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# Intermediate-Term Seismic Precursors to the Loma Prieta California Earthquake of 1989

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## Abstract

We use precise locations of earthquakes to study forerunning seismic activity to the 1989 Loma Prieta earthquake of magnitude 6.9 to the south of San Francisco, California, USA. Relocated shocks of magnitude 4.3 to 5.4 and smaller micro-earthquakes define a distinct zone of nearly the same orientation as the mainshock. That separate zone broke in the 15 months prior to the 1989 mainshock. That feature, which we call the Lake Elsman fault zone, is identified as the site of a prominent intermediate-term (yearly) precursor very close to the coming 1989 mainshock. That zone experienced a relatively large stress decrease during the nearby great earthquake of 1906. From the occurrence of the Lake Elsman shocks, we deduce that stress drop was only restored in the 15 months prior to the 1989 main event. Those stresses are consistent with little forerunning seismic activity in the region after 1906, later increases just before the 1989 mainshock and a decrease in activity thereafter. The southern Santa Cruz mountains segment of the San Andreas Fault zone, the location of the 1989 mainshock, had not been the site of events of magnitude 5 and larger for many decades prior to the occurrence of Lake Elsman earthquakes of magnitude 5.3 and 5.4 in 1988 and 1989. High-precision locations readily available in real-time might be used to monitor similar possible precursory activity very close to the San Andreas and other transform faults.

## Keywords

Earthquakes, Precursors, Prediction, California, Faults, Plate Tectonics

## 1. Introduction

The Loma Prieta earthquake of October 18, 1989 killed 63 people and caused billions of dollars of damage in the greater San Francisco Bay area of California even though it was located 40 to 60 km south of the city. Many remember it as the World Series earthquake. It was the largest earthquake in the Bay area since the great shock of 1906. It ruptured a 40 km segment of the San Andreas fault zone in the geologically complex southern Santa Cruz mountains where a component of compressional contemporary deformation occurs in addition to the more typical strike-slip plate motion observed along much of the longer 1906 rupture zone farther northwest. The very long-period magnitudes, Mw, for the 1989 and 1906 earthquakes are 6.9 and 7.9 [1].

Hundreds of papers were published for the 1989 mainshock and its effects. Aftershocks of the 1989 event have been described in detail. Relatively little work, however, has been devoted to forerunning activity. Here we pay particular attention to the detailed geometry of preceding seismic activity from 1984 to the 1989 mainshock using a catalog where hypocenters are located with respect to one another with precisions of 10s of meters or better [2] [3]. This greater precision resulted from the use of so-called double-difference computations of the locations and origin times for many nearby earthquakes using digital waveforms from a large number of local seismograph stations [4]. This was typically a 50 times increase in precision compared to those of routine locations in the area. This enabled us to identify a distinct nearby Lake Elsman fault zone in which precursors occurred in the 15 months prior to 1989. We conclude that forerunning activity was triggered as stress built up along the more active nearby San Andreas fault. Other close-by subparallel faults should be monitored for increased levels of moderate earthquakes in attempts to identify yearly precursors to large events along the San Andreas and other transform faults.

## 2. Results

High-resolution seismicity between San Francisco and the southeastern end of the 1989 rupture zone is shown in **Figure 1**, **Figure 2** for the San Andreas (SAF), Hayward (HF), Calaveras (CF), and the Sargent (SF) faults. The SF splays off the SAF near the northwestern end of the 1989 rupture zone. **Figure 1** shows that the majority of earthquakes of magnitude M 4 and greater since 1955 occurred either on the SAF southeast of the southern end of the 1989 rupture zone or on the CF. The epicenter of the 1989 mainshock (large blue circle in **Figure 1**) was about 3 km southwest of the main surface trace of the SAF.

**Figure 2** shows preceding events of $M \geq 1.0$ back to 1984 in an enlarged area near the 1989 rupture zone. Relative locations of events since 1984 (3) have average uncertainties of 30 m laterally and 50 m vertically. The region close to the mainshock is notable for its near lack of nearby activity of $M \geq 4.0$ prior to 1989. One exception is the events of M 4.3 to 5.4 (larger red circles with black outlines), which are the main focus of this paper.

The surface trace of the San Andreas fault near the 1989 rupture zone jumps westerly in several places in short zones of compressional (thrust or reverse) deformation (**Figure 2**). The San Andreas fault is structurally more complex than that along many of its other fault segments to the northwest (**Figure 1**). The earthquake was named for nearby Loma Prieta peak (LP) in the Santa Cruz mountains. Figure 2 includes contours of computed displacements during the mainshock of 1 and 3 m [5]. Only one very small preceding shock occurred within the two 3 m contours.

High displacement zones in large to great earthquakes are interpreted to be strong regions called asperities in the seismological and rock mechanics literatures [6]. The main 1989 rupture zone shows similar behavior and is here called a major asperity. The part of the San Andreas fault zone to the north of the Loma Prieta rupture as far as South San Francisco also has been very quiet for decades for events of M ≥ 4.0 (Figure 1). It ruptured in the 1906 earthquake.

Figure 3 shows earthquakes as small as M 1.0 as a function of depth and distance parallel to the surface trace of the segment of the San Andreas fault that ruptured in the main 1989 shock. The large red circles indicate the Lake Elsman earthquakes of 1988 and 1989 of magnitudes 4.3 to 5.4 that locate about 3 km northeast of the SAF. Few forerunning events in Figure 3 occurred between depths of 6 and 9 km and little preceding activity took place above the 1989 mainshock. The maximum depth of earthquakes becomes shallower in both directions along strike from the main shock. Rupture in 1989 propagated bilaterally along strike to the northwest and southeast [5] [7].

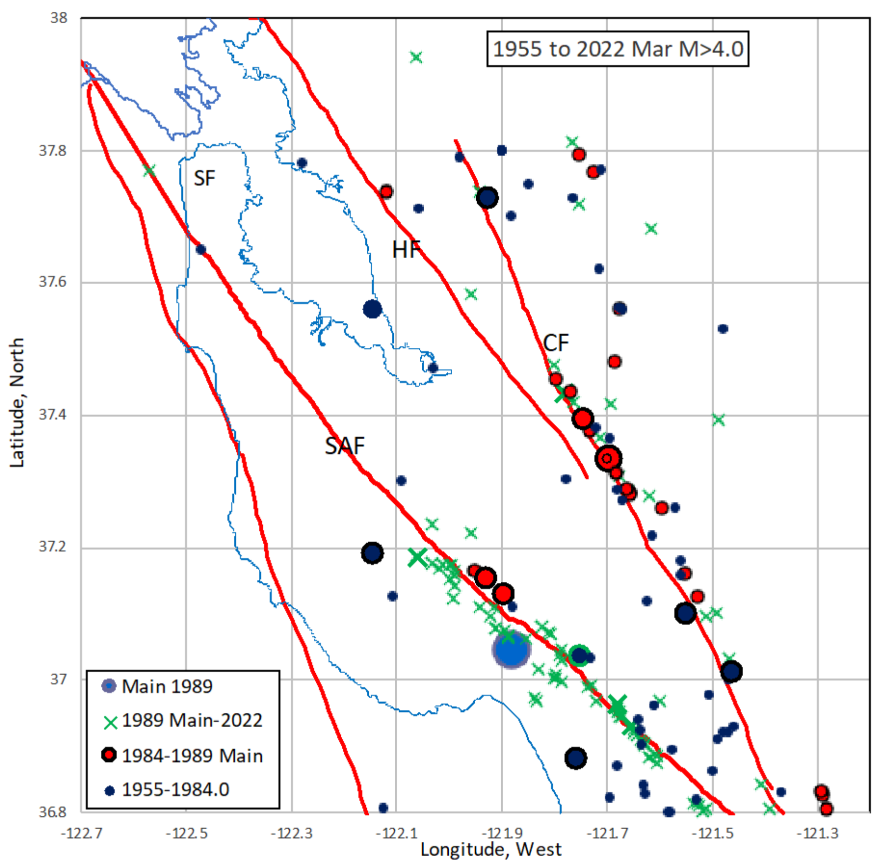


Figure 1. Earthquakes of seismic magnitude ≥ 4 in northern California to the southeast of San Francisco (SF) including shocks before and after the Loma Prieta mainshock of October 18, 1989. Events of magnitude ≥ 5 are indicated by larger symbols. SAF, HF and CF denote San Andreas, Hayward and Calaveras faults.

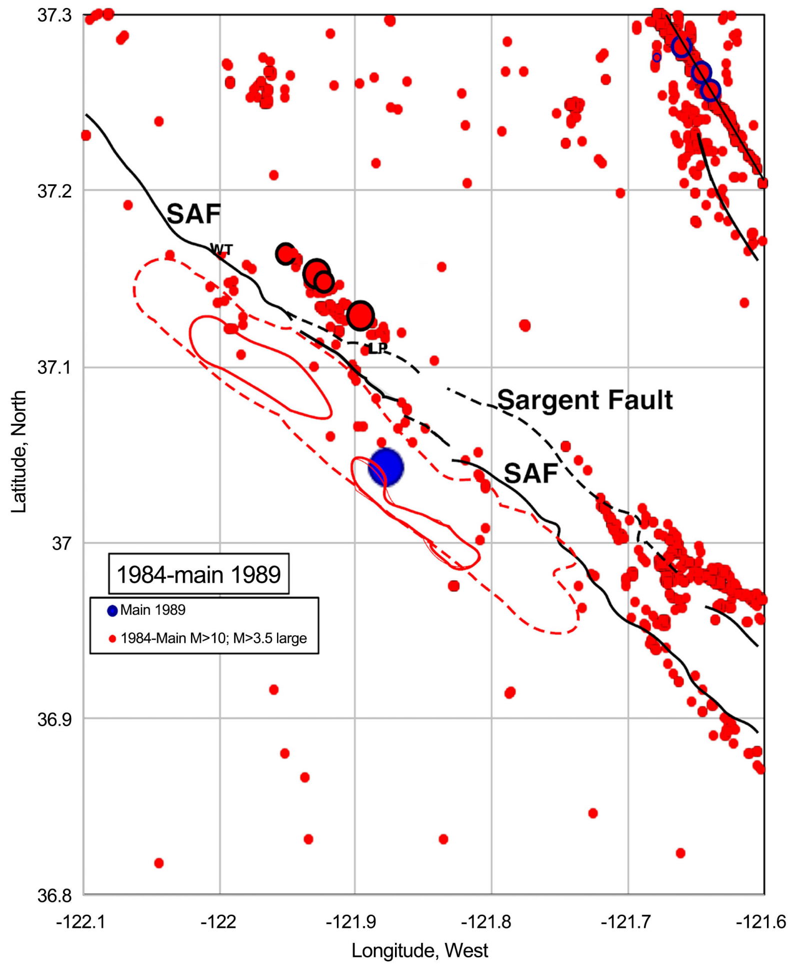


**Figure 2.** Earthquakes of seismic magnitude M ≥ 1.0 from 1984 until the Loma Prieta mainshock (large blue circle). Preceding events of M ≥ 3.5 are shown with large symbols. SAF denotes the surface trace of the San Andreas fault. The dashed and solid red lines indicate computed slip in the mainshock of 1 and 3 m (5). LP indicates Loma Prieta peak, WT Wrights tunnel.

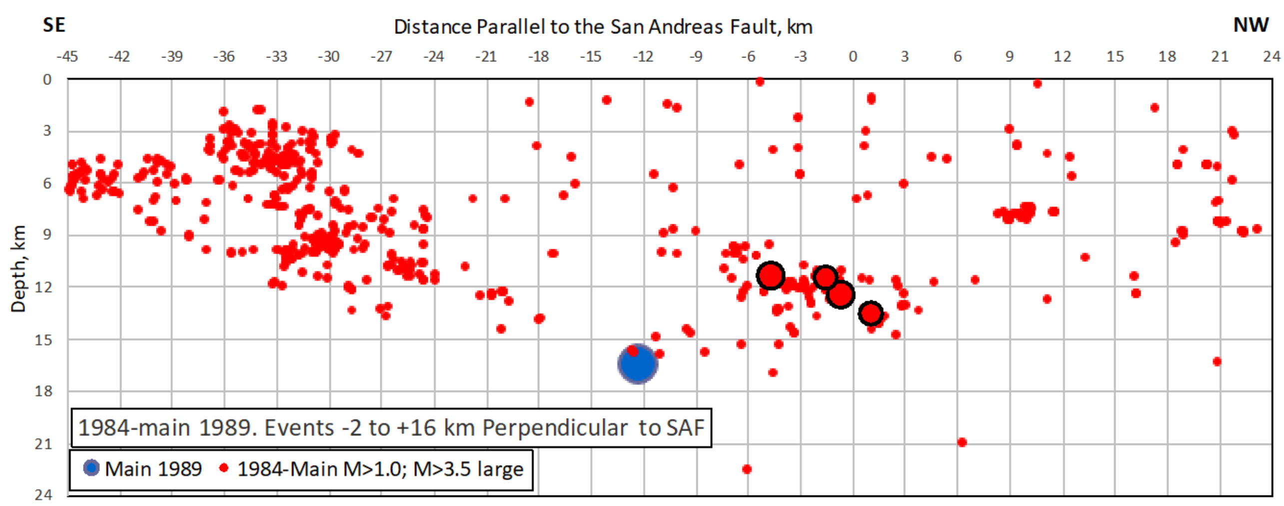


**Figure 3.** Earthquakes between 1984 and 1989 mainshock of magnitude ≥ 1.0 as a function of depth projected onto a plane parallel to the San Andreas fault.

### 2.1. Distinct Forerunning Events along the Nearby Lake Elsman Fault Zone

We show that the Lake Elsman forerunning events occurred close to but along a separate fault zone than the one that ruptured in the 1989 mainshock.

Figure 4 is a cross section of earthquakes as a function of depth perpendicular to the San Andreas fault across the northwestern zone of high displacement (an asperity), which includes the mainshock (Figure 2). The Lake Elsman events are concentrated in a narrow band about 1.5 km wide that dips about 62˚ southwesterly nearly perpendicular to the surface trace of the San Andreas fault.

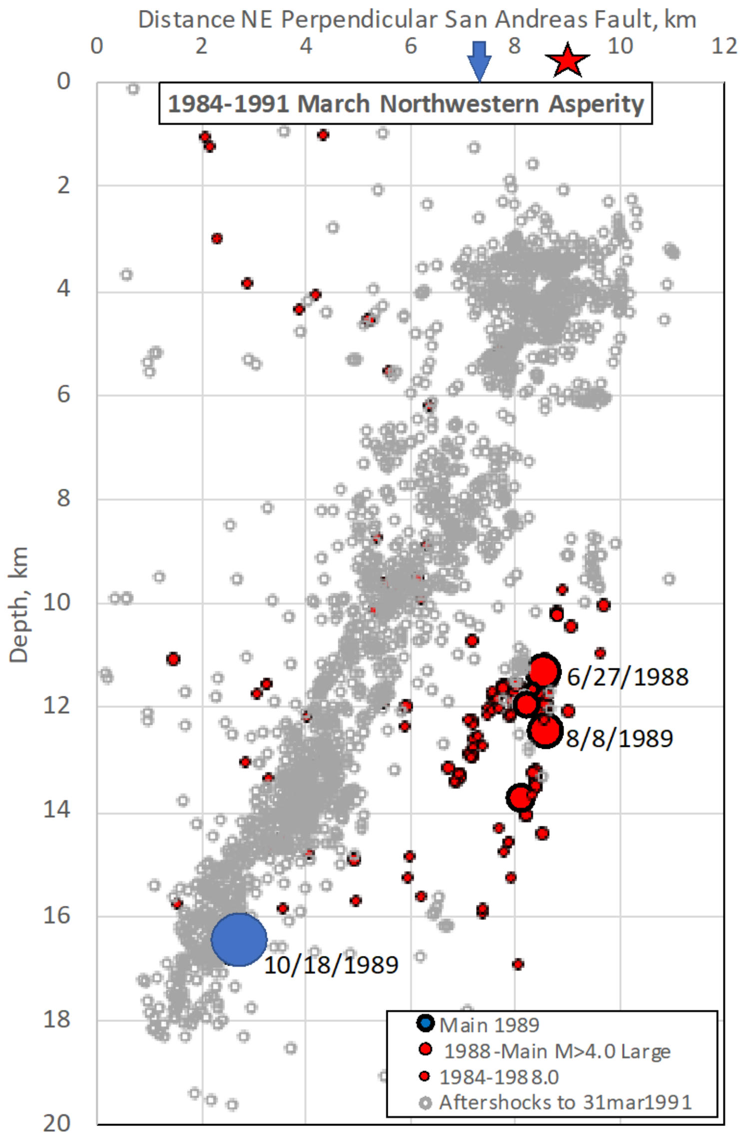


Figure 4. Earthquakes of magnitude ≥ 1.0 as a function of depth projected onto a horizonal axis perpendicular to San Andreas fault (SAF) between 1984 and 31 March 1991. Data shown are only from northwest of the mainshock for distances parallel to the SAF (Figure 3) between −13 and +5 km. [Distances perpendicular and parallel are arbitrary.] Large blue symbol indicates mainshock. Large blue arrow at the top denotes the surface trace of the SAF; red star, Loma Prieta peak.

Rupture in the main 1989 earthquake propagated up dip from its hypocenter at a depth of 16.5 km with highest slip being concentrated between its depth and 8 km. Slip of 1 to 3 m extending upward to depths shallower than about 2 km [7].

Aftershocks (Figure 4) occurred at depths of 18 to 2 km, an indication that some slip took place almost to the surface. The mapped location of the San Andreas fault at the surface (large blue arrow in Figure 4) is about 2 km southwest of a projection of the aftershock zone to the surface. Seismicity is not indicative of where deformation occurs in the upper 2 km [4].

The zone of forerunning activity is distinct from that of the main aftershock zone. Aftershocks in 1989 beneath Lake Elsman do not extend to depths shallower than 8.5 km, another indication that it is distinct from the main zone of rupture in the mainshock.

Figure 5 is an expanded view of activity beneath Lake Elsman from 1984 until the mainshock for a narrower range of distances perpendicular to the San Andreas fault and for depths of 8 to 17 km. Smaller events were concentrated near the magnitude 4.3 to 5.4 Lake Elsman earthquakes, with most of them in the 11

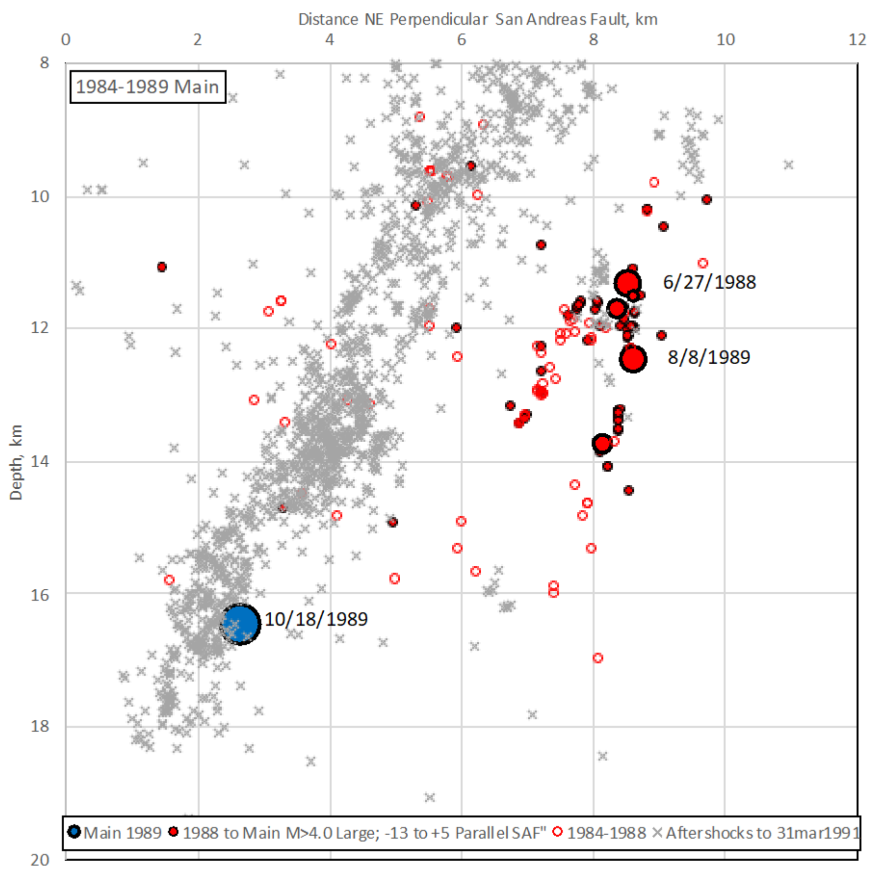


Figure 5. Blown up view of earthquakes of magnitude ≥ 1.0 below Lake Elsman projected onto a horizontal axis perpendicular to San Andreas fault as a function of depth between 1984 and main event of 1989. Mainshock is denoted by large blue symbol. Events shown are only for distances parallel to the San Andreas fault that include the subzone of forerunning shocks near Lake Elsman. Largest symbols denote magnitudes ≥ 4.0.

to 14 km depth range. Solid symbols, which indicate activity from 1988 to the mainshock, are even more concentrated. That activity defines two distinct narrow bands about 1.5 km apart that converge at shallower depths. A detailed investigation indicates that neither two separate faults nor a warped fault zone that includes both strands can be ruled out. We show, however, that the mainshock is part of the aftershock zone and not the nearby Lake Elsman zone (**Figure 4**, **Figure 5**). More work could be done to map the distribution of individual faults and structures in three dimensions.

We also examined well-located shocks of M > 1.6 between 1966 and 1984. They show a similar pattern to those in **Figure 5** but with a higher percentage of events close to the Lake Elsman shocks.

Mechanisms of many of the Lake Elsman shocks were published in 1993 [8]. Most, including the largest, have one steeply dipping nodal plane that is nearly parallel to the Sargent fault and subparallel to the San Andreas fault. [8] picked a nodal plane that dips 65˚ northeast as the causative fault. Their first motions, of which few are located near the centers of the equal-area diagrams, are not sufficient, however, to identify whether the dip is steep to the northeast, southwest or vertical. The distribution of preceding events (**Figure 4**) clearly indicates, however, that the dip was southwest, not northeast.

In the same volume [9] states, "it is now generally accepted that these events were, in some way, foreshocks to the main event." The distribution, timing and sizes of Lake Elsman pre-events (**Figure 4**, **Figure 5**) make a strong case for their being precursory and not a result of random occurrence.

We calculated the slope or $b$ value for the relationship logN = $a$-$b$M using data on the numbers of small shocks, N, of a given M from 1969 to the first large Lake Elsman event of 1988. It was restricted to earthquakes within the Lake Elsman zone. The $b$ value obtained is 0.4, an exceeding small value compared to most sequences elsewhere of 0.8 to 1.0 [10]. Small $b$ values have been shown to indicate high stress levels in lab experiments [10]. The observation within the Lake Elsman zone prior to 1988 could be regarded as a precursor to the main 1989 shock.

**Figure 6** indicates a similar distribution of preceding earthquakes and aftershocks for a perpendicular section across the southeastern asperity (**Figure 2**). It includes the mainshock at its northwestern end. As in **Figure 4**, aftershocks (**Figure 6**) extend from depths of 2 to 18 km in a zone that dips approximately 62˚ southwest. Depths and dips are similar for each cross section.

Farther southeast of the Loma Prieta rupture zone, the San Andreas fault dips nearly vertical and is the site of ongoing creep and many small earthquakes at shallow depth. Geodetic measurements indicate that the 1989 rupture zone and those segments as far north as the northern end of rupture in 1906 are characterized by no creep at the surface [8].

### 2.2. Triggering of Lake Elsman Shocks by Stress Buildup to 1989 Mainshock

We describe how stress dropped in the 1906 mainshock and then built up prior to the occurrence of moderate-size earthquakes along the Lake Elsman and Calaveras fault zones. Reid's seminal geodetic study [11] showed how shear strain (and stress) dropped as a function of distance from the San Andreas fault in 1906. We expand upon work [12] on major earthquakes in the greater San Francisco Bay area.

The numbers of earthquakes of magnitudes 5 and larger in the greater Bay area fluctuated significantly during the past 180 years [12]. Activity on the periphery of the rupture zone of the great 1906 earthquake increased appreciably from 1873 to 1906 then decreased until 1954. Starting about 1979, shocks of magnitudes 5 and larger increased about 30 km to the east of the 1989 rupture zone along the Calaveras and nearby faults (**Figure 1**, **Figure 2**). Each of those increases was taken in [12] to be long-term (decadal) precursors to the coming mainshocks of 1906 and 1989. Moderate-size earthquakes decreased in that area after 1989.

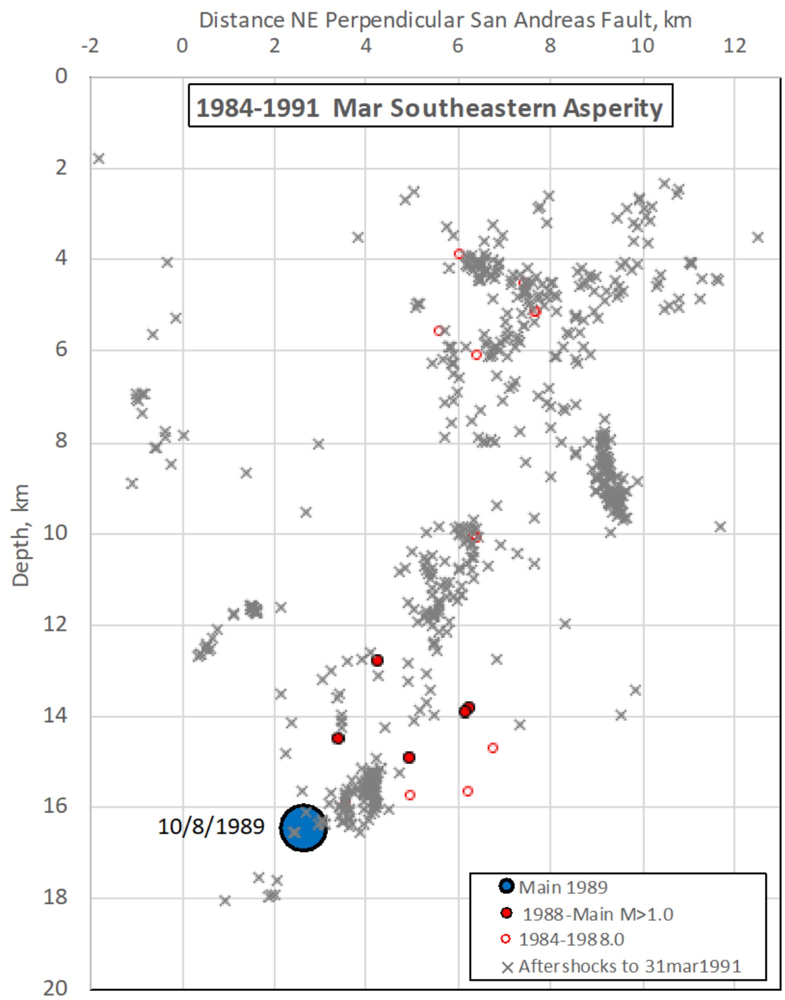


**Figure 6.** Earthquakes of magnitude ≥ 1.0 projected onto a horizonal axis perpendicular to the San Andreas fault (SAF) and vertical axis, depth, between 1984 and 31 March 1991. Data are from southeast of mainshock for distances along the SAF between −21 and −11 km (**Figure 3**). Large blue symbol indicates the mainshock.

Stresses deduced from geodesy dropped the most along the 1906 and 1989 rupture zones themselves. We estimate that they decreased to about 5% along the Calaveras fault zone about 30 km northeast of the 1989 hypocenter. For decades after 1906 and 1989, those stress drops decreased the occurrence of moderate-size shocks along the Calaveras and Lake Elsman fault zones. While active, their long-term slip rates are less than that of the San Andreas itself. As stress was restored by plate motion, moderate-size events were then triggered along the Calaveras zone from 1979 to 1989, including the 1984 Mw 6.2 Morgan Hill earthquake.

Hence, we conclude that the very close Lake Elsman zone experienced a relatively large stress decrease in 1906 that was only restored in the months before the 1989 mainshock. The distances and timing of forerunning activity along the Lake Elsman and Calaveras fault zones are consistent with a model of broad stress decrease in the region in 1906 and subsequent build up prior to 1989. It is consistent with little forerunning activity in the region after 1906 and its later increase before the 1989 mainshock.

Our characterization of yearly to decadal changes in seismicity near a major fault such as the 1989 rupture zone has the advantage of not being very sensitive to the exact distributions of slip as a function of depth and location in 1906 and 1989. Future workers should look for possible monthly to yearly increases in moderate-size earthquakes along various parts of the San Andreas fault such as those that occurred along the Lake Elsman fault.

We also examined whether the largest Lake Elsman events could have moved the 1989 mainshock closer to failure in terms of the Coulomb Failure Function (CFF). Modelled changes in CFF [13] indicate that the 1989 hypocenter was moved away from failure not closer. They took the Lake Elsman shocks to dip northeast, not southwest as we deduce. We calculated CFF for our choice of fault orientations and found a very small movement toward failure of about 0.01 MPa.

While the Lake Elsman events were large compared to other events along and near the 1989 rupture zone for many preceding decades, they were too small to have triggered significantly the 1989 mainshock months later. Thus, we focused instead in the previous paragraphs on triggering of the Lake Elsman shocks by the restoration of stress that was dropped along and in the vicinity of the great earthquake in 1906.

## 3. Discussion and Conclusions

Earthquake locations in northern California with uncertainties of a few 10s of meters provide great detail on the distributions of deformation and faults within the upper 20 km. More precise locations of preceding earthquakes to the 1989 mainshock and its aftershocks define two main zones of activity: one in which the mainshock and aftershocks occurred, and a second distinct sub-parallel feature that we call the Lake Elsman fault zone. The latter was active for shocks as large as M 5.4 15 months prior to the mainshock and was the site of a very low *b* value, which may indicate relatively high stress along it prior to 1988. In retrospect, the Lake Elsman shocks were part of a precursor that lasted a few years.

The San Andreas fault is very active long-term [14] based on pre-historic events from trenching. The aftershock zone of the Loma Prieta mainshock, which was the site of very little seismic activity prior to 1989, is taken to be a major asperity that broke in the mainshock. In contrast, the nearby Lake Elsman fault zone moves slowly long term. Hence, stress along the nearby Lake Elsman zone likely was low for long-times after mainshocks such as 1906. Inferred stress becomes high enough to trigger forerunning events only in the years before mainshocks like 1989. That pattern may continue in the future.

The two largest Lake Elsman shocks in 1988 and 1989 were of considerable concern to seismologists and State officials in California as to whether they might be precursors to a coming large earthquake. The State issued low-level warnings of 5-day durations for an M 6.5 earthquake soon after each occurred [15]. They used 5-day alarms following the work of [16] on foreshocks to earthquakes in southern California. [16] computed the probability of a larger earthquake as 6.5% ± 2.5% following an event of M ≥ 5.0. Each of the two warnings was cancelled by the State when a large shock did not occur. Once the 1989 mainshock took place, the two largest Lake Elsman events were identified as precursors with durations of 15 and 2.5 months.

A summary [17] of annual, monthly and weekly predictions for a large number of mainshocks in China of M ≥ 5.0 indicates annual predictions were the most reliable and weekly estimates the poorest. Too much attention in the United States has been given to predictions of several days and not enough to those of longer duration. The US has focused on monitoring the faults themselves that broke in past mainshocks rather than including surrounding areas and their forerunning activity [6].

Some argue that different faults broke the Loma Prieta segment of the San Andreas fault in 1906 and 1989. The dips of aftershocks in **Figure 4** and **Figure 5**, however, do not change significantly from 2 to 18 km. We do not see any evidence in the seismicity of yet a different fault that possibly broke the Loma Prieta zone in 1906. Seismicity does not give detailed information on how slip occurred in the upper 2 km that would show how surface slip connects with the top of the aftershock zone. It may well occur on several shallow faults that extend upward in a flower structure to the surface traces of the San Andreas, Sargent and other faults to the northeast of Loma Prieta peak [18]. One or more faults to the northeast must have moved during either the Quaternary or the Tertiary so as to uplift Loma Prieta peak, which was depressed in 1989. We think the steeply dipping aftershock zone (**Figure 4**, **Figure 6**) forms the plate boundary and should be considered to be the San Andreas fault. Its dip is consistent with that part of the San Andreas that broke in 1989 being rotated about 10˚ counter-clockwise with respect to that farther northwest and being the site of compressional as well as strike-slip deformation.

Key measurements of so-called slow earthquakes are now being made in many areas of the world. We do not know whether such phenomena occurred in the years to decades prior to the 1989 earthquake. A comprehensive search for repeating earthquakes did not find any repeater sequences north of the southern end of the 1989 rupture zone [19].

High felt intensities in the Monterey Bay area of coastal California indicate an earlier earthquake in June 1838 of Mw ≥ 7.2 probably ruptured the 1989 fault segment of the San Andreas fault as well as the San Francisco Peninsular zone to the northwest [20]. The 1838, 1906 and 1989 dates yield a repeat time of 75.7 ± 11.2 years (one SD). How applicable it is to the occurrence of future shocks remains debatable.

## 4. Materials, Methods and Data Availability

We use hypocenter locations from the updated high-resolution double-difference catalog for Northern California 1984-2014 [1] [2] [3]; NCAeqDD.v202112.1, http://ddrt.ldeo.columbia.edu). Digital waveforms were not available before 1984. Solutions from 1984 to 2022 were precisely located on average within 0.08 km laterally and 0.24 km vertically and most are complete down to magnitude 1.0. Bathymetry and topography are from [21].

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## Significance

Whether earthquakes might be predictable for time scales of decades to days remains debatable. We present descriptions of precursory changes in earthquake activity on a nearby sub-parallel fault deduced from hypocentral locations of high-precision 2 to 15 months before the Loma Prieta California mainshock of 1989. The zone of high displacements in the 1989 mainshock, however, was nearly devoid of forerunning activity. It is a strong region called an asperity that ruptures mainly in large shocks with forerunning events on its periphery. A separate fault zone about 3 km away at depths of 8 to 16 km was the site of abundant precursory activity with magnitudes of 1.0 to 5.4.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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