Seismic activity on neighbouring faults as a long-term precursor to large earthquakes in the San Francisco Bay area

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Activity in moderate-size earthquakes accelerated in the several decades before the large California earthquakes of 1989, 1906 and 1868. This type of precursor seems to require the presence of several major faults in close enough proximity to one another that moderate-size shocks are selectively triggered on surrounding faults during the latter stages of the cycle of strain buildup to large earthquakes. It may be possible to use quantitative aspects of similar seismic precursors to make predictions of large earthquakes on timescales of a few years to one decade.

THE number of moderate-size earthquakes in the greater San Francisco Bay area was much higher in the 25 years before the great San Francisco earthquake of 1906 than it was in the longer period from 1912 to 1955[1,2]. Ellsworth *et al.*[2] noted the re-emergence of earthquakes of magnitude $M = 5.0$–5.9 from 1955 to 1980 after a long quiescence and concluded that the region was entering a more active stage in which events as large as $M = 6$ to perhaps $M = 7$ could be expected in the decades before an eventual great earthquake. Sykes and Nishenko[3] remarked that the region of increased activity for the period 1955 to 1982 was not as large as that preceding the 1906 shock and instead was concentrated mainly to the east and southeast of San Francisco. They concluded that the pattern might represent a long-term precursor to an earthquake of magnitude near 7 along that segment of the San Andreas fault from opposite San Jose to San Juan Bautista. The Loma Prieta earthquake of 18 October 1989 of magnitude 7.1, the first large ($M \geq 6.8$) shock to occur along the San Andreas fault itself since 1906 was, in fact, centred along that fault segment.

We find that the activity in moderate-size shocks ($5 \leq M < 6.5$), particularly the seismic moment M_0, increased in the several decades before the 1989, 1906 and 1868 events, the three largest earthquakes in the San Francisco Bay area during the past 150 years. The accelerated release rates, two of which were terminated by the occurrence of the 1906 and 1868 shocks, resemble tertiary creep. This process occurs in a wide variety of materials including rocks and is characterized by accelerating deformation which leads to failure[4-6].

Forerunning activity to large earthquakes

We now examine the spatial and temporal distribution of seismicity before three large earthquakes in the San Francisco Bay area. Figure 1 shows earthquakes of $M \geq 5$ for 35-year periods preceding the 1906 and 1989 earthquakes, the 35-year period 1920–1954, which was well separated in time from a large shock, and the 14 years preceding the 1868 earthquake. The shorter period before the 1868 event reflects an incomplete record of moderate-size shocks. The area of our study is the same as that used by Ellsworth *et al.*[2] in their examination of long-term forerunning activity to the 1906 earthquake. It is bounded on the southeast by a segment of the San Andreas fault that shows continuous creep, rather than the stick-slip rupture of large earthquakes. It is unlikely that precursory changes related to large earthquakes in the study area extend into that region. The magnitudes used are from refs 7–11.

We chose to study only earthquakes of $M \geq 5.0$ in Fig. 1 because: (1) catalogues of events of smaller magnitude are not complete before the 1906 and 1868 earthquakes, the only two events in the past 150 years similar to or larger in size than the 1989 shock: (2) the frequency of occurrence of events of $M \geq 5$ is known to have varied greatly before and after the 1906 shock[1,2]; (3) we did not find a significant variation in the frequency of occurrence of events of $4 \leq M < 5$ for 1942–1989, during which period magnitudes were calculated by the same procedure and it is believed that there was uniform reporting of earthquakes of those sizes[9,12].

Figure 1*a* shows a high level of seismic activity for events of $M \geq 5$ in the San Francisco Bay area in the 35-year period before the great 1906 earthquake. Most, and perhaps all of those shocks, the largest of which was $M = 6.4$, occurred well away from the surface trace of the 1906 fault break. The magnitudes of most of those events are, in fact, larger than those of the aftershocks of the 1906 event. By 1912 activity in earthquakes of $M \geq 5$ had decreased to a very low level. As can be seen in Fig. 1*b*, no events of $M \geq 5$ occurred in the study area to the north of 37.0° from 1920 to 1954. Seismic activity in shocks of $M \geq 5.0$ was also high before the 1989 and 1868 earthquakes (Fig. 1*c*, *d*). Activity dropped to a very low level within two years of the 1868 shock (Fig. 1*d*); no events of $M \geq 5$ are known to have occurred in the area of Fig. 1 between 1871 and 1881. The low release rate is similar to that from 1912 to 1954, following the great 1906 earthquake. Ellsworth *et al.*[2] concluded that changes in the frequency of occurrence of events of $M \geq 5$ in the vicinity of the 1906 fault break from 1855 to 1980 were significant at the 95% confidence level.

As in Fig. 1*a*, the activity preceding the 1989 event (Fig. 1*c*) occurred on faults other than the one that broke in the 1989 earthquake. Even the two Lake Elsman shocks of June 1988 and August 1989 ($M = 5.0$ and $M = 5.2$), which occurred close to the epicentre of the 1989 earthquake and can be considered to be long-term foreshocks, were situated a few kilometres away from the main rupture zone of the Loma Prieta shock, on faults dipping in the opposite direction to the one that ruptured in the 1989 event[13].

Accelerating seismic moment release

Ellsworth *et al.*[2] remark that it is paradoxical that the production rate of smaller earthquakes in the Bay area remained virtually constant (the record is complete since 1930 for $M \geq 4$ and since 1942 for $M \geq 3$), in contrast to marked variations in activity for $M \geq 5$. Recognizing that the changes in seismic activity with time in Fig. 1 are also largely confined to shocks of $M \geq 5$, we measure changes in activity in terms of a temporal sum of the seismic moment, regarding this as a first-order approximation to the regional change in shear strain associated with earthquakes[14]. The principal contribution to the sum comes from the several largest shocks in a given sample; the smallest events contribute very little. Hence, an increase in seismic moment with time is consistent with the observation that the number of events of $M \geq 5$ increased before large shocks whereas the rate of occurrence of smaller shocks in the same broad area remained nearly constant. Unlike counts of numbers of earthquakes, the moment sum is relatively insensitive to changes in detection levels.

We use cumulative seismic moment ΣM_0 to quantify moment release, where M_0 is summed from a given date for shocks of $M \geq 5.0$ that occurred within the precursory areas of Fig. 1, which we describe below. As the release of seismic moment occurs virtually instantaneously during earthquakes, we prefer to sum moment release with time rather than work with moment rate. All of the seismic moments used were calculated[15] from $\log_{10} M_0 = 1.5M + 9.0$, where M is the local magnitude reported by the Berkeley seismographic station for events in the Bay area[9,10]. Moment has also been determined independently from long-period waves for most events of $M \geq 5.3$ in the study area since 1977[16]. The two determinations are in excellent agreement, indicating no significant biases in the calculation of moment since 1977.

Figure 2*a* shows ΣM_0 in the San Francisco Bay area as a function of time since 1955. The upward curvature indicates an increase in the rate of moment release (the slope) from 1955 to 1989. ΣM_0 increased much more rapidly from 1979 to 1988 than it did during previous decades. Much of that release is contributed by the 1979, 1980, 1984 and 1986 earthquakes (Fig. 1*c*). The rise time τ of the best-fitting exponential is 11 years. This function fits the data with an root-mean-square uncertainty that is ~50% smaller than that for the best-fitting linear increase in ΣM_0; this is also true for the three other data sets we examined.

Values of ΣM_0 for the periods leading up to both the 1906 and 1868 earthquakes are shown in Fig. 2*b*, *d*. A very low rate of moment release from 1872 to 1881 is followed by an accelerating rate. A similar effect is seen in the 14 years preceding the 1868 earthquake. The rise time of the best-fitting exponential for the pre-1906 sequence is 9 years. That for the pre-1868 data, 4 years, is poorly determined and is probably too small because it is based on only 14 years of data.

Can the accelerated releases of moment before the three large shocks be explained instead by a systematic error in the calculation of M_0 as a function of time? When M_0 is derived from M, ΣM_0 is sensitive to systematic changes in magnitude determination, which would produce an apparent change in the rate of moment release. We examined events of $M \geq 4.0$ from 1942 to 1989 for such changes using the techniques of Habermann[17] but found no evidence for a systematic magnitude change. For the decade before the 1989 event, ΣM_0 is 6.3 times larger than that for the preceding decade (Fig. 2*a*). An error in the magnitude of 0.5 is required to account for that difference, which seems unlikely because such a large systematic error is not indicated for events of $M \geq 4.0$. Also, it would be a very unlikely coincidence for large biases in M to occur such that they slowly increased before the 1868, 1906 and 1989 events and then suddenly decreased in the several years after the 1868 and 1906 earthquakes. More work is needed to obtain a better calibration of M_0 as a function of intensity for modern earthquakes and then to use it to derive moment for pre-instrumental earthquakes such as those before 1906 for which M was estimated from the area over which the earthquakes were felt.

Removal of the largest event from 1955 to 1989, the 1984 earthquake, results in linear and exponential relationships with comparable misfits, an indication of the sensitivity of ΣM_0 to the inclusion or exclusion of the largest events in a sample. In that case, however, the average yearly rate of moment release from 1955 to 1989 in the precursory area of the 1989 event is still six times that from 1912 to 1954.

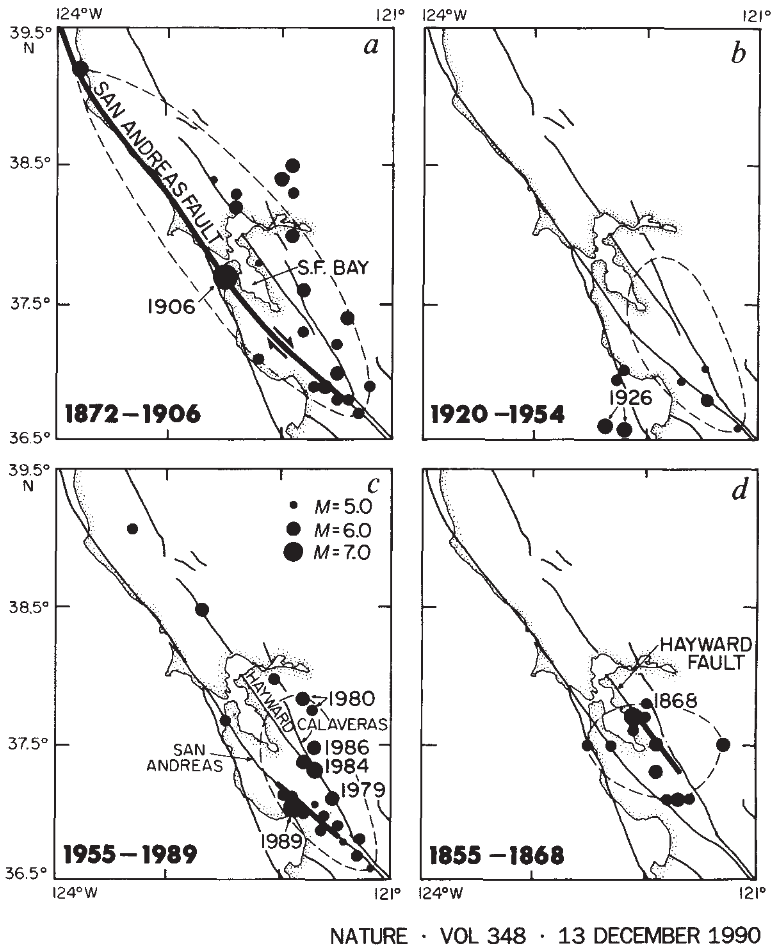

FIG. 1 Distribution of earthquakes of magnitude 5 or larger in San Francisco Bay area for four time intervals. Major faults are shown; epicentres of 1906, 1989 and 1868 earthquakes indicated by large solid circles. Locations of earthquakes and extent of rupture in three large shocks (heavy solid lines) are from refs 2 and 7–11. Arrows in *a* denote sense of strike-slip motion along the San Andreas fault. Dashes enclose events taken to be within the precursory area of the 1906, 1989 and 1868 events. The activity was low in the precursory area of the 1989 shock (dashes) in *b* from 1920 to 1954.

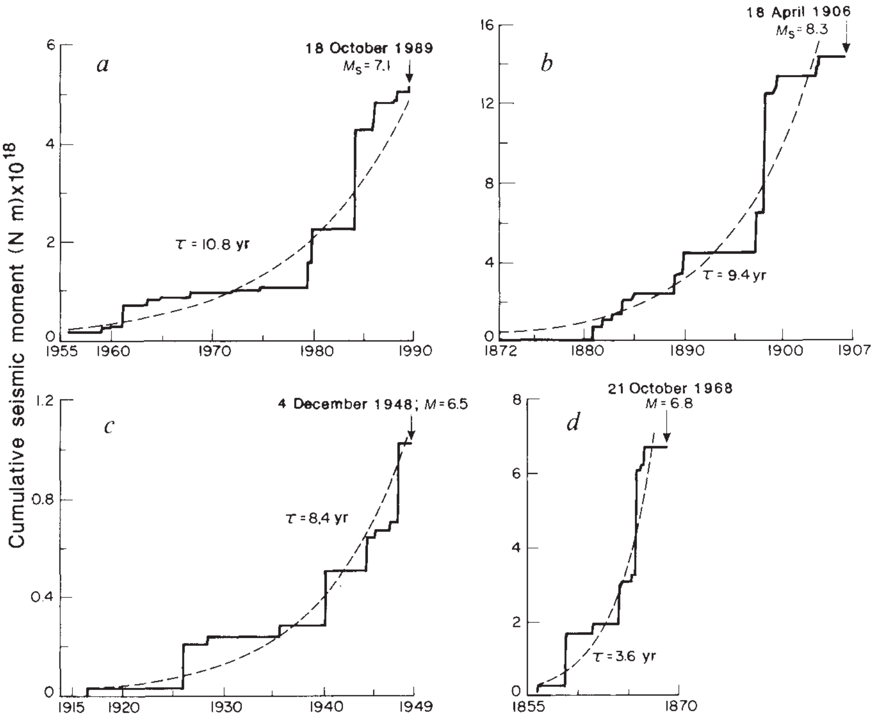

FIG. 2 Cumulative seismic moment ΣM_0 summed for events of $M \geq 5.0$ as a function of time t before three earthquakes in San Francisco Bay area and the 1948 shock in southern California. Dashed lines are the best-fitting exponential increases, $\Sigma M_0(t) = \Sigma M_0(0)e^{t/\tau}$, where τ is rise time.

Other examples of precursory moment release

The rate of occurrence of shocks of $5.0 \leq M < 6.0$ within 50 km of the epicentre of Desert Hot Springs earthquake of magnitude 6.5 in 1948 in southern California increased by a factor of 10 in the preceding 8.5 years[18,19]. For the 35-year period before that shock, ΣM_0, as calculated from the local magnitude, increased nearly exponentially with a rise time of 8 years (Fig. 2*c*). ΣM_0 for each of the four precursory sequences in Fig. 2 can be fit with functions other than increasing exponentials. Good fits to the data, however, seem to be restricted to functions that yield higher rates of moment release in the one or two decades before the large shocks and lower rates in the preceding few decades. None of the aftershocks of the 1948 earthquake exceeded $M = 4.9$, and none of the forerunning events occurred in its rupture zone (as deduced from the distribution of aftershocks)[18-20]. Thus, the 1948 event was very similar to the 1906 and 1989 earthquakes in having a large number of moderate-size events preceding it in a broad surrounding area.

The descriptions by Mogi[21] of doughnut-shaped patterns of $M \geq 6.0$ earthquakes surrounding the rupture zones of several great earthquakes at subduction zones are qualitatively similar in space and time to the patterns we report. Much of that forerunning activity occurred in the few decades before the great thrust events, either in adjacent portions of the upper plate or on nearby segments of the plate boundary along the strike.

Determination of precursory area

We have identified the regions that we think participated in the precursory release of seismic moment to three large earthquakes (Fig. 1, dashed lines) and have estimated their precursory area A (Table 1). More-quantitative techniques need to be applied to determine A more objectively and accurately in future studies. Activity in the 35-year period before the 1906 earthquake (Fig. 1*a*) extended along much of the 430-km length of the 1906 rupture zone. Only one event is taken to define the northern extent of A for that shock. Because it is one of the larger events in Fig. 1*a* and because it occurred only 8 years before 1906, we chose to include it in our definition of A. Shocks of $M \leq 5.5$ from 1872 to 1906 may not have been reported from sparsely populated areas north of 39° N. We also exclude from A the 1892 events that are farthest (80–100 km) from the 1906 rupture zone. Deformation in that area seems to be the thrust type, like that farther south along strike near Coalinga[22]. Inclusion of these events results in a poorer fit to a rising exponential in Fig. 2*b* but an even higher rate of precursory moment release.

Most of the forerunning activity to the 1989 shock (Fig. 1*c*), especially the larger events, occurred south of 38.0° N. Except for the two events in 1980, all of the shocks to the north of 37.5° occurred 20–35 years before the 1989 earthquake. Hence, those early events may not be part of the preparatory process of the 1989 event and were not included in our estimate of A. Judging from the distribution of newspapers in print, the basis for identifying and locating most of the events before 1906[7,8], the record of earthquakes of $M = 5$–5.5 in Fig. 1*d* may not be complete south of 37.0° or north of 38.5° N before 1860. Although forerunning activity to the 1868 event may have occurred farther south than indicated in Fig. 1*d*, the other boundaries of its

TABLE 1 Data on precursory sequences

Precursory sequence	Magnitude of mainshock	Precursory Area ($m^2 \times 10^9$)	Rise time, τ (yr)	Accumulated seismic moment ΣM_0 just before main event (N m $\times 10^{18}$)	Equivalent magnitude of ΣM_0	$\Sigma M_0/A$ (N $m^{-1} \times 10^8$)	$M_0/A = \Sigma M_0/A\tau$ ([N m^{-1} yr^{-1}] $\times 10^8$)
1872–1906	8.3*	22.0	9.4	14.3	6.8	6.5	0.69
1955–1989	7.1*	7.1	10.8	5.2	6.5	7.3	0.68
1855–1868	6.8	6.8	(3.6)	6.7	6.6	9.9	(2.7)
1914–1948	6.5	2.2	8.4	1.03	6.0	4.7	0.56

* M_s, surface-wave magnitude.

precursory area are not likely to be affected by the incompleteness of reports.

We chose to sum M_0 over a 35-year period for the four earthquakes we studied based on the data of the 1989 shock and the finding in ref. 2 that $M \geq 5$ events became more numerous after 1955. Shortening the summation interval to 25 years, the time period for which shocks of that size became more numerous before the 1906 earthquake, affects ΣM_0 very little, especially for the last decade of precursory release. Taking a longer time interval mainly affects the determination of A because events are included that may not be part of the precursory process.

We distinguish separate precursory sequences for the 1868 and 1906 mainshocks. From the temporal sequences alone, it is possible that the period of low activity from 1872 to 1881 occurred by chance and that the two precursory sequences are, in fact, one. The precursors we report, however, have spatial characteristics as well. The precursory areas and the magnitudes of those two mainshocks are quite different in size, providing strong evidence that the two events have distinguishable precursors. Although our determinations of A are considerably larger than the aftershock areas of major earthquakes, they are much smaller than estimates of A used in ref. 23.

Mechanism of precursory moment release

The region within about 50–75 km of each rupture zone contains several major active faults in addition to the fault that ruptured in each mainshock of Fig. 1. Several of the larger events that preceded the 1989 earthquake occurred along the southern Calaveras fault within 50 km of the 1989 rupture zone (Fig. 1*c*). Segments of several nearby faults that were already close to rupturing in moderate-size events seem to have moved more rapidly toward failure during the several decades before the shock. The locations and focal mechanisms of the moderate-size shocks in Fig. 1*c* and the 1989 event are in accord with the idea that strain buildup to the 1989 earthquake could have augmented the strain that was otherwise building up along the adjacent faults.

Figure 3 shows schematically our conception of the release of seismic moment as a function of space and time in the San Francisco Bay area and in the area of the 1948 shock. Our ideas expand earlier work on the seismic cycle of large earthquakes[24]. After the occurrence of a large earthquake and its aftershock sequence (Fig. 3*b*), strain is built up slowly in the area surrounding the main rupture zone. During the latter stages of that buildup, moderate-size earthquakes are preferentially triggered on various fault segments in the surrounding precursory area (Fig. 3*a*, *c*). The rate of moment release in the area accelerates as the time of the next large shock approaches (Fig. 3*c*). Dislocation models of candidate large earthquakes can be used to ascertain which nearby fault segments are expected to move closer to failure and which are not. Changes in the strain associated with moment release in a broad area, which appear to be akin to the non-elastic process of tertiary creep, should not be equated with strain buildup measured geodetically, which seems to be mainly an elastic process.

Mogi[21] found that forerunning seismic activity in fracture experiments in the laboratory was prevalent for heterogeneous materials and either infrequent or absent for homogeneous materials. By analogy, he proposed that large-scale structural heterogeneity in seismically active regions would be associated with seismic precursors whereas homogeneity would not. We expect that areas with only one major throughgoing fault, such as the Carrizo Plain segment of the San Andreas fault, to be typified by few if any seismic precursors of $M \geq 5$. Many seismically active areas, including the Bay area and large parts of southern California, however, are characterized by a greater complexity in the distribution of active faults, a situation that is commonly thought to make earthquake prediction very difficult. The type of seismic precursor we describe, however, seems to require a certain amount of tectonic complexity for its existence.

Dislocation modelling of geodetic data indicates that slip at the time of the 1989 earthquake extended to a depth of ~18 km (ref. 11). Significant changes in strain are likely to have occurred to distances a few times 18 km, both during the 1989 event and in the long period of strain buildup before it. The sizes of the precursory areas deduced for the 1868 and 1989 events (Fig. 1) seem reasonably attributed to such a process. Most of the forerunning activity to the 1906 and 1989 shocks (Fig. 1) is located asymmetrically with respect to the San Andreas fault as is the zone of strain accumulation of the past 20 years[25]. The asymmetrical patterns may result from the main plate boundary at depth being displaced to the northeast of the San Andreas fault[26]. The 1948 shock occurred in a similar setting[27], suggesting that this type of precursor may occur at greater distances when the plate boundary is not vertical throughout the lithosphere.

Predicting large earthquakes in the Bay area

Our work raises some questions. Did the 1989 shock terminate a sequence of accelerated or high moment release? When and where will the next large, $M \geq 6.8$, earthquake occur in the San Francisco Bay area? What are the uncertainties in such estimates? Are all large shocks in the region preceded by similar anomalies?

The 1868 and 1906 earthquakes were followed by long periods of low moment release and small numbers of events of $M > 5.0$ (Figs 1 and 2). Thus, they culminate as well as terminate the long-term increase in the rate of moment release. Using the patterns of moment release in the years to decades following the 1868 earthquake as a guide to what may happen on similar timescales after the 1989 event, which was of comparable size, we foresee three possibilities for future large earthquakes in the Bay area. If, within several years, the rate of moment release and the rate of occurrence of events of $M \geq 5.0$ drop to their

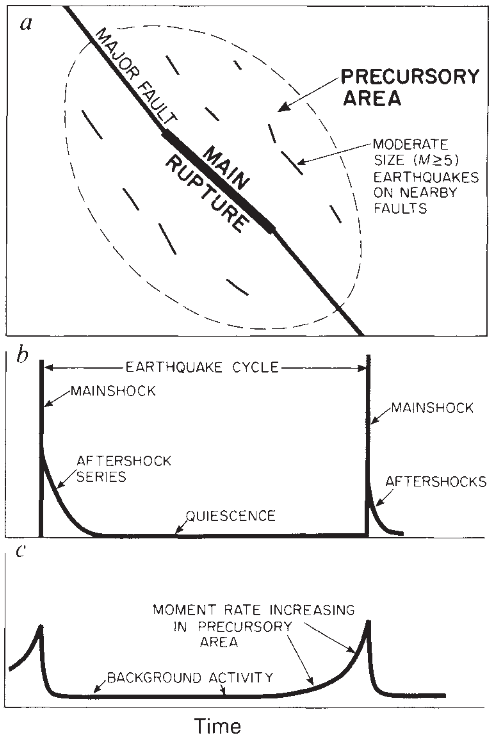

FIG. 3 Schematic diagrams showing relationship of seismic precursors to cycle of strain buildup and release in large earthquakes in the San Francisco Bay area. *a*, Map view of moderate-size shocks in the precursory area surrounding the rupture zone of the coming large earthquake. Rate of release of seismic moment as a function of time along *b*, the main rupture zone itself and *c*, in the precursory area.

low 1912–1954 levels, a large shock is unlikely to occur for at least a decade and then only when either ΣM_0 or the rate of moment release increases to values comparable to those just before the 1989 earthquake. But if it becomes evident with the next few years that those rates have remained high, a second large event can be expected. The third possibility is that a second large earthquake could occur within a few years, but after a period not long enough for a good determination of the rates.

Our experience with seismic precursors to large shocks in the Bay area comes from the southern half of the Hayward fault and from nearly the entire portion of the San Andreas fault in Fig. 1. It seems reasonable to assume that future large earthquakes along these fault segments will be preceded by similar anomalies. As the northern Hayward fault, last broken in the large event in 1836[8], is partly surrounded by faults that ruptured in moderate-size events before the 1906 shock, it seems likely that a repeat of the 1836 shock would also be preceded by a pattern like that before the 1868 event but centred around the northern half of the fault. Not very much of the activity in Fig. 1*c* is situated within 50 km of that segment, however, in contrast to that in the decades before the 1868 and 1989 earthquakes. Two of the six events that occurred within that distance between 1955 and 1989 occurred over 33 years ago. If a large event were imminent along the northern Hayward fault in the next few years, it seems likely that greater nearby activity would have occurred already. Likewise, there is no indication of a buildup of activity surrounding the San Andreas fault to the north of San Francisco, supporting the idea that there is a low probability of that fault segment rupturing in a large to great shock in the next few decades[3].

The situation for the southern Hayward fault and for the San Andreas fault between San Francisco and the 1989 rupture zone is more equivocal because $M \geq 5$ events of the past 30 years within 50 km of these segments could be interpreted as precursors of either the 1989 shock alone or of both it and a future large earthquake along one of those segments. The amount of damage and loss of life in a shock of about $M = 7$ along either the Hayward fault or along the peninsular section of the San Andreas fault, when it occurs, are likely to be considerably larger than those in the 1989 earthquake. Hence, although such an event would be smaller than the 1906 earthquake, it is likely to be called 'the big one' by the public.

There are several ways in which information on moment release might be used quantitatively in making predictions of future large earthquakes in the study area. For example, ΣM_0 can be thought of as a seismic stress gauge indicating the likelihood of a future large earthquake in the Bay area. The values of ΣM_0 just before the 1989 and 1868 events are very similar (Table 1). If other considerations, such as the dimensions of a candidate fault segment, indicate that a future earthquake in the Bay area is likely to be of magnitude near 7, then the experience from the 1868 and 1989 shocks indicates that the mainshock is likely to occur within a few years of the time when ΣM_0 reaches 6×10^{18} N m.

Table 1 shows values of ΣM_0 just before the three large shocks in the study area and the 1948 earthquake. Both ΣM_0 and the precursory area increase as the size of the mainshock increases. We normalize for this effect by dividing ΣM_0 and its time derivative $\dot{M}_0$, by A. The values of $\Sigma M_0/A$ in Table 1 are similar; their mean and standard deviation are $(7.1 \pm 2.2) \times 10^8$ N m^{-1}. Using $\tau = 10.8$ years from the 1955–1989 sequence, one standard deviation translates into an uncertainty in predicting the time to failure T_f (the time required to accumulate 2.2×10^8 N m^{-1} when $\Sigma M_0/A$ is close to the mean value) of about three years. A smaller uncertainty in T_f would be associated with smaller values of τ in Table 1. Values of $\dot{M}_0/A$ before each mainshock (Table 1) exhibit less scatter than values of $\Sigma M_0/A$, providing the more uncertain rate for the pre-1868 sequence is omitted. Thus, the levels of $\Sigma M_0/A$ and $\dot{M}_0/A$ may be useful in predicting future large earthquakes to within a few years for regions of similar precursory release.

Discussion

Voight[5] describes rate-dependent failure in a variety of materials by the empirical equation

$$\ddot{\Omega} - A\dot{\Omega}^{\alpha} = 0 \qquad (1)$$

where A and α are constants, and $\ddot{\Omega}$ and $\dot{\Omega}$ are the first and second time derivatives of a measure of the deformation process. For $\alpha = 1$, Ω grows exponentially and $A = \tau^{-1}$. For $1 < \alpha < 2$, Ω becomes very large at a finite time to failure. For a variety of materials[5] and for foreshocks[28], α is typically somewhat smaller than two. Equating ΣM_0 and Ω in equation (1) and taking ΣM_0 to include M_0 for the mainshock at its known time of occurrence, we obtain a best fit to the data for the precursory sequences of the 1948 and 1989 events for similar values of α. The similarity in α for these phenomena suggests a similarity in the associated failure processes. We have not been successful, however, in making accurate estimates of T_f from ΣM_0 using equation (1).

Each of the patterns of precursory seismicity we have described involves an accelerated release of seismic moment with time and a clustering of activity in the region surrounding the coming large event. The similarity of the sequences in time and space before three large earthquakes in the Bay area and the 1948 shock argues that these patterns are causally related to the four mainshocks. We are optimistic that large earthquakes preceded by this type of precursor will be predictable with greater accuracy. The number of examples, however, is still too small to ascertain the reliability of the predictions.

Note added in proof: High rates of moderate-size earthquakes that are similar to the patterns we report occurred in the decades before the large shocks of 1703 and 1923 in Japan[29], 1952 in southern California[30], and 1957 in the central Aleutian Islands[31]. □

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