8:24 a.m.) is restricted to west-central California by the distribution of earthquake reports.

Figure 1 and Table 1 summarize the times and places the shocks were felt. Determining to what degree the variation in reported times of this activity is due to inaccurate and imprecise timekeeping is critical to the interpretation of the activity. It will be shown that if substantial inaccuracies and imprecision are assumed, moderately large early-morning shocks can be postulated. If, on the other hand, the reported times are strictly accepted, one can only conclude that most of central California began to pop with a series of small local events prior to the main shock.

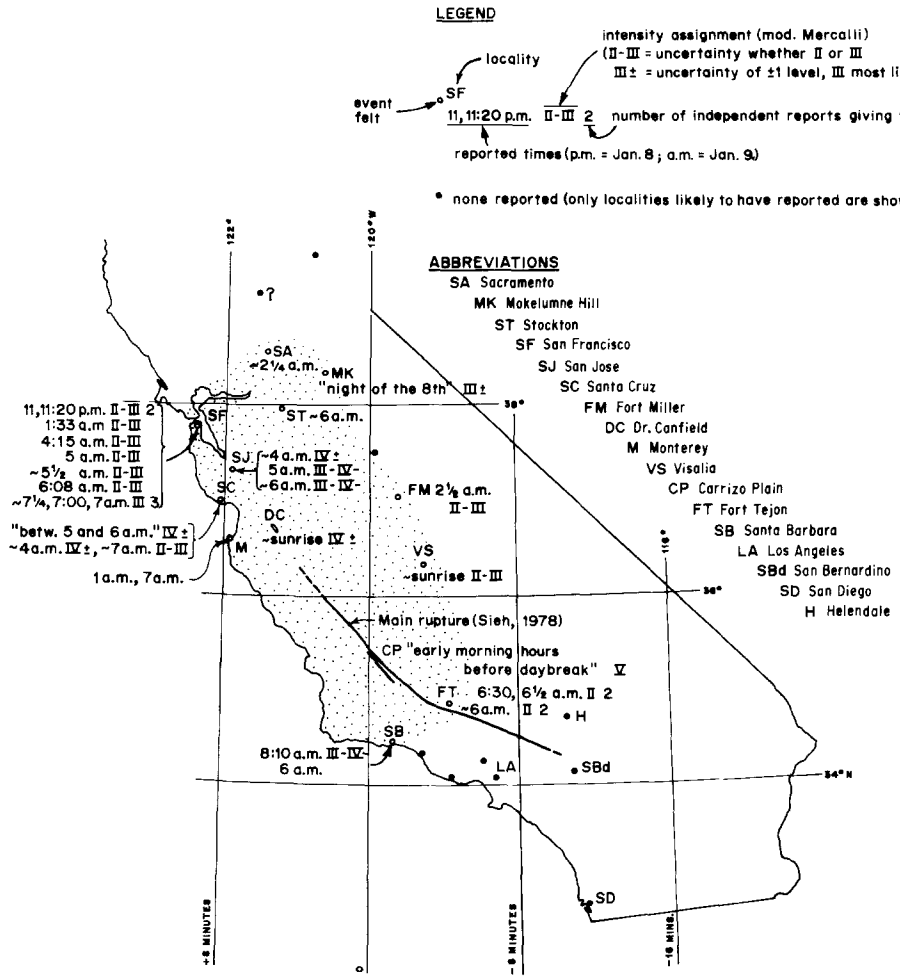

FIG. 1. Reports of shocks felt during the hours prior to the great earthquake of 9 January 1857 (08:24 PST) come from many localities within central California (*stippled region*). The great variety of times reported certainly indicates the occurrence of several shocks, but is due in part to poor timekeeping and to the use of local, rather than standard, time in 1857. The difference between local time and Pacific Standard Time is shown as a function of longitude.

The analysis that follows demonstrates that substantial imprecision and, in some cases, inaccuracy in the reports must be taken into account in interpreting the data.

Precision of individuals' accounts. In several cases, it is clear that the witness or reporter of an earthquake was not concerned with precise reporting of the time the event was experienced. For example, Mr. Canaday, an expressman from Ft. Tejon, reportedly told the Stockton *Daily Argus* (57) that a light shock was felt at Ft. Tejon at "about 6" a.m., whereas he reportedly told the Stockton *San Joaquin*

Republican (61) that a very slight shock was felt "at 6½" a.m. at Ft. Tejon. From the context of the two articles, it is relatively certain that the two references are to the same event. Clearly then this fellow's reports cannot be given more precision than about ±1/2 hr. C. H. Randall, editor of the Santa Barbara *Gazette* (Dawson, 1950, p. 157), reports a main-shock time of "half past 8" (20). In the same article he alternatively gives 8:22 a.m. as the main-shock time, "according to those who assert they had the 'correct' time." His sarcasm in reporting the 8:22 a.m. time suggests there was some disagreement among Santa Barbarians as to the "correct" time of the shock. The later, more precise (but not necessarily more accurate) time, 8:22 a.m., may represent his best judgment at a later date [see (39)].

Local time. A factor that must be considered in comparing reported times *between* separate localities is that all observers were using "local" time in 1857, as "standard" time was not adopted until the 1880's. Between San Francisco (at 122.43°W) and San Diego (at 117.10°W), for example, the difference in local time at any one instant is about 22 min (4 min per degree of longitude). Figure 1 shows the corrections that must be applied to the reporting locations to convert local times to Pacific Standard Time (PST), which is actually local time along the 120th meridian. Figure 2 illustrates the reported times corrected to PST (large dots). The error bars shown are determined farther along in the paper. PST times reported for the main shock [Table 2; Figure 2 (triangles)] are much closer to agreement than the uncorrected local times but still differ by as much as an hour. San Francisco times are probably the most reliable, that city being the major center of activity in the State in 1857, and having chronometers. The best time for the earthquake in San Francisco is 8:24 PST (54). Uncertainties in (1) the distance from the epicenter and (2) the point in time during the shaking at which the observer read the clock, limit the level of meaningful disparity between reporting localities to about ±5 min. Fifty per cent of the reported times differ no more than about 5 min from the 8:24 felt time and can thus be regarded as precise and accurate records (Table 2). Within San Francisco itself, however, three reports (37, 44, and 45) are significantly in error. It is important to note that these are accounts for which the wording indicates lesser precision (i.e., "about 8 o'clock", "a few minutes after eight", etc.). Generally speaking, it is these reports with rounded-off felt times that have the greatest discrepancy, many being ±10 to 30 min and a few being 1/2 hr to 2 hr in error.

Aftershock timing precision and accuracy. A final effort to assess the precision of felt times is based on the reported times for two large aftershocks—one on the evening of January 9, the other in the late afternoon of January 16. The reported times for these events are listed in Table 3. The shock of January 16 appears to be a single event, as all reporting localities indicate only one shock or two closely timed shocks. That only one moderately large earthquake is responsible for the reports is also suggested by the high intensities reported at widely separated localities (Santa Barbara, V±; Los Angeles, V to VI; San Bernardino, V±). Preliminary study of modern isoseismal maps for $M \geqq 5.0$ earthquakes (U.S. Earthquakes, 1928–1974) suggests that a $M \approx 6$ aftershock originating on the San Andreas fault southeast of Tejon Pass but northwest of Cajon Pass could have produced the reported intensities. However, a source south of the fault, perhaps in the Los Angeles Basin, cannot be ruled out.

For the present purposes, the important observation is that the reported times (PST, Table 3) are spread over about 1 hr. Thus, it seems reasonable to attribute the spread in reported times for the precursory events of January 9 at least in part to imprecise reporting.

TABLE 1

REPORTED MAIN-SHOCK AND FORESHOCK TIMES

Location Felt (and source)*	Reported Main-shock Time †, ‡	Reported Foreshock Time(s)
San Diego		
(2)	$08\frac{1}{2}^h$	
(3)	08:50	
(4)	08:31	
San Bernardino		
(5)	$\sim 08^h$	
(6)	08:25	
(14)	~08:08	
Los Angeles		
(8, 9)	08^h	
(11)	$\sim 08\frac{1}{2}^h$	
(14)	08:25	
(41)	$\sim 08\frac{1}{2}^h$	
Near Helendale		
(14)	Between $\sim 08^h$ and 09^h	
San Fernando		
(18)	08^h, 08:25	
Sycamore Cyn.		
(19)	08:24	
Santa Barbara		
(20)	$\sim 08\frac{1}{2}^h$	
(38)	09^h	06^h
(20, 39)	08:22	08:10
(48)	$08\frac{1h}{4}$	
Fort Tejon		
(14, 23)	08:33	~06:30, beginning at $\sim 06^h$
(57, 61)	$\sim 08\frac{1}{2}^h$	$\sim 06^h$, $06\frac{1}{2}^h$
Carrizo Plain		
(73)	Before daybreak	
Visalia		
(58)	08:15	~Sunrise
Fort Miller (29)		
15 to 20 miles NW of San Benito	08^h	$02\frac{1}{2}^h$
(30)	$\sim 08^h$	~Sunrise
Monterey		
(41)	$\sim 07^h$	
Santa Cruz and Monterey area		
(32, 33)	07^h	01^h, 08^h
Santa Cruz		
(31)	$\sim 08^h$	Between 05^h and 06^h
(75)	$\sim 07\frac{1}{2}^h$	$\sim 04^h$, "a few minutes before" 07^h
San Jose		
(35)	~08:05	05^h, $\sim 06^h$
(36)	$\sim 08\frac{1}{2}^h$	$\sim 04^h$
San Francisco		
(37)	A few min. after 08^h	
(40)	$08\frac{1h}{4}$	"Several shocks ... were felt ... last night and this morning"
(44)	$\sim 08^h$	

* Numbers in parentheses refer to sources in Table 1 of Agnew and Sieh (1717–1730, this volume).

† "~" means "about".

‡ $08\frac{1}{2}^h$ indicates a less precise account than does 08:30.

TABLE 1—*Continued*

Location Felt (and source)*	Reported Main-shock Time †, ‡	Reported Foreshock Time(s)
(45)	08^h	$\sim 05\frac{1}{2}^h$
(46)	08:15	
(47)	08:15	05^h
(49)	08:14	23:20 (8th), 01:33, 04:15, 06:08, 07:00
(52)	08:20	23^h (8th), 07^h
(53)	$\sim 08\frac{1h}{4}$	$\sim 07\frac{1h}{4}$
(54, 55)	08:13:30	
(72)	"A little before" 08^h	
Stockton		
(56)	$\sim 08^h$	
(59)	~08:20	$\sim 06^h$
Mokelumne Hill		
(50)		The night of the 8th and 9th
Sacramento		
(36, 37)	Between 07^h and 08^h	
(39)	08:15	02:15
Sacramento		
(49)	$08:19\frac{1}{2}$	
(62)	~08:20	
(64)	08:10	
(65)	$10\frac{1h}{4}$	$\sim 02\frac{1h}{4}$
(66)	$\sim 08^h$	
(70)	08:05	

The spread in reported times for shocks of the evening of January 9 (Table 3) also support this point of view. Many localities reported one to four evening shocks. Preliminary comparison with the isoseismal maps of instrumentally recorded events (U.S. Earthquakes, 1928–1974) suggests a $M \geq 6$ for the latest event. The reported times for this event range from just before 2200 to just before 2300 p.m. (PST). The rounded-off times are clearly more disparate (by $\frac{1}{2}$ hr) than the precisely reported times (10 min).

Reports of seismic activity prior to the main shock can now be analyzed, with the knowledge that a 1-hr disparity between reported times for the same event is not at all unlikely, especially if the reporter rounded his time to the nearest hour or half-hour. Because the earthquakes discussed below occurred before or about at sunrise, even greater inaccuracy might be suspected in the reports of the groggy, awakened observers. Hence, a $1\frac{1}{2}$-hr disparity for rounded-value reports might be expected.

In the Appendix each reported foreshock time is analyzed and assigned a probable error. These times, with their assigned probable errors, are summarized in Figure 2.

Limitations on the Source of the Early-Morning Events

Reports are most abundant and widespread for the three shocks felt about one, two, and four hours prior to the main shock (Figure 2). I refer to these as the "pre-dawn", "dawn", and "sunrise" shocks. Comparison of the felt areas and intensities of these shocks with those of modern events of known source and size enables limits to be placed upon their size and source region. The pre-dawn shock apparently jostled folks in San Francisco (II to III), San Jose (IV±), Santa Cruz (IV±), and perhaps in the Carrizo Plain (≥V). As nearly as can be determined, the dawn shock

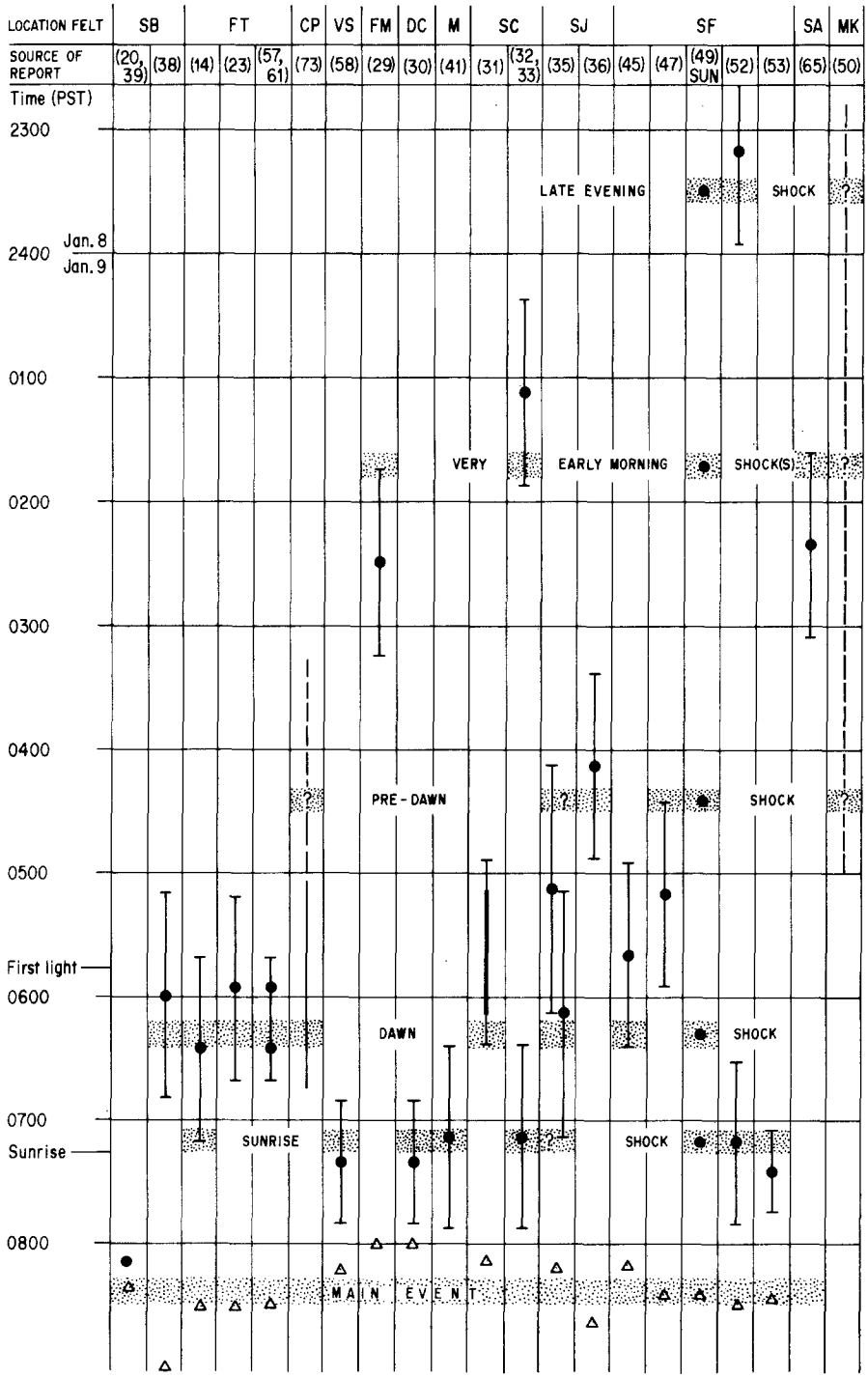

FIG. 2. Reported times of shocks felt at various localities corrected to Pacific Standard Time (PST). Error bars are based upon a qualitative analysis of the precision of each account. At least five shocks seem to have occurred within 9 hr of the main shock. Abbreviations of localities are as in Figure 1 and numbers in parentheses refer to listing of accounts in Table 1 of Agnew and Sieh (1719, this volume).

was felt in San Francisco (II to III), Santa Cruz (IV±), San Jose (III to IV−), Santa Barbara (?), Fort Tejon (II), and possibly in the Carrizo Plain (≥V) (Figure 3). The sunrise shock was felt at San Francisco (III), Monterey (IV±), Dr. Canfield's (IV±), Visalia (II to III), and perhaps at Fort Tejon (II) and San Jose (III to IV−) (Figure 3). None of the events is reported from Los Angeles, San Bernardino, Stockton, or Sacramento.

Within the past half-century, only three earthquakes have produced felt reports similar in distribution and intensity to the dawn and sunrise foreshocks (U.S. Earthquakes, 1928–1974). Gross comparisons of the dawn and sunrise earthquakes with these more recent events of known size and source suggest that both events originated in central coastal California, somewhere between Pt. Conception and Monterey, perhaps as far inland as the westernmost San Joaquin Valley or perhaps offshore. With the past half-century, no central California earthquakes of $M < 5.0$ have had a felt area as large as either 1857 foreshock. Shocks of $M \geq 6$ have had somewhat larger felt areas. Thus, the two shocks probably were moderate events ($5.0 \leqq M \leqslant 6.0$).

If the events originated on the San Andreas fault. If the dawn earthquake originated on the San Andreas fault, its source can be limited to within a 95-km reach between about 35.7°N and 36.4°N, that is, within the central and southern parts of the currently creeping reach of the fault. Three observations eliminate the possibility that the dawn shock occurred on the San Andreas system near or northwest of Hollister (36.9°N). In the first place, intensities of the dawn shock at San Francisco (II to III) and San Jose (III to IV−) are much lighter than result from moderate events in the Hollister region, east of Monterey Bay (e.g., 8 April 1961, $M = 5.6$; 24 June 1939, $M = 5.5$; 9 March 1949, $M = 5.2$; 25 April 1954, $M = 5.3$; 2 March 1959, $M = 5.3$; 15 November 1964, $M = 5.0$; 18 December 1967, $M = 5.3$). Second, the southern felt limit of events originating in the Hollister or Monterey Bay area is always at least 130 km northwest of Santa Barbara or Fort Tejon, and intensities probably capable of stampeding cattle (≥V?) have not been produced in the Carrizo Plain by moderate events in the Hollister or Monterey Bay area.

Finally, an intensity ≧VI 15 to 25 km southeast of Hollister would almost certainly have awakened and been reported by Dr. Canfield. As $M \geqq 5\frac{1}{2}$ events in this region generally produce Modified Mercalli Intensities (MMI) ≧ VI up to 40 to 60 km from the source (7 June 1934, $M = 6$; 8 April 1961, $M = 5.6$; 27 June 1966, $M = 5.5$), the source of the dawn shock, if produced by slip on the San Andreas fault, can be reasonably placed at least 40 km southeast of Dr. Canfield (about at Bitterwater Valley Oilfield, 36.4°N).

Earthquake sequences originating along the Parkfield-Cholame reach of the fault in 1901 ($M \approx 6$), 1922 ($M \approx 6\frac{1}{4}$), 1934 ($M \approx 5{,}6$), 1966 ($M \approx 5\frac{1}{2}$) help define a southeastern limit for the source of the dawn event. Maps displayed in Figure 4 indicate the intensities reported for each of these events. The distribution and values of felt intensities for each of these shocks is remarkably similar to those for the 1857 dawn event. Unlike the dawn shock, however, all but one of the Parkfield-Cholame events were felt in parts of the Los Angeles area. All but the 1922 event were felt with intensity similar to the dawn event to the northwest of the source, i.e., San Francisco, San Jose, Santa Cruz, etc. Thus one cannot postulate a dawn Parkfield-Cholame shock smaller than the four 20th-century events in order to have it not felt in Los Angeles because a smaller event would probably not have been felt in San Francisco or San Jose.

Because three of the four known Parkfield-Cholame events were felt somewhat

TABLE 2

INACCURACY OF REPORTED MAIN-SHOCK TIMES

Location (and source)	Felt Time (PST)	Deviation from 8:24 (PST) to Nearest 5 Min
San Diego		
(2)	$08\frac{1}{2}^{h} - 12^{m}$*	−5
San Diego		
(3)	08:38	+15
San Diego		
(4)	08:19	−5
San Bernardino		
(5)	$08^{h} - 11^{m}$	−35
San Bernardino		
(6)	08:14	−10
San Bernardino		
(14)	07:57	−25
Los Angeles		
(8, 9)	$08^{h} - 7^{m}$	−30
Los Angeles		
(11)	$08\frac{1}{2}^{h} - 7^{m}$	0
Los Angeles		
(14)	08:18	−5
Los Angeles		
(41)	$08\frac{1}{2}^{h} - 7^{m}$	0
San Fernando		
(18)	08:18	−5
Sycamore Cyn.		
(19)	08:20	−5
Santa Barbara		
(20)	$08\frac{1}{2}^{h} - 1^{m}$	+5
Santa Barbara		
(38)	$09^{h} - 1^{m}$	+35
(20, 39)	08:21	−5
(48)	08:14	−10
Ft. Tejon		
(14, 23)	08:29	+5
(57, 61)	$08\frac{1}{2}^{h} - 4^{m}$	0
Visalia		
(58)	08:12	−About 10
Ft. Miller		
(29)	$08^{h} - 1^{m}$	−25
15 to 20 miles NW of San Benito		
(30)	$08^{h} + 5^{m}$	−About 20
Santa Cruz		
(31)	$08^{h} + 8^{m}$	−About 15
(75)	$07\frac{1}{2}^{h} + 8^{m}$	−About 60
San Jose		
(35)	08:13	−About 10
(36)	$08\frac{1}{2}^{h} + 8^{m}$	+About 15
San Francisco		
(40)	08:25	0
(45)	$08^{h} + 10^{m}$	−15
(47)	08:25	0
(49)	08:24	0
(52)	08:30	+5
(53)	08:25	0
(54, 55)	08:24	0

* That is, $08\frac{1}{2}$ hr minus 12 min.

TABLE 2—*Continued*

Location (and source)	Felt Time (PST)	Deviation from 8:24 (PST) to Nearest 5 Min
Stockton		
(56)	$08^h + 5^m$	−About 20
(59)	08:25	0
Sacramento		
(36, 37)	Between 07^h and 08^h	−About 25 to 85
(39)	08:21	−5
(49)	$08:25\frac{1}{2}$	0
(62)	08:26	0
(64)	08:16	−10
(65)	10:21	+About 120
(66)	$08^h + 6^m$	−About 20
(70)	08:11	−15

TABLE 3

FELT REPORTS FOR TWO AFTERSHOCKS

Locality (and source)	Time		Intensity
	Local	PST	
	16 January, p.m.		
Santa Barbara			
(21)	"At or about 4"	At or about 16^h	V±
Castaic Junction			
(21)	"At or about 4"	At or about 16^h	?
Sycamore Cyn.			
(19)	4:46 (?)	16:42 (?)	II–III
Los Angeles			
(9, 13)	5^h	$17^h - 7^{m*}$	V–VI
San Bernardino			
(6)	4:45	16:34	V±
San Diego			
(3)	5:10	16:58	III–V
Santa Cruz			
(75)	—	—	Not mentioned
	9 January, p.m.		
Sacramento			
(65)	10:20	22:26	
Visalia			
(58)	8:45, 10:25, $10\frac{1}{2}^h$	20:42, 22:22, $22\frac{1}{2}^h - 3^m$	
Ft. Tejon			
(23)	Substantial damage between 8 p.m. on 9th and 9 a.m. on 10th		
Near Helendale			
(14)	9^h, 11^h	$21^h - 11^m$, $23^h - 11^m$	
Santa Barbara			
(20, 38)	2 light, 1 heavy		
Ventura			
(19)	8:27, 8:45, 10:36	20:23, 20:41, 22:32	
Sycamore Cyn.			
(19)	8:30, 8:40, 10:00, 10:40	20:26, 20:36, 21:56, 22:36	
Los Angeles			
(9, 14)	11^h	$23^h - 7^m$	
San Bernardino			
(6)	Two "severe" shocks during night of 9–10 January		

* 1700 minus 7 minutes.

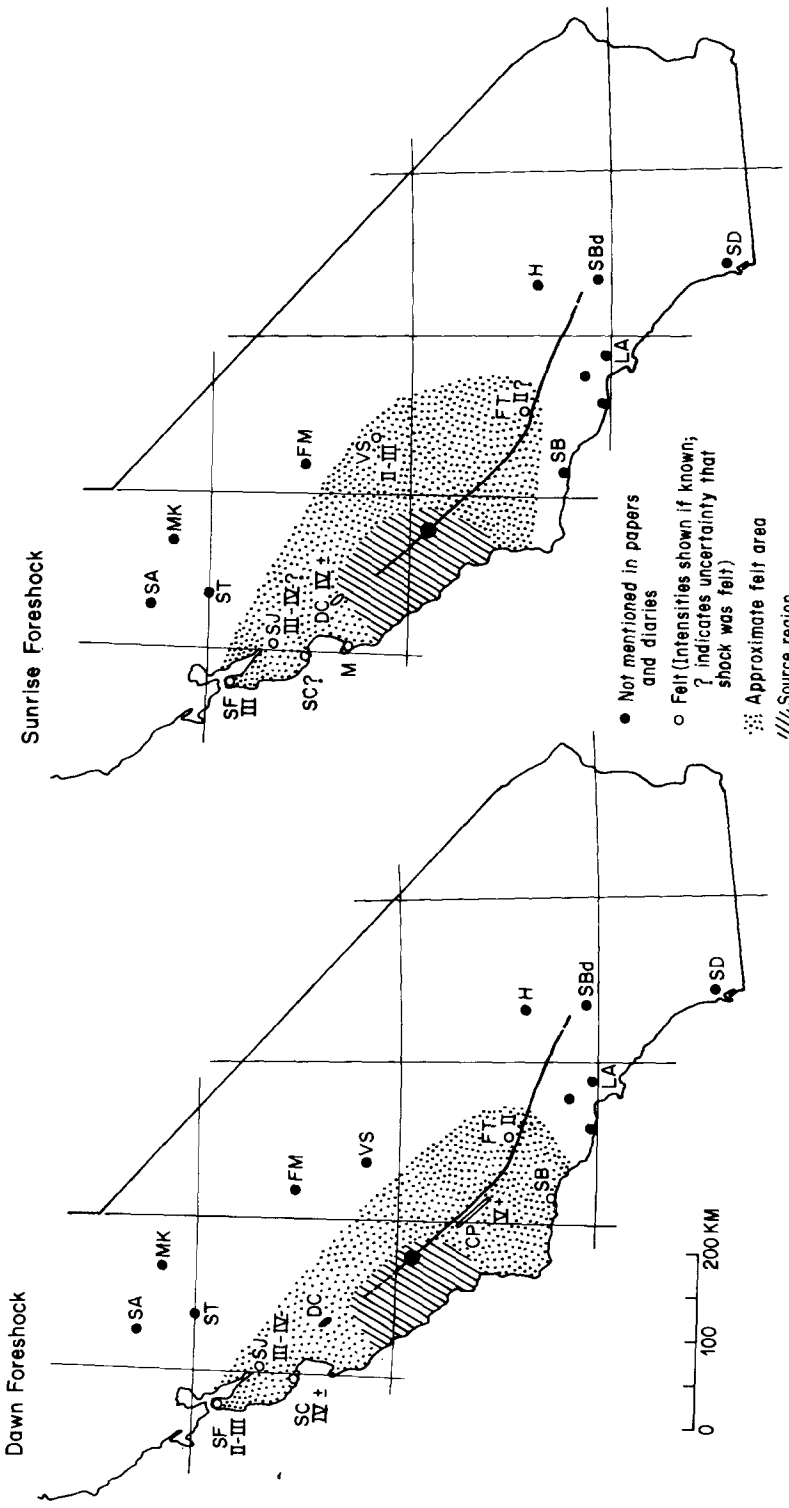

FIG. 3. Felt reports and source regions of the Dawn and Sunrise foreshocks.

farther southeast than the dawn shock, it seems reasonable to conclude that the Parkfield-Cholame reach is the southeasternmost segment of the fault likely to have produced the observed 1857 dawn-shock intensities. Thus, if the San Andreas fault was the source of the dawn shock, the event probably originated somewhere along

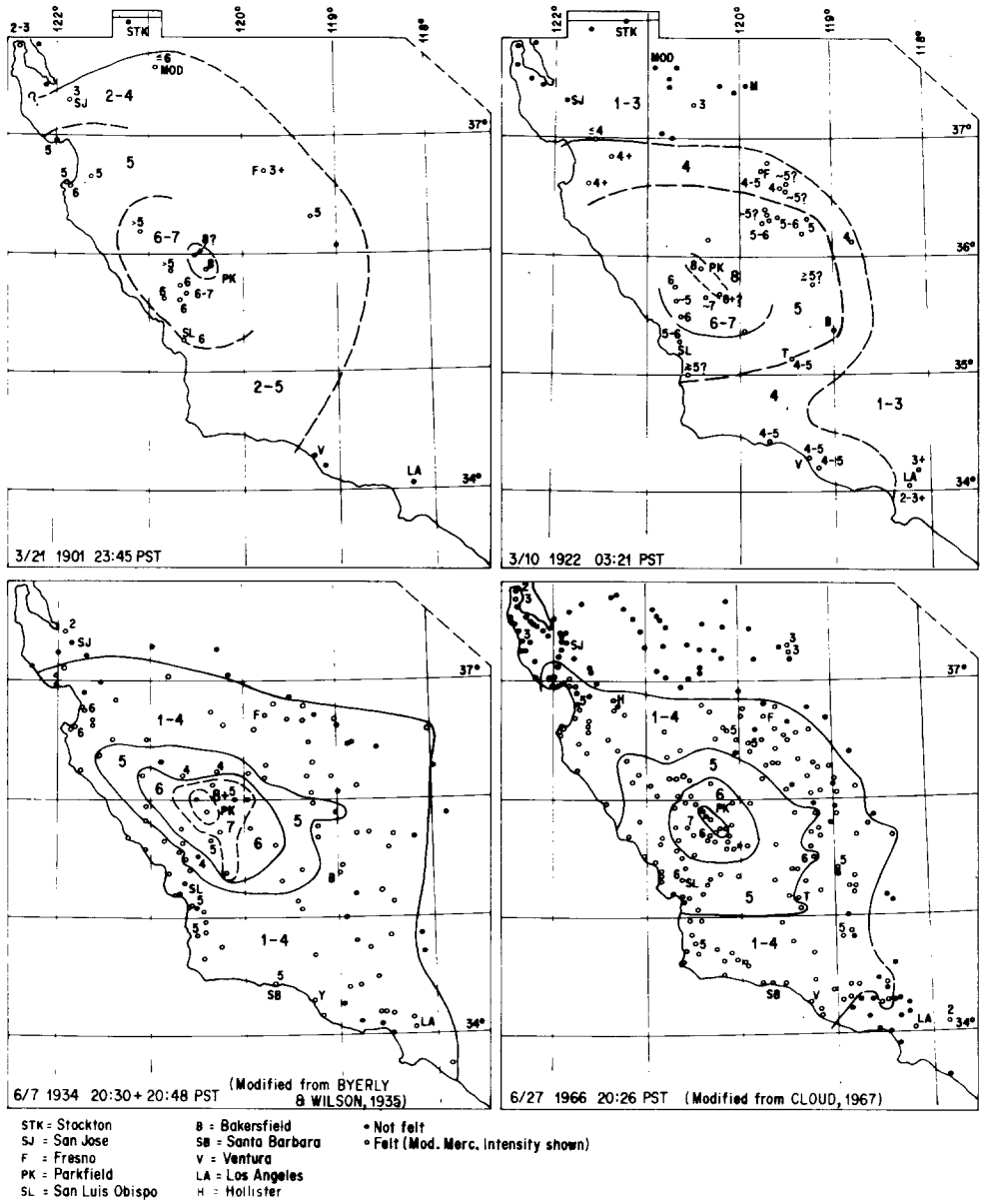

FIG. 4. In the 20th century, four Parkfield-Cholame earthquakes have produced isoseismals similar to the dawn and sunrise foreshocks. Cholame is located about 24 km southeast of Parkfield (PK).

the southeastern 95 km of the currently creeping reach of the fault, that is, between Bitterwater Valley Oilfield and Cholame.

An identical conclusion could be drawn for the 1857 sunrise shock, which occurred about 1 hr after the dawn shock, if it could be ascertained that the event was indeed felt at Fort Tejon. Without that certainty, the following assessment can be made.

Intensities for the sunrise shock at San Francisco (III), Monterey (IV±), Visalia (II to III), Dr. Canfield's (V±), and perhaps at San Jose (III to IV−) indicate a source somewhat distant from all these localities, and yet an event of sufficient magnitude to be felt at such widely separated localities. An event in the Hollister/Monterey Bay area can be ruled out on two accounts. In the first place, an event of sufficient magnitude to be felt in Visalia would probably require somewhat higher intensities than were reported at San Jose, Dr. Canfield's, and San Francisco. Indeed, even the largest modern event originating in this area ($M = 5.6$, 8 April 1961), which produced an intensity V at the above mentioned localities was not felt near Visalia. Second, such an event would almost certainly have been felt strongly (~intensity V) at Santa Cruz and reported by the *Pacific Sentinel* of January 10 (31).

Dr. Canfield's report of the sunrise shock (intensity IV to V) creates some doubt that the source of the moderately large sunrise shock could be close to Canfield's location. However, a source to the southeast, perhaps as close as 10 or 20 km, could have produced the reported intensities.

As it is for the dawn shock, the Parkfield-Cholame reach is a logical southeastern limit on possible origins for the sunrise shock, as a $M \geqq 5.0$ shock originating on the fault much farther to the southeast would have been felt in and between Santa Barbara and Los Angeles but probably not in San Francisco and San Jose. Thus, if the sunrise shock occurred on the San Andreas fault, it probably originated at some point between 36.6°N (about 10 km southeast of Dr. Canfield's 36.7°N) and 35.7°N (Cholame). Judging from modern-event isoseismal maps, the magnitude of the event was between 5 and 6.

Possible sources other than the San Andreas fault. The dawn and sunrise shocks did not necessarily originate on the San Andreas fault. Their intensity distributions can be satisfied by moderate events originating in other areas within central coastal California. The 1952 $M = 6.0$ Bryson earthquake, for example, very nearly duplicates the felt reports of the 1857 dawn shock. The 1952 earthquake might have been produced by movement on the Nacimiento fault (Richter, 1969), although the highest intensities are centered on the Rinconada fault, about 35 km southwest of the San Andreas fault. A slightly smaller event at the same location as the 1952 shock might satisfy the felt intensities for the 1857 dawn shock. That two modern events (2 March and 2 November 1955, $M = 4.8$ and $M = 5.2$) originating in this vicinity were not felt near Santa Barbara, Fort Tejon, or San Jose suggests a lower magnitude limit of about $5\frac{1}{2}$ for an 1857 event originating there.

The pre-dawn shock. The pre-dawn shock is not reported from as many localities as the dawn and sunrise shocks, and so its source is not as firmly bound. Reported intensities are compatible with a source identical to that of the dawn and/or sunrise foreshocks. An epicenter within the source region of the dawn and sunrise shocks is especially likely if the pre-dawn shock was large ($M \geqslant 5.0$) and indeed was felt in the Carrizo Plain. A smaller event (say $4 \leqslant M \leqslant 5$) originating in the region east of Monterey Bay cannot be ruled out.

Summary and Discussion

The isoseismal maps constructed from available documentary data constrain the magnitudes of the dawn and sunrise foreshocks to $5 \leqq M \leqslant 6$. These data also confine the epicenter(s) of these foreshocks to within a crude circle of radius ≈ 60 km centered upon 35.7°N, 120.9°W (Figure 3). The pre-dawn shock may also have originated within this region. The northwesternmost 40 to 80 km of the approximately 360-km long 1857 fault break lies within this source region (Sieh, 1978). As

foreshocks tend to occur near the epicenter of the impending main event (e.g., Kelleher and Savino, 1975; Lindh and Fuis, 1978; Allen and Nordquist, 1972) the 1857 main-shock epicenter probably lies within the source region of the foreshocks and, thus, at or within a few tens of kilometers of the northwestern terminus of the main rupture. This would imply that the main rupture propagated principally in a unilateral fashion toward the southeast. This would also imply that the 1857 rupture originated in a region of relatively high historic seismicity and propagated into and through a region of low seismicity, analogous to the behavior of large earthquakes in 1939, 1942, and 1943 on the Anatolian fault in Turkey (Dewey, 1976).

Parkfield-Cholame events?

The temptation to further constrain the foreshock (and perhaps the main-shock epicenters) to the Parkfield-Cholame reach of the San Andreas fault is great. In the first place, four of the five historical events that have produced felt reports very similar to the 1857 foreshocks are Parkfield-Cholame earthquakes (Figure 4). Hence, if the 20th-century record of moderate events is fairly representative of the record for the century or two preceding the 1857 earthquake, a Parkfield-Cholame foreshock source is the most probable.

Another aspect of the Parkfield-Cholame events curiously similar to the 1857 foreshock record is that half of the historical Parkfield-Cholame events were multiple-event sequences, as the 1857 foreshock sequence was. The 1966 sequence included three shocks $M \geqq 5.0$—one ($M = 5.1$) 17 min before the $M = 5.5$ mainshock and one ($M = 5.0$) about 40 hr after the main shock (McEvilly *et al.*, 1967). The 1934 sequence included several shocks prior to the $M = 6.0$ main shock—including one ($M = 5.0$) 18 min prior, and one ($M = 5.0$) 55 hr prior (Byerly and Wilson, 1935).

The likelihood that the Parkfield-Cholame segment of the fault ruptured during the main shock (Sieh, 1978) might also be a point favoring Parkfield-Cholame foreshocks over a foreshock source more distant from the main rupture.

Finally, a Parkfield-Cholame foreshock sequence might be preferred because it would be located at a point of unusually high stress concentration along the main rupture—that is, at the present junction of the creeping and dormant segments of the fault.

A speculative model

The fact that certain material properties and geometric characteristics along the San Andreas fault are rather long-lived has led some to propose that the historical behavior of the fault is characteristic of the long-term behavior (Allen, 1968; Wallace, 1970). That is, great earthquakes followed by long periods of dormancy might characterize the segments of the fault which ruptured in 1906 and 1857, whereas relatively continuous slip by creep and small to moderate earthquakes might characterize the intervening 170-km long segment. I have described evidence along the 1857 break which suggests that 1857-size slip events do characterize that segment of the fault (Sieh, 1977). Others have published evidence that certain "patches" of fault plane within the creeping segment are characterized by the periodic repetition of moderate events separated in time by periods of relative dormancy (Bufe and Harsh, 1976). If, in truth, the bends and discontinuities in the fault plane and heterogeneities in materials juxtaposed along the fault influence the behavior of the fault, that behavior might be somewhat regular or predictable over periods of time roughly equivalent to the longevity of these features (that is, $\geqq$ thousands of years).

This sparks the hope that the process of failure for great 1857-like events may be

somewhat repetitive and predictable.

Let me suggest one very simplistic and perhaps naive model for the initiation of 1857-like events. This model assumes that indeed it was a Parkfield-Cholame sequence that preceded the great 1857 event. The horizontal axis of Figure 5 includes a 100-km section of the San Andreas fault centered upon Parkfield-Cholame. On the vertical axis I have plotted fault slip. The stippled right-hand third of the figure slips only during occasional great earthquakes. The non-stippled left-hand third slips relatively constantly at a rate of about 3 cm/yr (e.g., Brown and Wallace, 1968). The intermediate segment of the fault slips during both creep events (e.g., Goulty and Gilman, 1977) and moderate earthquakes (nos. 1, 2, 3, 4, etc.) such as occurred in 1901, 1922, 1934, and 1966. These events originate at the north end of their

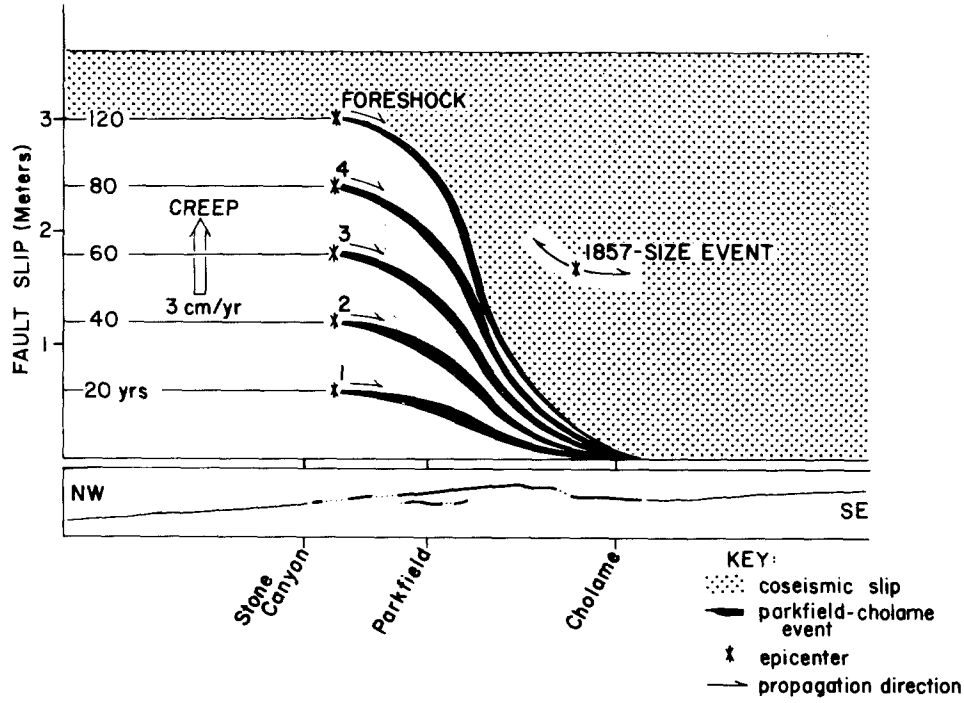

FIG. 5. Hypothetical relationship of creep and moderate Parkfield-Cholame earthquakes to the initiation of great 1857-size earthquakes near Parkfield-Cholame. Relatively continuous right-lateral fault slip occurs along the creeping reach of the fault; creep punctuated about every 20 years by a moderate-magnitude Parkfield-Cholame event occurs between Stone Canyon and Cholame; fault dormancy southeast of Cholame is broken every few hundred years by a great earthquake triggered by a moderate foreshock, such as occurred in 1857. A map view of the fault trace at the base of the figure shows the segment which broke in 1966 (heavy line) and a large bend in the fault near Cholame.

ruptures as in 1934 (Byerly and Wilson, 1935) and 1966 (McEvilly *et al.*, 1967) at some sort of geometrical or material asperity (Lindh and Boore, 1974) and propagate toward the southeast, terminating at a stronger asperity near Cholame (perhaps related to the unusual 1-km wide jog in the surface trace of the fault in Cholame Valley). Every few hundred years the several-hundred-kilometer-long dormant reach of fault to the southeast will become loaded to the point of imminent failure. A Parkfield-Cholame earthquake or earthquake and aftercreep sequence then occurs, applying stresses to the stronger asperity which break it and a great 1857-type rupture proceeds to cascade along the fault toward the southeast. The buildup of strain both regionally and at the tip of the creeping reach would then begin anew.

APPENDIX

Analysis of Reports of Seismic Activity Prior to the Main Shock

Shocks reported by the San Francisco Sun. The San Francisco *Sun* of January 10, 1857 (49) gives a unique account of seismic activity prior to the main shock in that it reports precise times for several late-evening and early-morning earthquakes. Shocks at 23:30 PST (January 8), 01:43, 04:25, 06:18, and 07:10 are listed as well as a time of 08:24 PST for the main event. The precision of the times implies that the recorder consulted a watch at the time of each event and was either sleeping lightly or up all night. If this account is correct, at least five shocks occurred prior to the main shock. Prof. George Davidson, who himself experienced only one shock prior to the main event in San Francisco (53), relied upon the *Sun's* report in writing his section of the report on the 1906 earthquake (54). This indicates that at least one local "scientist" considered the *Sun* account reliable. Davidson, himself, was probably not awakened by the earlier shocks. The *Sun's* 08:24 PST time for the main shock is completely reliable, being nearly identical to several other times (40, 47, 53, 54 and 55) given for the event at San Francisco. Several accounts shall be seen which also support the occurrence of the *Sun's* 07:10 shock. Hence, there is no reason to doubt the reliability or precision of the *Sun's* report. In the following discussion I assume that the *Sun's* account is reliable and attempt to correlate shocks reported by other sources with the *Sun's* five shocks.

The late-evening shock. Four independent San Francisco sources reported a slight shock (Modified Mercalli Intensity II to III) in the late evening of January 8, but only two of them (49 and 52) indicate felt times. The more precise 23:30 PST time of the *Sun* is probably the more reliable of the two. As no other known sources reliably report an event within 2 hr of this time, the late-evening shock was probably a very small event (say $M \leqq 3\frac{1}{2}$) originating within a few tens of kilometers of San Francisco.

The very-early-morning shock(s). Three, and perhaps four or five, independent sources report that a shock was felt between about 1 a.m. and about $2\frac{1}{2}$ a.m. The *Sun* gives the only precise time—01:43 a.m. PST. From the report it can be surmised that the intensity was II or III. The *Pacific Sentinel* of January 31 (32, 33) reports that some person(s) other than themselves near Santa Cruz and/or in Monterey County felt a shock at about 1 a.m. Inasmuch as the *Sentinel* plagiarizes a San Francisco paper at one point, is inaccurate in some details, and appears to be ambivalent in the earthquake times it reports (compare January 10, January 31, and February 21 accounts), this report has low credibility. If valid, however, it suggests the 01:43 PST event felt in San Francisco was also felt in the Santa Cruz/Monterey Area.

Reports from Sacramento (65) and Fort Miller (29) indicate that a light earthquake was felt after 2 a.m. Both reports give rounded-off times, and so the events might actually be synchronous with the 01:43 PST San Francisco event. The report in the *Sun* (50) of a rapid succession of slight shocks accompanied by lights in the night sky at Mokelumne Hill, in the Sierran Foothills, may indicate that a very-early-morning shock was felt there also.

The data for this (these) shock(s) are of questionable reliability and too scanty and enigmatic to enable much discussion of possible source(s) or magnitude(s). A moderate event east of San Francisco in the Sierran Foothills, far from the locus of main-shock activity, might be the least unlikely explanation of both the felt reports from San Francisco, Sacramento, Mokelumne Hill, and Ft. Miller, and the *lack* of felt reports from elsewhere in the State. Nevertheless, it is difficult to explain the

absence of a Stockton report, if this is the case. Thus, the very-early-morning phenomena remain enigmatic.

Early-morning earthquakes. Many sources from San Francisco to Fort Tejon report experiencing one or more shocks between about 4 and $7\frac{1}{2}$ a.m. Three or perhaps four accounts indicate that more than one shock was felt within this period. The *Sun* (49) reports that shocks were felt at 04:25, 06:18, and 07:10 PST. The San Jose *Telegraph* (35) reports two events—one at 5 a.m. and another at "about 6" a.m. The Santa Cruz *Pacific Sentinel* (75) reports events at "about 4" and "a few minutes before 7" a.m. Lt. Col. Beall (23) at Ft. Tejon writes that the shocks began at "about 6" and continued with more or less severity at 5- to 10-min intervals throughout the day. One cannot be sure that this truly means there were events between "about 6" and the main shock at 8:24 a.m., because his principal reference must have been to the main event and its aftershocks. Nevertheless, it is clear from at least the San Jose, San Francisco, and Santa Cruz accounts that more than one early-morning shock occurred.

Each of the remaining several accounts of early-morning earthquakes mentions only one event. This does not cast doubt upon the probability of two or three events, because intensities II through V are often not felt by a large percentage of a population. If, as the *Sun* (49) reports, three events occurred during the three hours before sunrise, timing imprecision and inaccuracy in the remaining accounts dims the prospect for their specific assignment to one of the three events precisely reported by the *Sun*. Figure 2 illustrates the problem. All times are assigned uncertainties based on the following analyses.

The San Francisco *Daily Morning Call* of January 10 (45) reports a slight shock at "about half-past five o'clock". The main-shock time reported by this paper is also rounded to the nearest hour (8 a.m.) but is within 15 min of the actual felt time. Assuming the earlier shock time is also properly rounded to the nearest hour, but allowing for a bit less precision because of the predawn hour, the time is assigned an uncertainty of ±45 min in Figure 2.

The San Francisco *Herald* of January 10 (47) reports "five o'clock" for an early-morning shock. This is regarded as a reliable time because of the reliability of the 08:25 time given for the mainshock. The early shock time is assigned an uncertainty of ±45 min, however, because it is a rounded-off figure, and because the observer might have been more prone to imprecision if awakened from sleep by the event.

The San Francisco *Daily Town Talk* (52) reports that an early-morning shock occurred at "seven o'clock". In all probability, this is a properly rounded time for the shock, judging from the apparent reliability of the rounded time it gives for the late-evening shock (11 p.m.) and the reasonably precise reported time for the main shock (08:30 PST). The figure is almost certainly reliable to ±40 min, based on the approximately 5-min error in its main-shock time, and the likelihood that the reporter was not sleeping at the time of the event.

Prof. George Davidson, in his letter of January 19 (53) to Prof. A. D. Bache, superintendent of the U.S. Coast Survey, indicates that the first shock he felt was at "about $7\frac{1}{4}$" a.m. and the main shock was at "about $8\frac{1}{4}$" a.m. (08:25 PST). The main-shock time given by Davidson is essentially identical to the best estimate of the time of the event at San Francisco. Considering that he phrased the timing of both shocks in the same way, his time is judged to be accurate to ±20 min.

The Stockton *San Joaquin Republican* of January 10 (59) reports that a 6 a.m. foreshock was felt by one gentleman who allegedly did not feel the subsequent main shock. It seems unlikely that this man would not have felt the main shock, as heavy

shaking was reported by most of the people in Stockton. Furthermore, he described the 6 a.m. shock in terms of intensity similar to that indicated by others for the main shock. This suggests that his timepiece or estimate of time was incorrect by 2 hr or so and that he experienced the main shock rather than a foreshock.

The San Jose *Telegraph* of January 13 (35) reports concerning the morning of the 9th: "It is said that at five o'clock and again at about six . . . very distinct shocks of an earthquake were felt." The given times are clearly approximate, and the observations were made by a person or persons other than the reporter, yet there is clear implication of two distinct events. The 08:13 time indicated for the main shock, about 10 min too early, probably represents the reporter's or paper's own time. It is not known whether the reports came from persons who were awakened from sleep or who were up and about, or whether reliable timepieces were promptly consulted. Thus, the times cannot be regarded as more than rough estimates. Reasonable ranges might be 5 a.m. ±1 hr and 6 a.m. ± 1 hr.

The San Jose *Tribune* of January 14 (36) reports a shock felt at "about four o'clock." Allowing for rounding of the actual time to the nearest hour and the probable foggy state of mind of the observer at that hour, this report can be given a precision of ±45 min.

All but two reports from the Monterey Bay region are enigmatic because they confuse the 7 o'clock foreshock and the $8\frac{1}{4}$ o'clock main shock. Only the *Pacific Sentinel* reports of January 10 and 17 (31, 75) are consistent with reports from elsewhere in the State. The January 10 account states

> "Yesterday morning was experienced two severe shocks of an earthquake, the first between 5 and 6 o'clock, A.M., and the other about 8 o'clock A.M."

The reported time for the main shock is about 15 min early, but a proper approximation of the actual main-shock time. Therefore, there is no reason to distrust the early-shock timing. The generalized nature of the reported time, however, bespeaks some imprecision, perhaps as much as $\pm\frac{1}{2}$ hr. And if the accuracy of the reporter's timepiece was ±15 min, the shock time can be regarded to have an uncertainty of ±45 min. The very inaccurate reporting of the main-shock time in the January 17 report ($7\frac{1}{2}$ a.m., 1 hr too early) suggests that the foreshock times (~04 a.m. and ~07 a.m.) could also be very inaccurate.

Alexander S. Taylor, a Monterey correspondent of the San Francisco *Bulletin*, reports in the issue of January 12 (41) that the main shock was felt at Monterey at "about 7 o'clock!". This report seems to have convinced the Santa Cruz *Pacific Sentinel* (33) that its own observation of an 8 o'clock main shock was in error. At this time, let us assume that a shock was felt at 7 a.m. at Monterey, and assign it an uncertainty of ±45 min, as has been done for the rounded, reported times above.

A Dr. C. A. Canfield (30), apparently living "15 to 20 miles northwest of San Benito" (Holden, 1898) (that is, along the fault, east of Monterey), reports a shock at about sunrise accompanied by noise and lasting no more than about 5 sec. Let us assume the shock occurred within 30 min of sunrise (that is 7:16 ± 30 min).

The Stockton *Daily Argus* of January 19 (58) printed a letter from the Visalia area which reports a "slight shock" at "about sunrise". The precision of this account is assumed to be ± 30 min.

As Wood (1955) has pointed out, the report of the cowboy who was on the Carrizo Plain at the time of the great earthquake (73) is confused. Undoubtedly this observer is in error in stating that the main earthquake occurred "before daybreak". Whether this means before first light (about 5:45 PST) or before sunrise (about 7:15 PST) is

uncertain, but in either case, it is likely that when he recounted that morning's experience, some 50 years after the fact, the details were somewhat nebulous and perhaps rearranged in his mind. Apparently, due to seismic activity, he was awakened and his cattle stampeded "before daybreak". Because the cowboy waited until it was light enough to round them up this activity probably was associated with one or more early-morning shocks prior to sunrise (see Figure 2). The stampeding of the cattle may suggest the shock had at least moderately high intensities (perhaps V or higher) on the Carrizo Plain.

Three individuals report a slight early-morning shock at Ft. Tejon prior to the very severe main shock. Alonzo C. Wakeman, the Quartermaster's deputy at the Fort, reported in the Los Angeles *Star* January 17 (14) that the "first shock took place at about thirty minutes past six o'clock, A.M. . . .".

Mr. Canaday, the expressman arriving in Stockton from the Fort, told the Stockton *Daily Argus* of January 16 (57) that a shock was felt at "about 6". To the Stockton *San Joaquin Republican* (61) he reports the shock occurred "at $6\frac{1}{2}$". If each report is assigned an uncertainty of ± 45 min, it can be argued that the shock occurred between $5\frac{3}{4}$ and $6\frac{3}{4}$.

Lt. Col. B. L. Beall, commander of the Fort, noted in a letter written to his superiors on the evening of January 9 (23) that "at about six o'clock this morning, the shocks of an earthquake commenced and have continued with more or less violence, at intervals of five or six minutes, up to this time." This may be an indication that more than one shock was felt at the Fort prior to the main shock, but, as was said previously, this reference is probably to the main shock and its aftershocks. Beall's 6 o'clock time is given an uncertainty of ± 45 min in Figure 2.

A Santa Barbarian's letter in the San Francisco *Daily Alta California* of January 13 (38) reports that the first shock occurred at "6" and the main shock occurred at "9". The writer's rounding off of the 8:24 main-shock time to 9 rather than 8 indicates his timepiece was at least several minutes fast, but otherwise perhaps fairly reliable. Thus the uncertainty assigned in Figure 2 to the time of the first shock (±50 min) is a function of the rounding off (±30 min), the imprecisions of the timepiece (say ±10 min), and the probability that the fellow was asleep at the time of the event (say ±10 min).

Acknowledgments

My interest in finding historical accounts of the 1857 earthquake was sparked by a discussion with Al Lindh about the nature of its mysterious foreshocks (Lawson *et al.*, 1908, p. 461). Dan Burd's persistent searches yielded most of the previously unknown accounts I have used. Rad Wagner found newspaper accounts enabling construction of isoseismal maps for the 1901 and 1922 earthquakes. Discussions with John Rudnicki were helpful in development of the speculative model.

This work was supported by U.S.G.S. Contracts 14-08-0001-15225 and 14-08-0001-16774.

References

Agnew, D. C. and K. E. Sieh (1978). A documentary study of the felt effects of the great California earthquake of 1857, *Bull. Seism. Soc. Am.* **68,** 1717–1730.

Allen, C. R. (1968). The tectonic environments of seismically active and inactive areas along the San Andreas fault system, in *Proceedings of Conference on Geologic Problems of San Andreas Fault System,* W. Dickinson and A. Grantz, Editors, *Stanford Univ. Publ. Geol. Sciences* **11,** 70–82.

Allen, C. R. and J. M. Nordquist (1972). Foreshock, mainshock, and longer aftershocks of the Borrego Mountain earthquake, in *The Borrego Mountain Earthquake of April 9, 1968, U.S. Geol. Surv. Profess. Paper 787,* 16–23.

Bufe, C. G. and P. W. Harsh (1976). Earthquake recurrence in central California (abstract), *EOS, Trans. Am. Geophys. Union* **57,** 959–960.

Byerly, P. and J. T. Wilson (1935). The central California earthquakes of May 16, 1933 and June 7, 1934,

Bull. Seism. Soc. Am. **25,** 223–246.

Cloud, W. K. (1967). Intensity map and structural damage, Parkfield, California, earthquake of June 27, 1966, *Bull. Seism. Soc. Am.* **57,** 1161–1178.

Dawson, M. (1950). Southern California newspapers 1851–1876, *Hist. Soc. So. Calif. Quart.* **32,** 5–40 and 139–174.

Dewey, J. W. (1976). Seismicity of northern Anatolia. *Bull. Seism. Soc. Am.* **66,** 843–868.

Goulty, N. R. and R. Gilman (1978). Repeated creep events on the San Andreas fault near Parkfield, California recorded on a strainmeter array (in press).

Holden, E. S. (1898). Catalogue of earthquakes on the Pacific Coast 1769 to 1897, *Smithsonian Misc. Collections no. 1087.*

Kelleher, J. and J. Savino (1975). Distribution of seismicity before large strike slip and thrust-type earthquakes, *J. Geophys. Res.* **80,** 260–271.

Lawson, A. C. and others (1908). *The California Earthquake of April 18, 1906, Report of the State Earthquake Investigation Commission,* Carnegie Inst. of Washington, Washington, D.C., 2 vol. and Atlas, 461 pp.

Lindh, A. and D. M. Boore (1974). The relation of the Parkfield foreshocks to the initiation and extent of rupture, *Earthquake Notes* **44,** 54.

Lindh, A. and G. Fuis (1978). Seismic amplitude measurements suggest foreshocks have different focal mechanisms from aftershocks (submitted for publication).

McEvilly, T. V., W. H. Bakun, and K. B. Casaday (1967). The Parkfield, California earthquakes of 1966, *Bull. Seism. Soc. Sm.* **57,** 1221–1244.

Richter, C. R. (1969). Possible seismicity of the Nacimiento fault, California, *Bull. Geol. Soc. Am.* **80,** 1363–1366.

Sieh, K. E. (1977). A study of Holocene displacement history along the south-central reach of the San Andreas fault, ch. 2, *Ph.D. Dissertation,* Stanford Univ., Stanford, Calif.

Sieh, K. E. (1978). Slip along the San Andreas fault associated with the great 1857 earthquake, *Bull. Seism. Soc. Am.* **68,** 1421–1448.

United States Earthquakes 1928–1974 (1968–1975). National Earthquake Information Center, Coast and Geodetic Survey, Rockville, Md.

Wallace, R. E. (1970). Earthquake recurrence intervals on the San Andreas fault, *Bull. Geol. Soc. Am.* **81,** 2875–2890.

Wood, H. O. (1955). The 1857 earthquake in California, *Bull. Seism. Soc. Am.* **45,** 47–67.

DIVISION OF GEOLOGICAL AND PLANETARY SCIENCES 170–25
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA 91125
CONTRIBUTION NO. 3090

Manuscript received June 12, 1978