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Decadal Forecasts of Large Earthquakes along the Northern San Andreas Fault System, California: Increased Activity on Regional Creeping Faults Prior to Major and Great Events

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Abstract

The three largest earthquakes in northern California since 1849 were preceded by increased decadal activity for moderate-size shocks along surrounding nearby faults. Increased seismicity, double-difference precise locations of earthquakes since 1968, geodetic data and fault offsets for the 1906 great shock are used to re-examine the timing and locations of possible future large earthquakes. The physical mechanisms of regional faults like the Calaveras, Hayward and Sargent, which exhibit creep, differ from those of the northern San Andreas, which is currently locked and is not creeping. Much decadal forerunning activity occurred on creeping faults. Moderate-size earthquakes along those faults became more frequent as stresses in the region increased in the latter part of the cycle of stress restoration for major and great earthquakes along the San Andreas. They may be useful for decadal forecasts. Yearly to decadal forecasts, however, are based on only a few major to great events. Activity along closer faults like that in the two years prior to the 1989 Loma Prieta shock needs to be examined for possible yearly forerunning changes to large plate boundary earthquakes. Geodetic observations are needed to focus on identifying creeping faults close to the San Andreas. The distribution of moderate-size earthquakes increased significantly since 1990 along the Hayward fault but not adjacent to the San Andreas fault to the south of San Francisco compared to what took place in the decades prior to the three major historic earthquakes in the region. It is now clear from a re-examination of the 1989 mainshock that the increased level of moderate-size shocks in the one to two preceding decades occurred on nearby East Bay faults. Double-difference locations of small earthquakes provide structural information about faults in the region, especially their depths. The northern San Andreas fault is divided into several strongly coupled segments based on differences in seismicity.

Keywords

San Andreas and Hayward Faults, California, Fault Creep, Forecasts, Double-Difference Relocations

1. Introduction

The San Andreas fault system in California marks the boundary between the Pacific plate to the northwest and the North American plate to the southeast (**Figures 1-4**). Much of the San Andreas fault itself in northern California ruptured in the great earthquake of 1906. It is more active long-term than the other nearby faults of the plate boundary zone. The Hayward, Calaveras and Sargent faults are close enough that major and great shocks along the San Andreas fault, such as 1906 and 1989, influenced the stress distribution out to distances that include those three partly creeping faults.

Since the occurrence of the great shock of 1906, many authors have proposed dates of future major or great earthquakes in northern California. Most of the 1906 rupture zone has not rebroken in a great or major earthquake as of early 2024. It is a large seismic gap. Most of it is locked and is currently building up stresses that were reduced in 1906. The 1989 mainshock seems to be the first in a series of large earthquakes that will break the rest of the 1906 rupture zone in the next decades or longer.

Much work on earthquake prediction has involved short-term forecasts of several days. I focus instead on decadal changes prior to past great and major shocks in northern California. I go on to examine whether the occurrence of moderate-size events since 1990 is indicative or not of future large earthquakes. The northern Hayward fault may be closest to rupturing in a major shock.

Many seismologists have assumed incorrectly that forerunning shocks have and will occur along the same fault as a coming major or great earthquake. Many moderate-size forerunning events, however, took place decades ahead of time on surrounding regional faults, what has been called a donut pattern [1] [2] [3]. For example, those and other authors showed that the great and damaging Tokyo earthquake of 1923 exhibited a pattern of decadal pre-shocks surrounding the coming rupture zone. In contrast, forerunning decadal earthquakes in northern California occur along creeping faults themselves. This may be occurring today along the northern Hayward fault.

A similar surrounding pattern (**Figure 1**) was described by [4] for the few decades preceding the great 1906 and the two major historic earthquakes in northern California of 1868 and 1989. A conclusion of this paper is that a similar pattern of moderate-size earthquakes exists today surrounding the San Andreas fault between San Francisco and the rupture zone of the 1989 Loma Prieta mainshock.

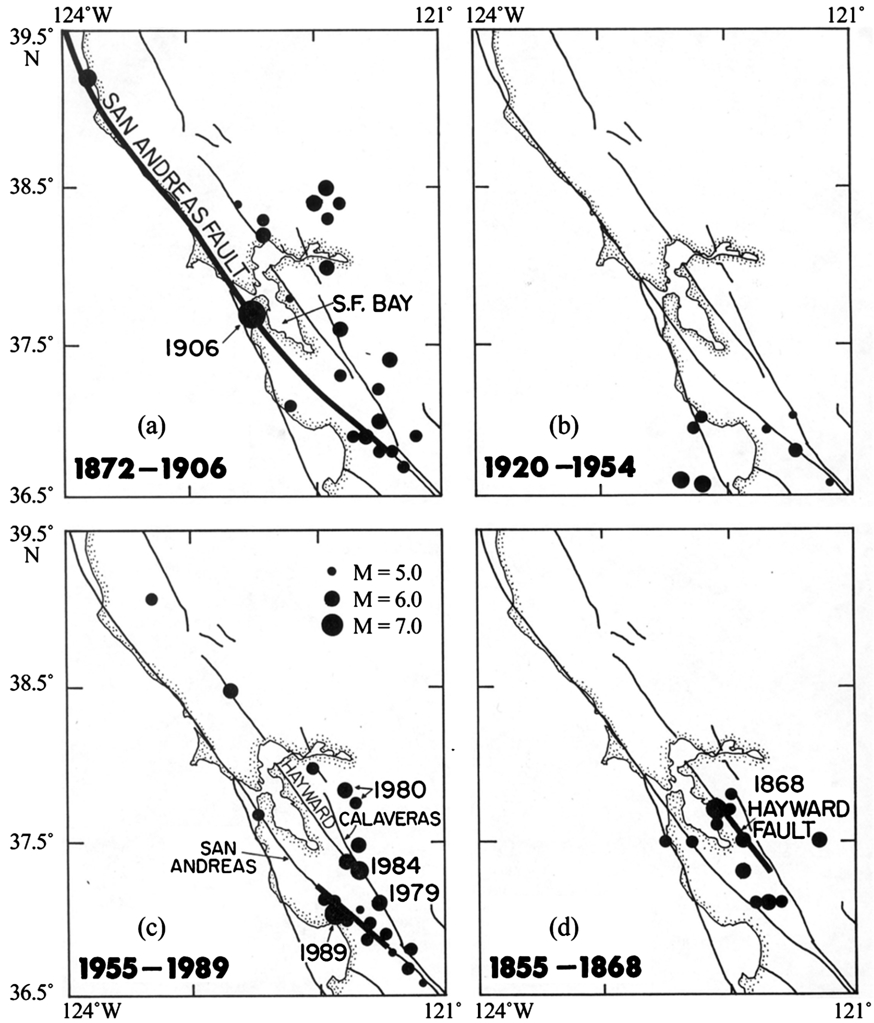

Figure 1. Distribution of earthquakes of magnitude 5 and larger in the greater San Francisco Bay area for four-time intervals (reprinted from [4]). Major faults are shown. Epicenters of 1906, 1989 and 1868 earthquakes are indicated by large solid circles. Arrows in sub-figure (a) denote sense of strike-slip motion along the San Andreas fault. Dashes enclose events taken to be within three decadal precursory areas. Activity was low in the forerunning area of the 1989 shock (dashes) in *b* from 1920 to 1954 as well as to the northwest of San Francisco. Activity before the 1989 mainshock is described later.

I show that seismic moment release on faults surrounding those sections of the San Andreas fault has not been as strong from 1990 to early 2024 as occurred before the 1989 mainshock.

Much remains to be done in examining changes in seismicity, detecting fault creep and understanding the physical bases of fault and earthquake behavior. When a major or great earthquake occurs in the study area, it likely will cause much damage and perhaps significant loss of life. The region examined here includes areas of high population and industrial activity like San Francisco, Silicon Valley and the Hayward fault.

Figure 2 shows abbreviations and names of faults and places examined in the paper.

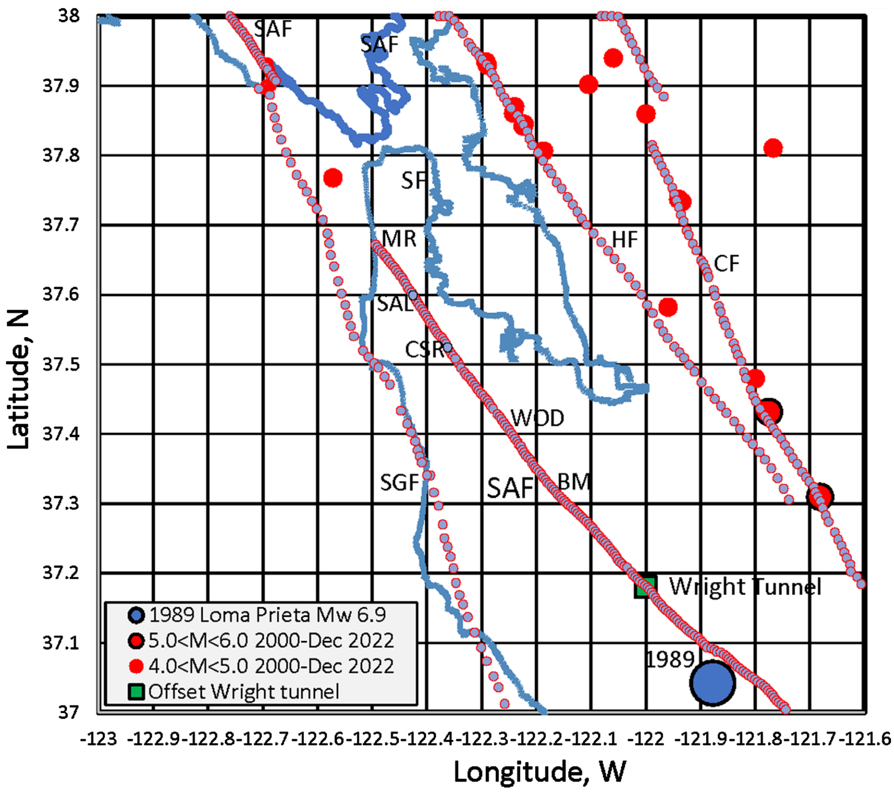

Figure 2. Active faults and place names used in the paper. Fault abbreviations: SAF San Andreas, HF Hayward, CF Calaveras and SGF San Gregorio. I divide the northern San Andreas fault into several strongly coupled segments. The San Andreas fault enters the Pacific Ocean at Mussel Rock, MR, and returns on land north of SF, San Francisco. SAL San Andreas Lake, CRS Crystal Springs Reservoir, BM Black mountain, WOD Woodside. Woodside is near Menlo Park.

I use precise locations of small to large shocks, so-called double-difference solutions, with precisions of about 30 m [5] [6]. These improved locations permit the structural geology of active faults to be examined in time and in three dimensions, especially depth. This is a major improvement compared to using just the mapped distribution of active faults at or near the earth's surface.

The distribution of small shocks of local magnitude, M_L 1 to 4 is illustrated in **Figure 3**. The numbers and locations of double-difference locations differ greatly along and near the northern San Andreas fault. They are numerous between offshore San Francisco and Crystal Springs Reservoir (CSR), few between the Reservoir and Woodside (WOD). Many epicenters were located on two sides of the San Andreas farther southeast between Woodside and Wright tunnel (WT) where few occurred along the San Andreas itself. The 1989 Loma Prieta earthquake of magnitude Mw 6.9 ruptured the main fault at the southern end of **Figure 3**. I update findings by [4] [7] and others. Thirty four years have now passed since the 1989 event.

Figure 4 illustrates a donut pattern of moderate-size earthquakes (magnitudes 4 to 6) surrounding the San Andreas fault between San Francisco and the northwestern end of the 1989 rupture zone. Note the activity on regional faults

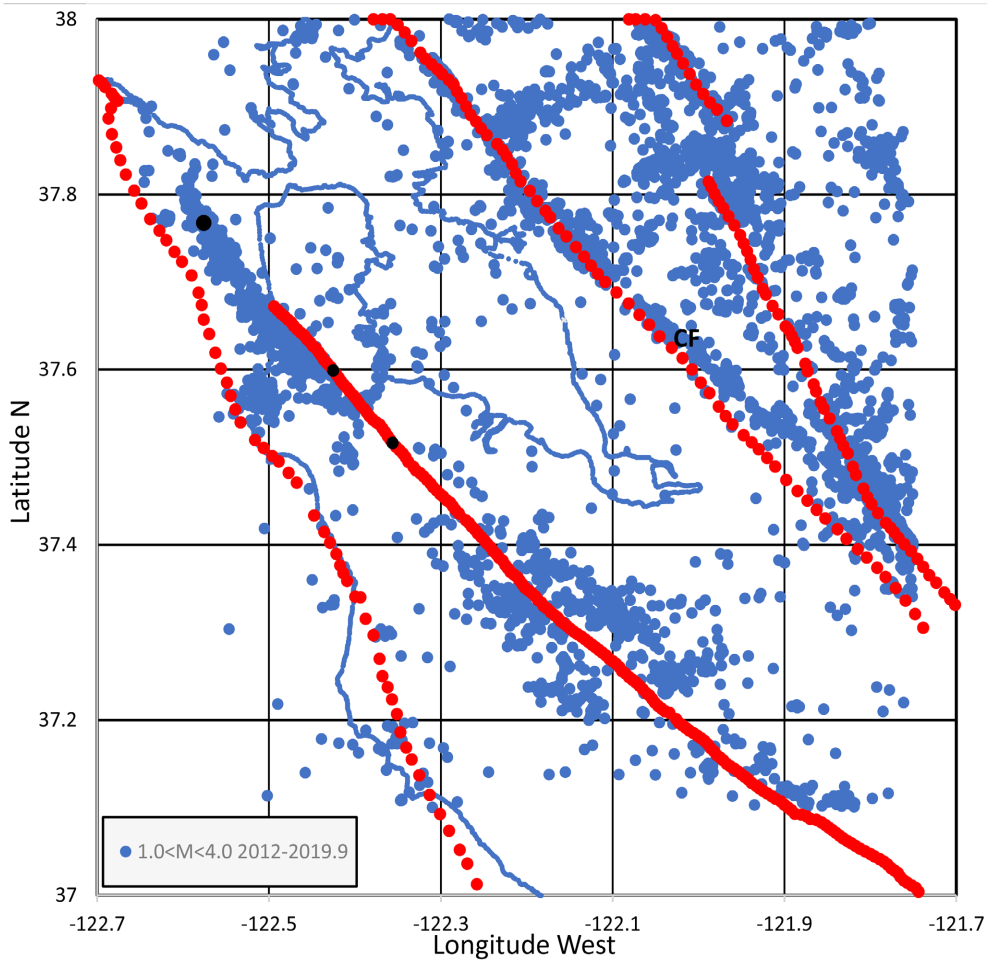

Figure 3. Blue dots indicate double-difference locations of small earthquakes in the study area between 2012 and 2019.9 of seismic magnitude, M_L 1.0 to 4.0. Red lines depict major active faults from maps of U.S. Geological Survey.

surrounding the segments of the San Andreas that last broke in 1906 and the near lack of moderate-size activity along the San Andreas fault between San Francisco, SF, and the 1989 aftershocks near the bottom. Similar patterns occurred before many large mainshocks elsewhere [1] [8] [9]. Many events in such Mogi donuts patterns occur on surrounding faults but not necessarily on all sides of the rupture zones of coming major earthquakes.

2. Decadal Patterns of Moderate-Size Earthquakes Surrounding the Rupture Zones of Major and Great Historic Shocks

I take great to be earthquakes of very long-period seismic magnitudes $Mw \geq 7.8$ and major as shocks of $6.7 < Mw < 7.8$. Events are described as moderate for $4 < M < 6.7$ and small for $1 < M_L < 4$. The very-long period magnitude Mw is available for many shocks larger than Mw 5 [10]. Double-difference precise locations and most local magnitudes M_L are reported by [5] [6]; they are available at Northern California Earthquake Data Center, UC Berkeley Seismological Laboratory.

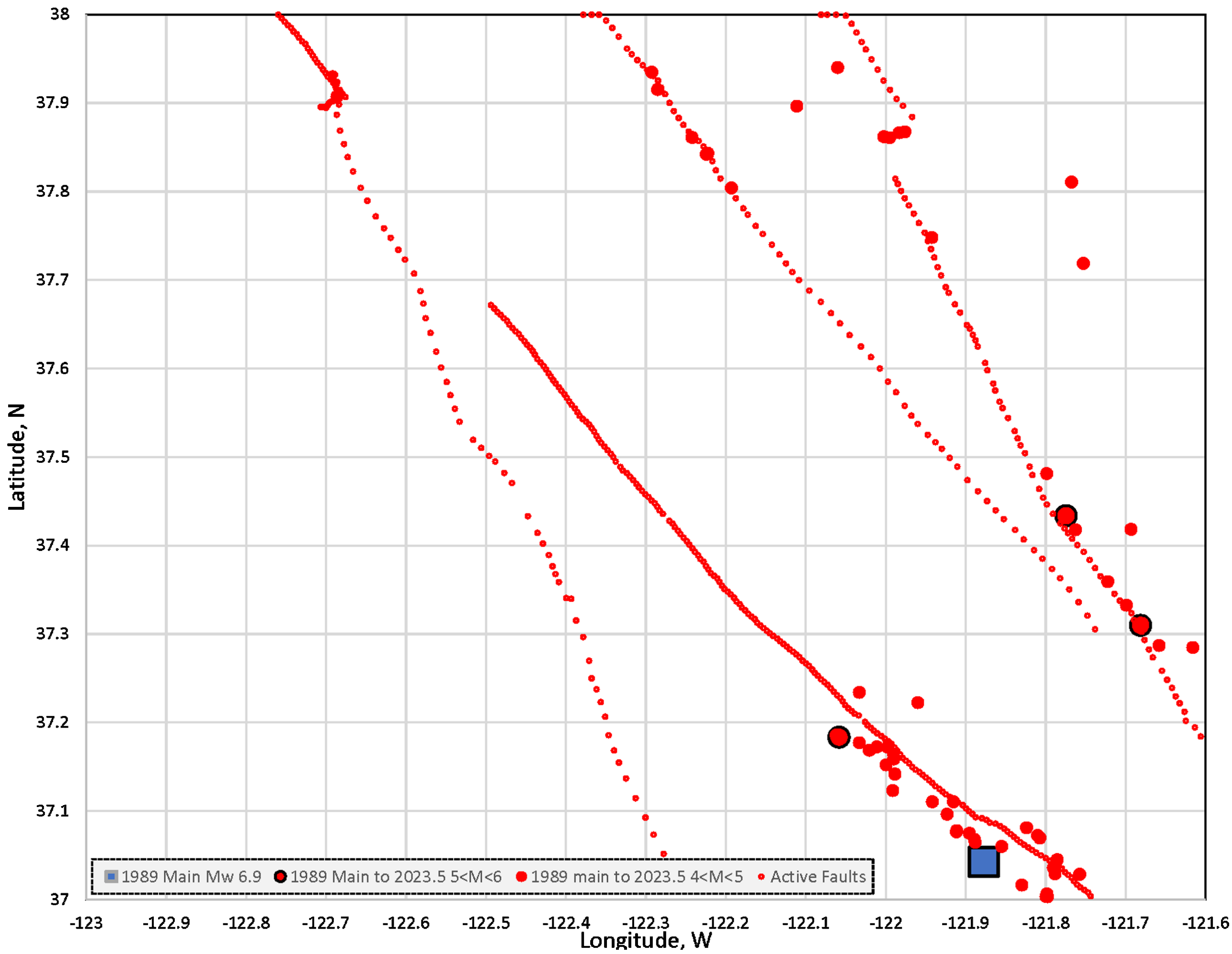

Figure 4. Earthquakes of magnitude ≥ 4 in the study area between the 1989 Loma Prieta main shock and 2024.0. Red lines show major active faults.

Dataset. doi:10.7932/NCEDC. Similar solutions were recently extended back to 1966 for the greater San Francisco Bay area by [5] [6].

In 1990 [4] studied moderate and small earthquakes in the decades preceding the three largest shocks in northern California since 1860—the great and damaging 1906 event of Mw 7.9, the Hayward fault earthquake of 1868 of Mw 6.8 and the 1989 Loma Prieta shock of Mw 6.9. Greater details, especially on forerunning phenomena and their validity as long-term precursors, can be found in [4] and [11]. This paper extends their work for more than the three decades since 1989.

The number of moderate-size earthquakes was much higher from 1872 until the 1906 great shock than it was from 1920 to 1954 (**Figure 1**). By 1912 most activity had died down after the 1906 event. [12] noted the re-emergence of events of magnitude M 5.0 to 5.9 from 1955 to 1980 after a long quiescence. He concluded that the region was entering a more active stage in which shocks of M 6 and perhaps M 7 could be expected in the decades before an eventual great earthquake. The region of increased activity from 1955 to 1982 was not as large as that preceding the 1906 shock but instead was concentrated to the southeast and east of San Francisco (**Figure 1**) [13]. This suggested that the next major earthquake would not be as large or its rupture zone as long as that of 1906. Those conclusions were correct when the 1989 event took place. It may be the first major earthquake of one or more that will eventually fill in the other fault segments that were last broken in 1906.

Most shocks of M ≥ 5.0 in the greater Bay area before 1906, the largest of which was Mw 6.4, occurred well away from the surface rupture zone of the 1906 earthquake (**Figure 1**). A similar pattern occurred before the major event of 1989 and the 1948 earthquake of M 6.5 in southern California. Data are more uncertain before the shock of 1868 on the Hayward fault since they extended back only to 1855.

Several groups were aware that two earthquakes of magnitude larger than 5 occurred in 1988 and 1989 along the southeastern part of the 1906 rupture zone near Loma Prieta mountain (**Figures 3-5**). Events of that size had not taken place along that segment of the San Andreas fault for many decades. The State Geologist of California issued statements after each that a larger shock might occur within five days. When it did not occur, the State discontinued their statements.

Those two quakes beneath Lake Elsman occurred within two years of the Loma Prieta earthquake of 1989 of Mw 6.9. [14] examined shocks as small as magnitude 1.0 before and after the 1989 earthquake (**Figure 5**).

All of the events shown were precise double-difference solutions. The two shocks of M > 5 and several other previous events beneath Lake Elsman (in red) occurred on what [14] called the Lake Elsman fault. It likely is part of the Sargent fault zone (**Figure 6**). Its dip was nearly the same as that defined by small aftershocks of the main 1989 earthquake (gray circles) but displaced from the latter by about 3 km and located at depths of 10 to 16 km. In retrospect, [14] regarded the largest red events as one to two-year forerunners to the 1989 mainshock.

I propose that seismologists search frequently for similar future activity on faults close to but not on parts of the San Andreas fault between San Francisco and the 1989 rupture zone for possible sites of forerunning activity to future major or great events on the San Andreas itself. Many such nearby faults are described later. Whether they are sites of small events and/or fault creep is largely yet to be explored.

I re-examined shocks of magnitude ≥ 4 in the region surrounding the main 1989 earthquakes (**Figure 6**) going back to 1966. Those events occurred along the Calaveras, Sargent or Lake Elsman faults to the north and northeast of the 1989 rupture zone. The largest of Mw 6.1 occurred in 1984 along the Calaveras fault. None of them took place within the 1 and 3 m displacement contours computed by [15]. **Figure 6** is one of the best documented cases of moderate-size earthquakes on surrounding regional faults preceding a large shock. More preceding regional activity from October 1979 to the 1989 mainshock occurred than in either the three 11-year comparable times from 1990.5 to 2023.5

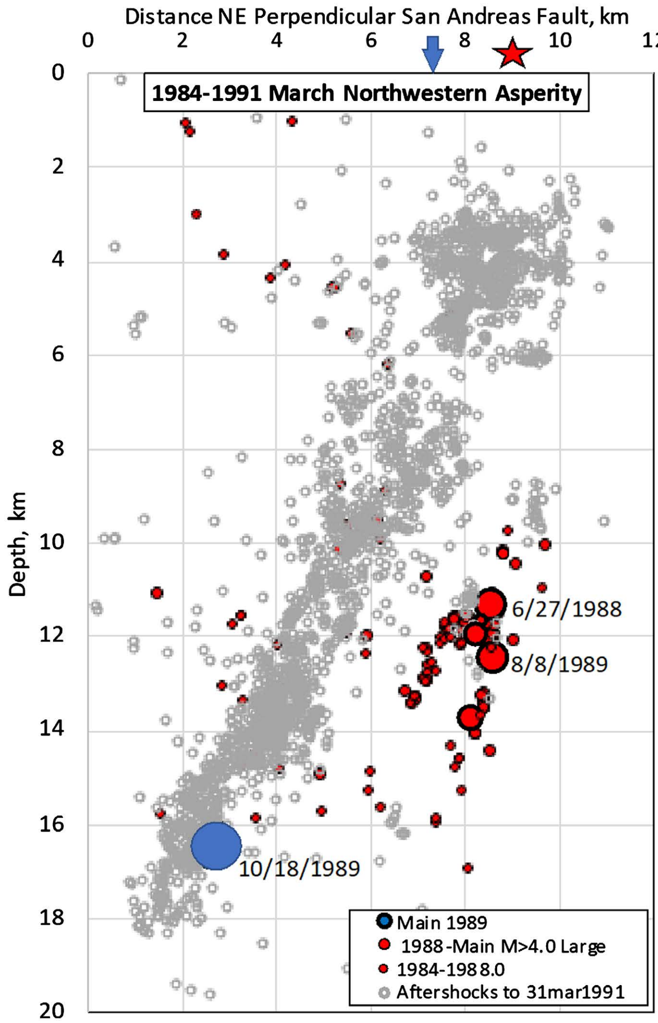

Figure 5. Earthquakes of magnitude ≥ 1.0 as a function of depth and distance perpendicular to the San Andreas fault from 1984 to March 1991 (reprinted from [14]). Distances from the San Andreas were calculated from a straight line fit for the study area; they do not reflect changes along it. Large blue circle denotes the hypocenter of the 1989 mainshock. Large blue arrow at the top marks surface trace of the SAF. Red star denotes Loma Prieta Mountain.

or between 1920 and 1954 (**Figure 1**).

Prior to the 1989 mainshock, it was not possible to conclude that the increased activity on East Bay faults was a forerunner to either the 1989 mainshock or a possible coming large shock on the Calaveras fault. [16] discussed this soon after the 1989 shock. They said, "If activity [for M > 5.5 events] remains high after a few years, the possibility remains that this section of the Calaveras fault will rupture" in a large shock. By early 2024 it was clear that activity on the southern Calaveras dropped after the 1989 event and did not change significantly for the next 34 years. Thus, the activity in the 10 to 20 years prior to 1989 was, in fact, a forerunner to the 1989 mainshock. This is very important since regional faults as well as the San Andreas should be searched for preceding decadal activity.

[16] showed that activity increased in the years after all four M > 5.5 shocks

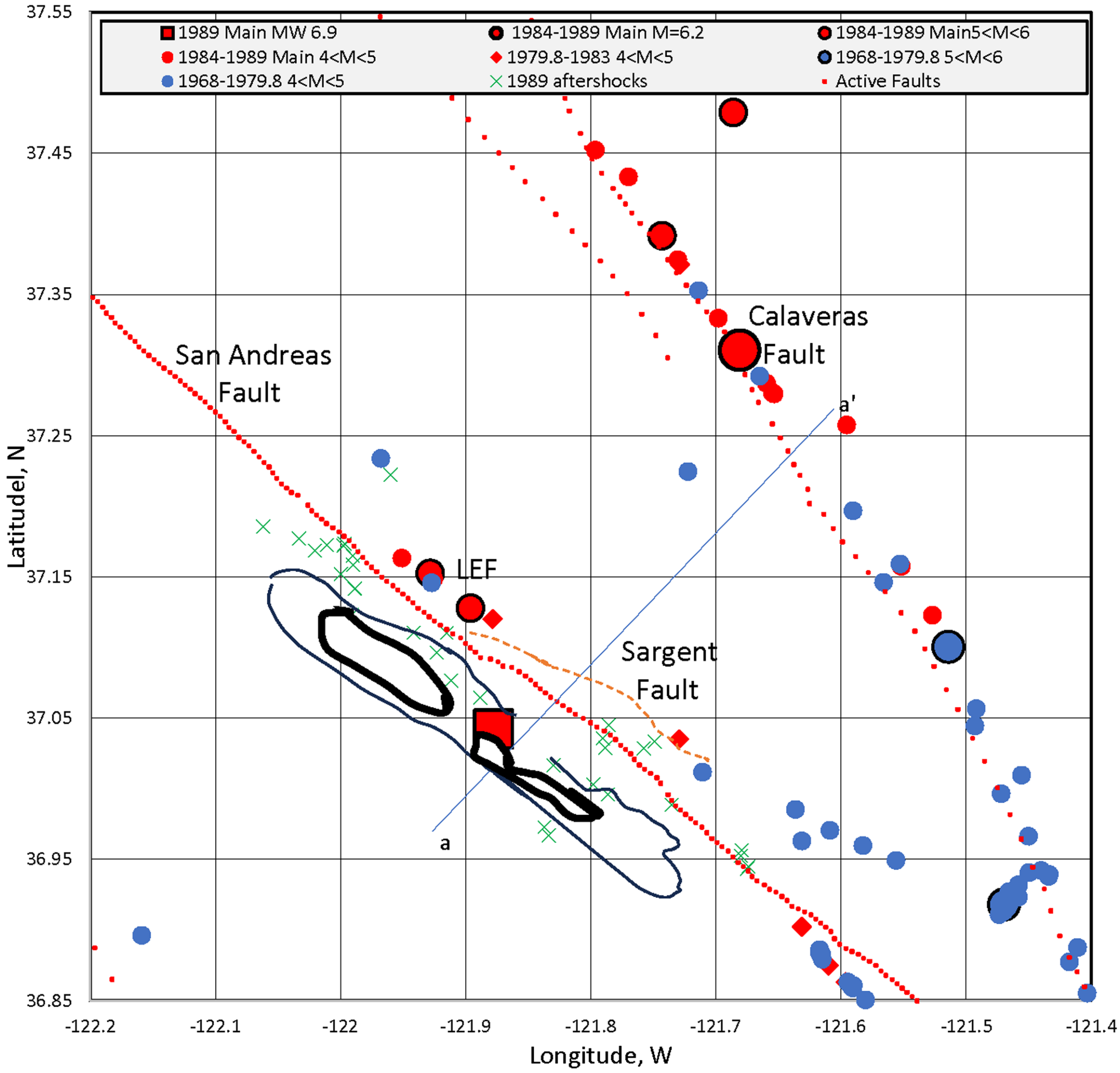

Figure 6. Double-difference locations of earthquakes of magnitude, M 4.0 and larger from 1966 until the 1989 mainshock as well as its larger aftershocks. Heavy and light lines enclose computed displacements for 1989 of 3 and 1 m from [15]. Red square indicates epicenter of 1989 mainshock. Activity near line a-a' is described later. LEF is Lake Elsman fault and its larger forerunning events.

on the southern Calaveras fault prior to 1989. They say, "This increased activity is the signal we use as the basis of the forecast of a coming larger earthquake." They found activity decreased after several similar big events in southern California that were not followed by larger shocks. Identifying similar patterns in the year to a decade after a big earthquake of M > 5.5 is important for decadal and shorter-term forecasting.

The San Andreas fault differs to the southeast of the 1989 rupture zone in that it and adjacent faults creep [17] and were the sites of preceding seismic activity to the 1989 mainshock (**Figure 6**). The Sargent fault was particularly active from 1968 until 1973 as well as in the comparable 11-year period from 1979.8 until the 1989 mainshock.

Forerunning decadal seismic activity occurred before all three large and great historic earthquakes in the Bay Area but little took place during other time periods. In that sense they too can be considered decadal forecasts. The scientific community needs to examine other well-monitored strike slip faults and their regional decadal activity. A number of continental transforms are multi-branched whereas many in oceans are not.

3. Activity along and near the Northern Hayward Fault Since 1989

In contrast to the locations of events preceding the 1989 shock, activity in the following 34 years occurred along the northern Hayward and Calaveras faults (Figure 7). Some of the activity in the southeastern part of Figure 7 may still be aftershocks of the 1989 event.

Seven shocks of 4.0 < M < 5.0 occurred from 2001.5 to 2024.0 along the northern Hayward fault itself (Figure 7). That fault segment is just to the northwest of the 1868 rupture zone (Figure 1). It may not have ruptured since 1776 and not in 1836 as some proposed [18]. None of the events since 1989 along the northwestern Hayward were larger than magnitude 4.6. It and fault creep are described by

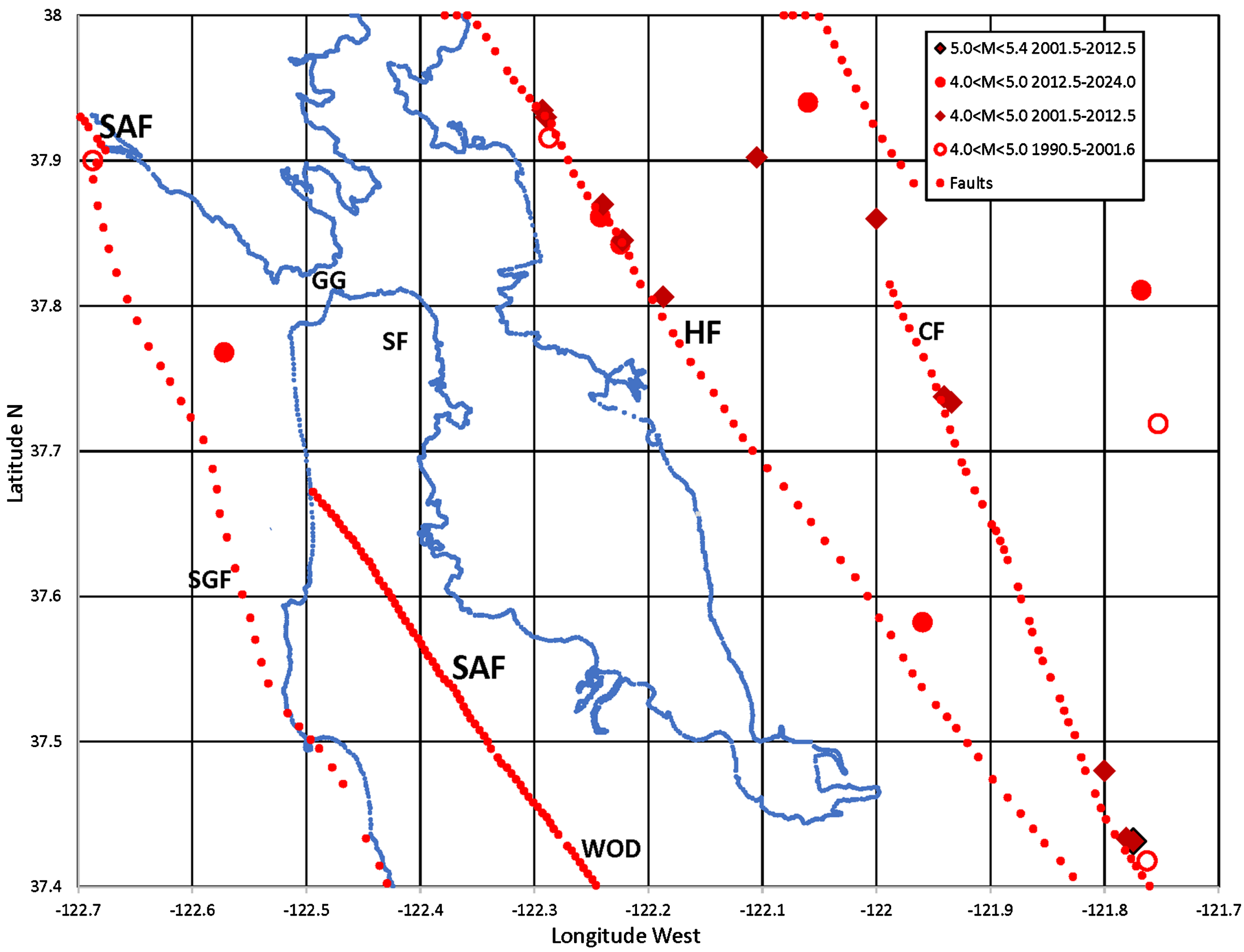

Figure 7. Earthquakes in the vicinity of the Hayward fault from 1990.5 to 2024.0.

[19]. It is only about 20 km long (30 km if extended to the northwestern limit of the fault). If it broke by itself, it could be of about 6.3 ≤ Mw ≤ 6.7. Such an event could be very destructive in the East Bay area. The nearby 1868 shock was known as the "great San Francisco earthquake" prior to 1906.

Some activity during the same period occurred to its east along the Calaveras and nearby faults. Whether the earthquake of August 14, 2014 (Mw 6.1) to the northwest may be part of a decadal precursory sequence is unknown. If two shocks of M > 4 off the coast of San Francisco might be part of a decadal forerunning sequence is problematic.

Only two of the eight shocks in **Figure 7** occurred in the last period 2012.5 to 2024.0.

The sequence may constitute a false alarm of a coming earthquake. It cannot be ruled out, however, that a future larger event could re-rupture part of the 1868 fault segment as well as the Hayward fault as far as its northwestern end. Events in **Figure 7** along the northern Hayward fault itself occurred at depths of 5 to 16 km similar to aftershocks of the 1989 mainshock. [20] indicated that creep on the Hayward fault increased and that on the nearby Calaveras fault decreased since 2010. Creep often occurs at shallow depth along each of the two. A large event could rupture locked parts of the Hayward fault at depth. Careful attention needs to be given to the Hayward fault since population on and near it is high. It also needs to be examined whether these events instead could be part of a decadal forerunner to a future large event along the San Andreas fault near San Francisco.

4. Earthquakes along Regional Faults outside of Historic Rupture Zones and Implications for Future Major and Great Shocks

I follow Reid [21] in concluding that earthquakes result from the buildup of strain and stress in the vicinity of faults like the San Andreas. They are released mainly at the times of large earthquakes not only along the fault itself but also in regions tens of kilometers wide surrounding those shocks. I take advantage of the existence of multi-branched active faults to search along them for forerunning activity prior to major and great San Andreas events.

When did the pattern of surrounding shocks develop before 1989 and did it change with time? What has happened since 1989? I examine three 11-year periods from 1990.5 to 2023.5. Those data, of course, were not accessible soon after the 1989 mainshock. Activity levels may bear on whether or not large earthquakes may be expected in the future.

[4] showed that seismic moment release, Mo, accelerated prior to those three historic large earthquakes in the study area (**Figure 8**). They calculated seismic moments from $\log_{10}Mo = 1.5M + 9.0$. The exponential fits to the moment sums, τ, is dominated by the larger forerunning events. τ was 11 and 9 years for the periods prior to 1989 and 1906. The time constant of 3.6 years prior to 1868 is not as well determined since it was based on a preceding shorter interval, 1855-1868.

Figures 9-11 depict three successive 11-year periods for the study area starting

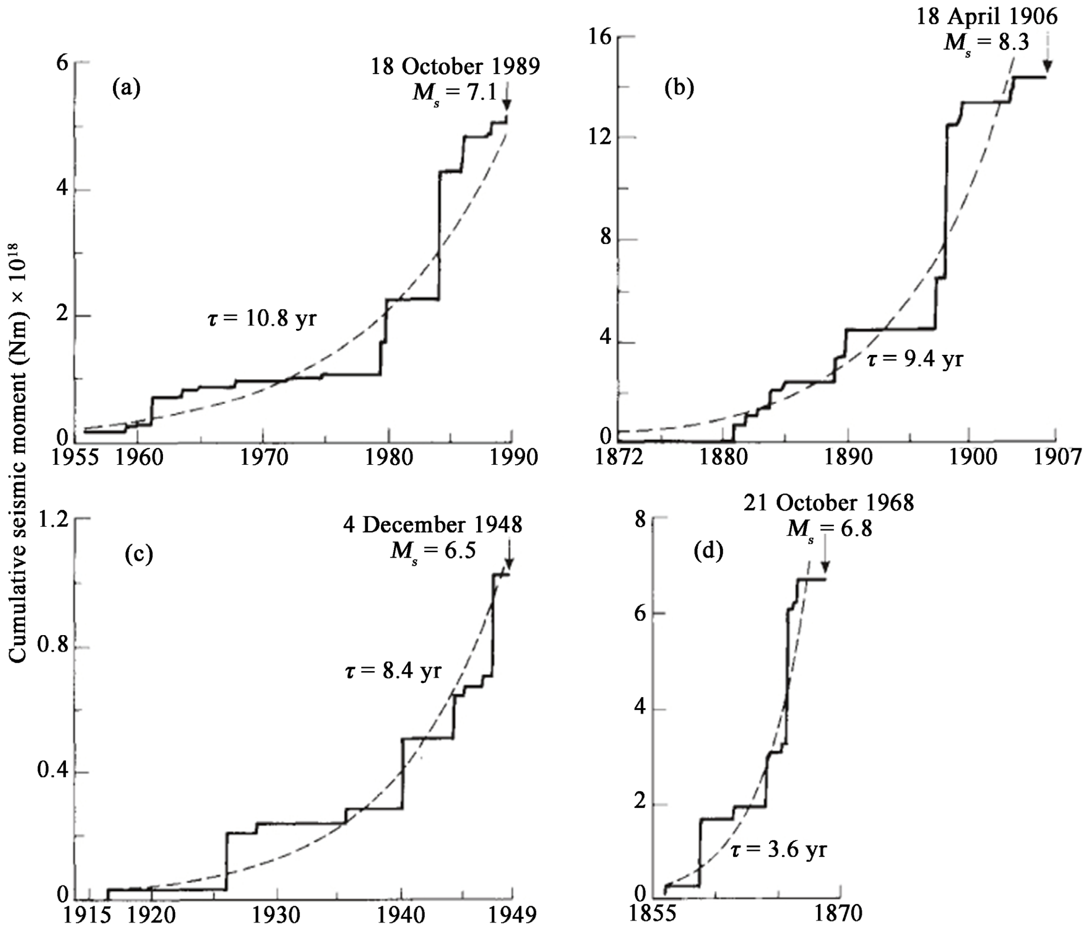

Figure 8. Cumulative seismic moment ∑Mo summed for earthquakes of M ≥ 5.0 as a function of time for three large shocks in San Francisco Bay area and for the 1948 Desert Hot Springs shock in southern California (reprinted from [4]). Dashed lines are best-fitting exponential increases with time where τ is rise time.

in 1990.5, 2001.5 and 2012.5. The 1990.5 period was not started until several months after the 1989 mainshock to avoid most aftershocks. I compare the number of events of magnitudes M ≥ 4 and ≥5 with one another in time as well as with those in **Figure 6** prior to the 1989 mainshock.

Forerunning activity in each 11-year period after 1990.5 was concentrated on East Bay faults and not the San Andreas fault itself. Nevertheless, activity was relatively low in all three recent 11-year periods compared to that prior the Loma Prieta earthquake of 1989. Only two events of M 5.0 and 5.4 occurred in those 33 years, fewer and smaller than those preceding the 1989 event. Activity dropped in the decade after the 1989 mainshock.

Large numbers of forerunning events before 1989 occurred on faults other than the San Andreas, which was the rupture zone of the mainshock. The largest prior event of Mw 6.1 in 1984 was located about 25 km from the rupture zone of the main 1989 earthquake. Seismicity in the 11-year period before the 1989 event was concentrated on faults to the east and northeast of it (**Figure 6**). Higher prior activity, lower after 1989 and their prior nearby locations are three strong reasons for thinking they were decadal forerunners and not a result of chance occurrence.

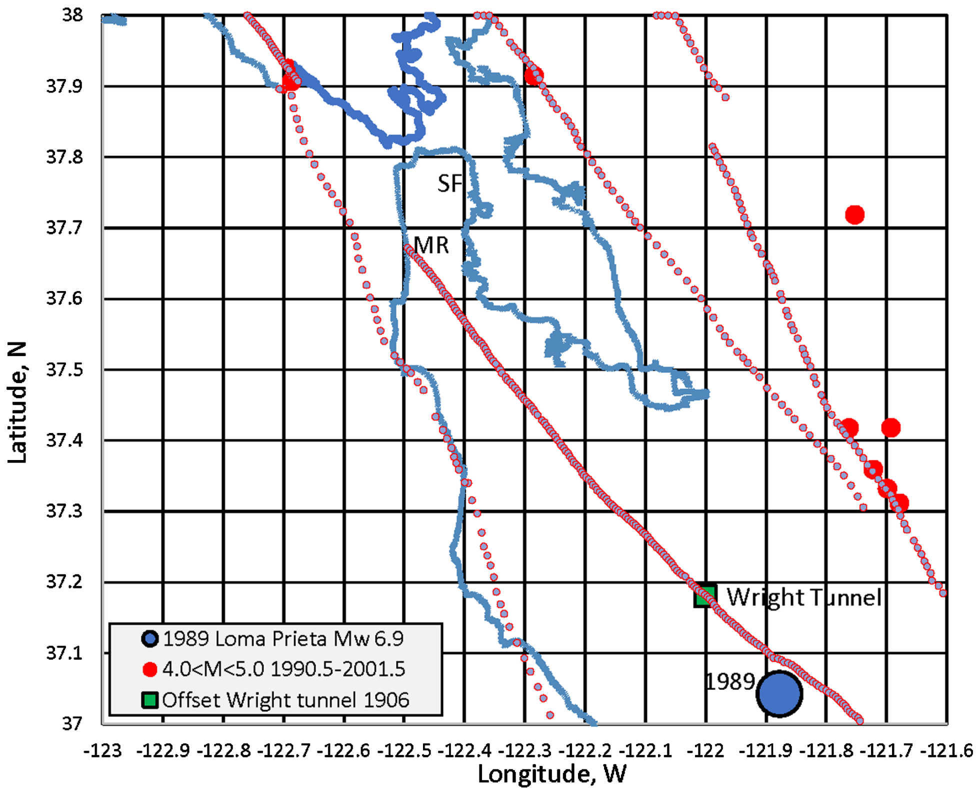

Figure 9. Distribution of shocks of M ≥ 4.0 in the greater San Francisco Bay area from 1990.5 to 2001.5.

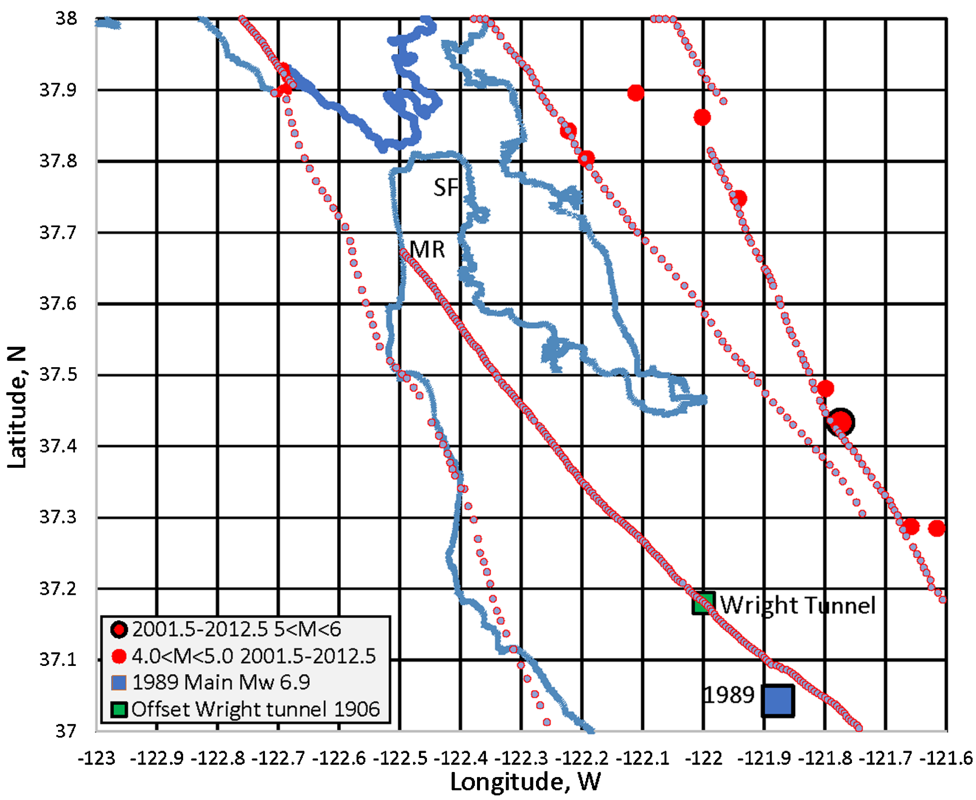

Figure 10. Events of M ≥ 4.0 in the greater San Francisco Bay area from 2001.5.to 2012.5.

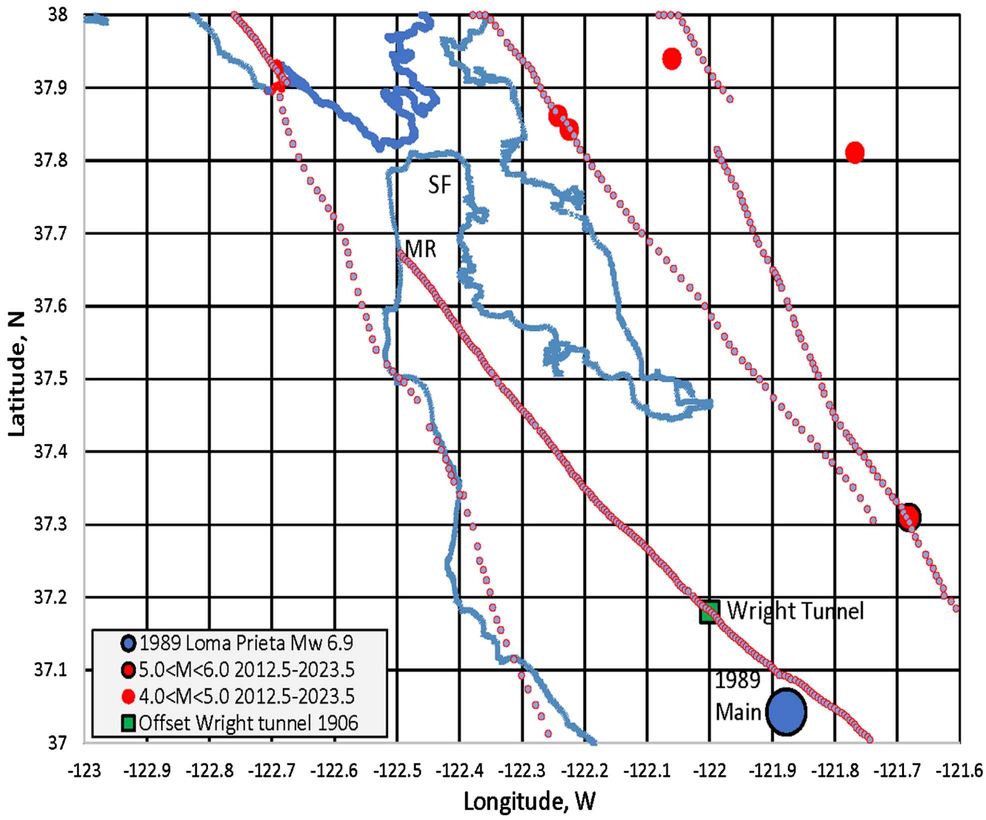

Figure 11. Shocks of M ≥ 4.0 in the greater San Francisco Bay area from 2012.5 to 2024.0.

5. Precise Distribution of Small Earthquakes Define Segments of Northern San Andreas Fault

Figures 6-12 to 16 depict the distribution of precisely located earthquakes for sub-regions of the study area between San Francisco and the 1989 rupture zone. Small shocks of local magnitude $M_L < 4$ are used to better define the distribution of active faults but not to depict forerunning behavior. [22] find, "Most of the seismicity in the San Andreas fault system…is resolved at levels of (completeness of Mc > 1.6."

Epicenters between Wright tunnel and Woodside (**Figure 12**) scatter within about 5-km either side of the surface trace of the San Andreas fault with few along the fault itself. **Figure 13** shows hypocenters as a function of depth and distance perpendicular to the fault. Activity was mostly concentrated in two zones: those on either side of the San Andreas and the others near East Bay faults.

[23] described a major asperity near Black mountain (**Figure 12**) where the San Andreas fault changes strike such that a component of compression takes place to its southeast. The asperity consists of the Franciscan complex and marks a change in the amount of slip in 1906 from larger northwest to smaller southeast.

[7] found a similar change in tectonism and earthquake mechanisms between the two zones. They state "The southern one is characterized by thrust- and reverse-faulting focal mechanisms… A 1- to 2-km-wide vertical zone beneath the surface trace of the San Andreas is characterized by its almost complete lack of

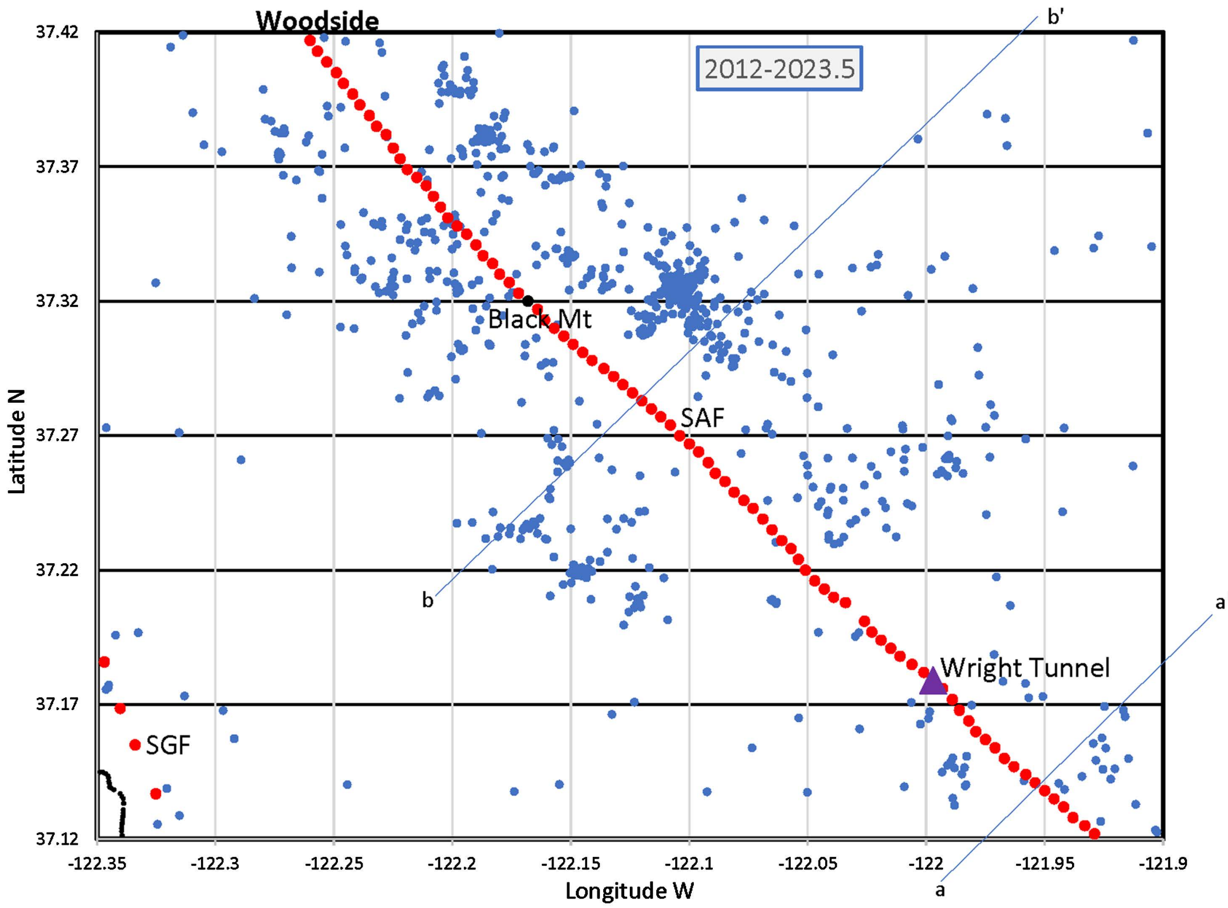

Figure 12. Epicenters of earthquakes of M > 1.0 from 2012 to 2024. between Woodside and Wright tunnel. Data along Line a-a' are shown in Figure 5.

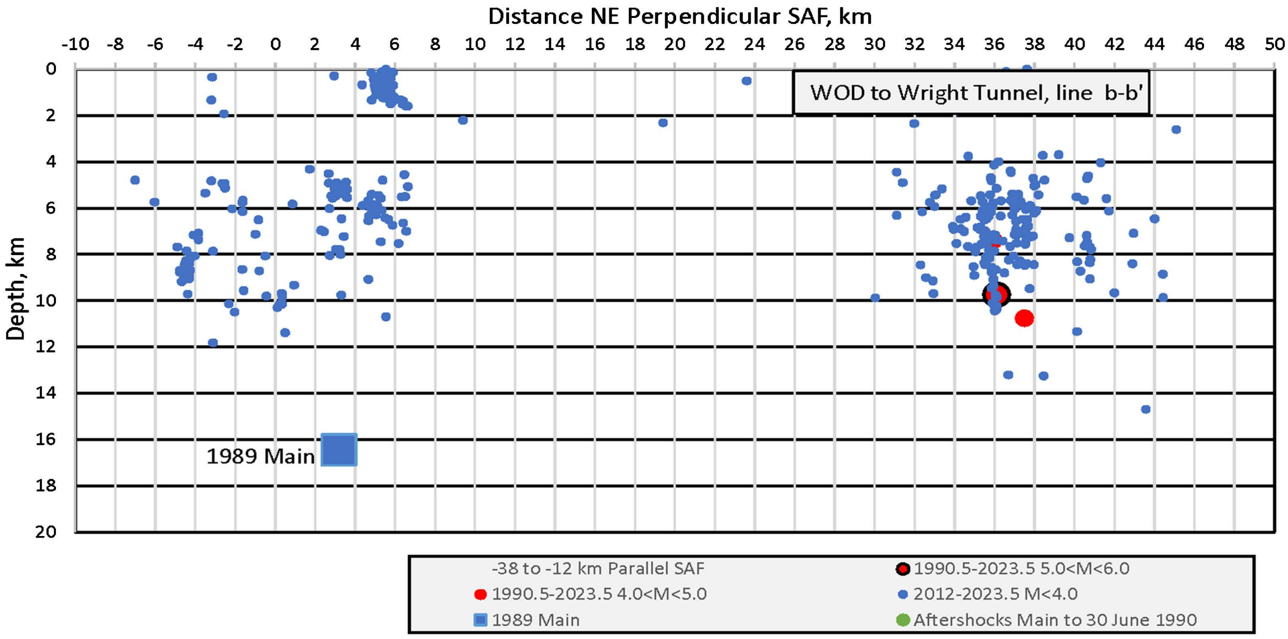

Figure 13. Hypocenters of earthquakes of M > 1.0 from 1990.5 to 2024.0 between Woodside (WOD) and Wright tunnel (WT) centered along line b-b' of Figure 12.

seismicity. The compressional deformation is consistent with the young, high topography of the Santa Cruz Mountains/Coast Ranges as the San Andreas fault makes a broad restraining left bend (−10˚) through the southernmost peninsula. A zone of seismic quiescence, 15 km long, separates this compressional zone to the south from a zone of combined normal-faulting and strike-slip faulting focal mechanism (including a M_L = 5.3 earthquake in 1957) on the northernmost peninsula and offshore on the Golden Gate platform. [7]"

Because only small shocks occurred along the part of the San Andreas fault between Woodside and Wright tunnel since 1990, little can be ascertained about a possible component of compression, which is seen in **Figure 5** for the 1989 rupture zone farther southeast. Small earthquakes do not indicate a well-defined steeply dipping rupture zone as in the 1989 segment. The depths of small shocks in the vicinity of the San Andreas fault extend only to 12 km (**Figure 12**). Whether a future large event could extend deeper as in 1989 is not known.

Figure 14 and **Figure 15** show results for segment c-c' between Woodside

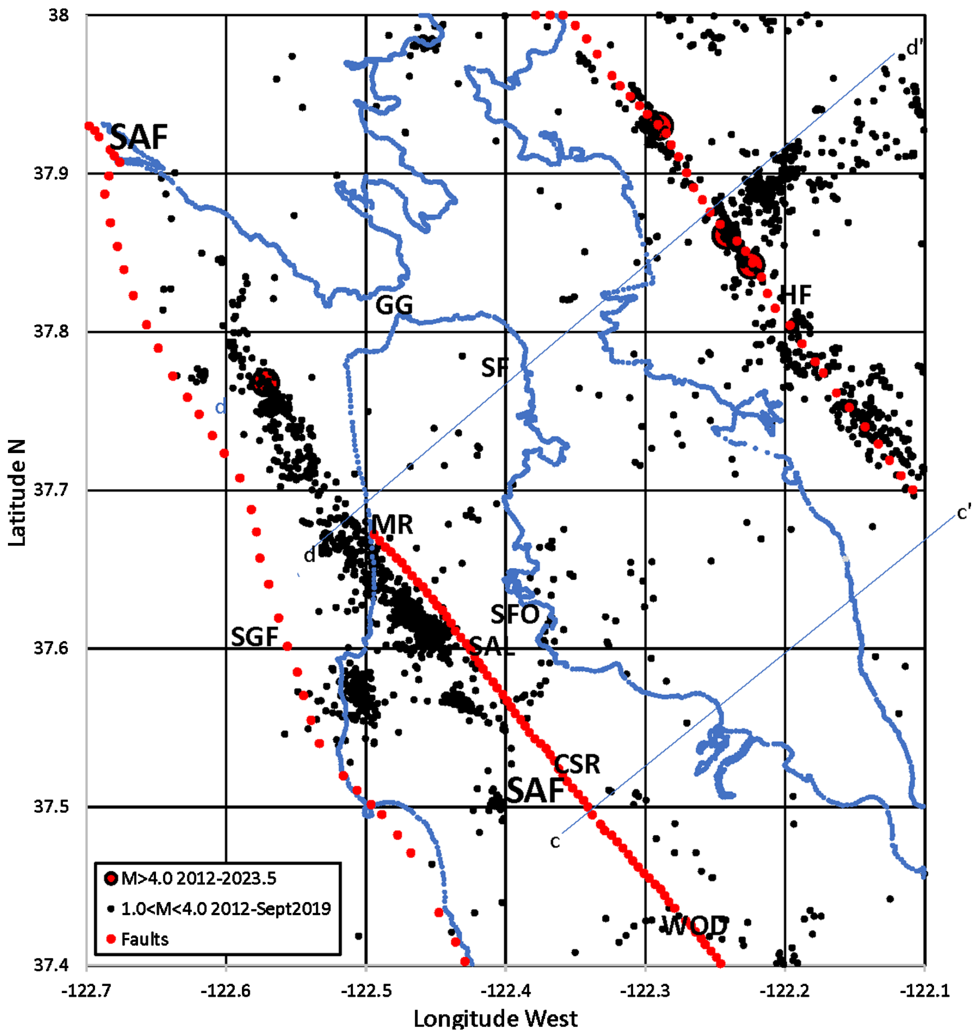

Figure 14. Epicenters of earthquakes of M > 1.0 from 2012 to 2024.0 between the Golden Gate (GG), San Francisco (SF) and Woodside (WOD).

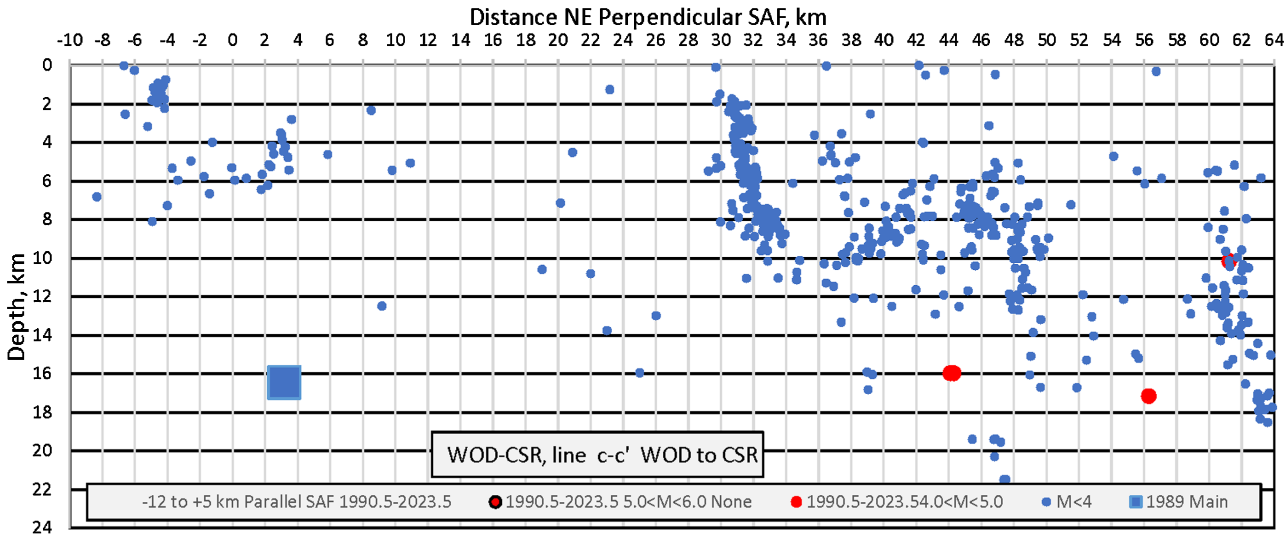

Figure 15. Hypocenters of earthquakes of M > 1.0 from 1990.5 to 2024.0 between Woodside (WOD) and Crystal Springs reservoir (CSR) centered along line c-c' of **Figure 14**.

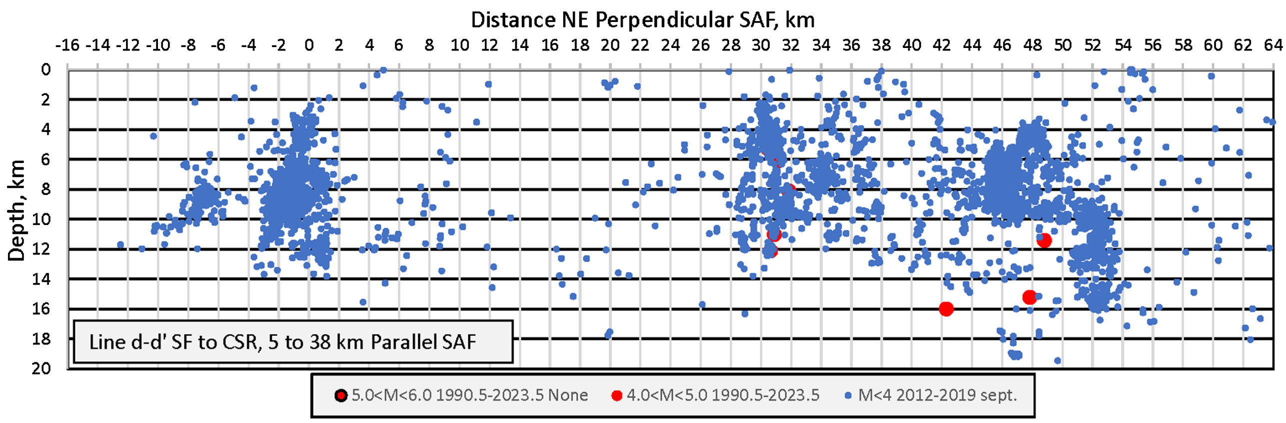

Figure 16. Hypocenters of earthquakes of M > 1.0 from 1990.5 to 2024 between Crystal Springs reservoir and the Golden Gate centered about line d-d' of **Figure 14**.

(WOD) and Crystal Springs reservoir (CSR). The segment is characterized by very few small events compared to sections of the San Andreas to the northwest and southeast. They are restricted to depths shallower than 8 km.

More activity within 5 km of the San Andreas fault occurred between Crystal Springs Reservoir, San Francisco and the Golden Gate in Figure 14 and Figure 16 (line d-d'). That segment clearly differs from those farther southeast. Many of its focal mechanisms have a component of normal faulting. Most of the events in Figure 14 and Figure 16 occurred just to the southwest of the mapped surface trace of the San Andreas fault by USGS between Mussel Rock (MR) and San Andreas Lake (SAL). [7] found a similar distribution. That zone of small events does not coincide with the fault that broke at the surface in 1906 even although it is nearby. [24] report a number of shorter faults that maybe the loci of the small shocks in Figure 14 and Figure 16.

A zone of small shocks directly west of the Golden Gate, GG, in Figure 16 extends northeasterly, indicating a component of crustal extension. It is not long enough by itself, however, to generate a major earthquake. The San Andreas resumes it northwesterly strike to its northwest and merges with the San Gregorio fault at the northwestern end of the study area.

A number of smaller faults in these figures near the San Andreas fault are active based on the distribution of small earthquakes. They need to be examined regularly to ascertain if moderate-size activity initiates along them that may be similar to that seen along the Lake Elsman fault in the two years prior to the 1989 mainshock.

6. Displacements and Stress Changes during the 1906 Earthquake-Implications for Recurrence of Future Major and Great Shocks along the San Andreas Fault Itself

A major shock in 1838 along the San Andrea fault between San Francisco and the southeastern end of rupture in 1906 was estimated to be larger than Mw 7 [25]. Data for it are poorer than those for shocks since the California gold rush of the late 1840s. They also estimated that an earthquake of about Mw 6.5 occurred northeast of the Loma Prieta segment in 1865.

Stresses changed by the 1838 event likely affected the San Andreas to the southeast of San Francisco, perhaps resulting in displacements in 1906 being smaller and/or shallower compared to those north of the City. Perhaps the 1838 event may have resulted in small or no displacements at depths greater than about 8 km in 1906 south of San Francisco. That could explain why much slip in 1989 occurred at greater depths. Stresses, which were released deeper in 1989 [15], may have been accumulated earlier than 1906. Little is known about the 1838 earthquake to the north of San Francisco. It was occupied then by the Russian Empire. Will slip occur in a future large mainshock at the same depths as were assumed to have broken in 1906?

[26] concluded that the average fault displacements in very large earthquakes do not scale linearly with rupture length but flatten out as length increases. The 1838 shock is known to have broken only part of that ruptured in 1906, *i.e.* between South San Francisco and the southeastern end of the 1989 rupture zone. The time elapsed between major events in northern California, such as 1906-1838, is not a reliable forecast of the next major earthquake. That time interval of 68 years has now been exceeded by 117 years since most of the 1906 zone last ruptured.

Since average slip in 1906 was larger than that in 1838, the time interval to the next shock after 1906 should be greater than 68 years. Not enough is known, especially about down-dip slip in the two events, to estimate it accurately. If we take downdip width = 20 km for each. the ratio of lengths = (90 to 140)/545 and stress drop for the two as constant, the ratio of slip in 1838 to that in 1906 is 0.57 to 0.70. Thus, the time interval following 1906 = 68/(0.57 to 0.70) = 97 to 119 years. The projected date of about 2003 to 2025, while uncertain, is closer to the reality of no such event as of early 2024.

The geodetic data in Figure 17 suggest that rupture could occur in a shock of Mw ≥ 6.7 along one of several fault segments to the northwest of Wright tunnel, perhaps sooner where slip in 1906 was either smaller or zero at depth. The fault segment between Wright tunnel and Black Mountain shares some characteristics [23] with the Loma Prieta segment. Will the next future rupture along that segment be similar to that in 1906 or extend deeper as in 1989?

Geodetic data collected after the 1906 earthquake were used by several authors to calculate displacements along the San Andreas fault. Those of [27] are shown in yellow in Figure 17. They indicate slip in 1906 was smallest near Loma Prieta

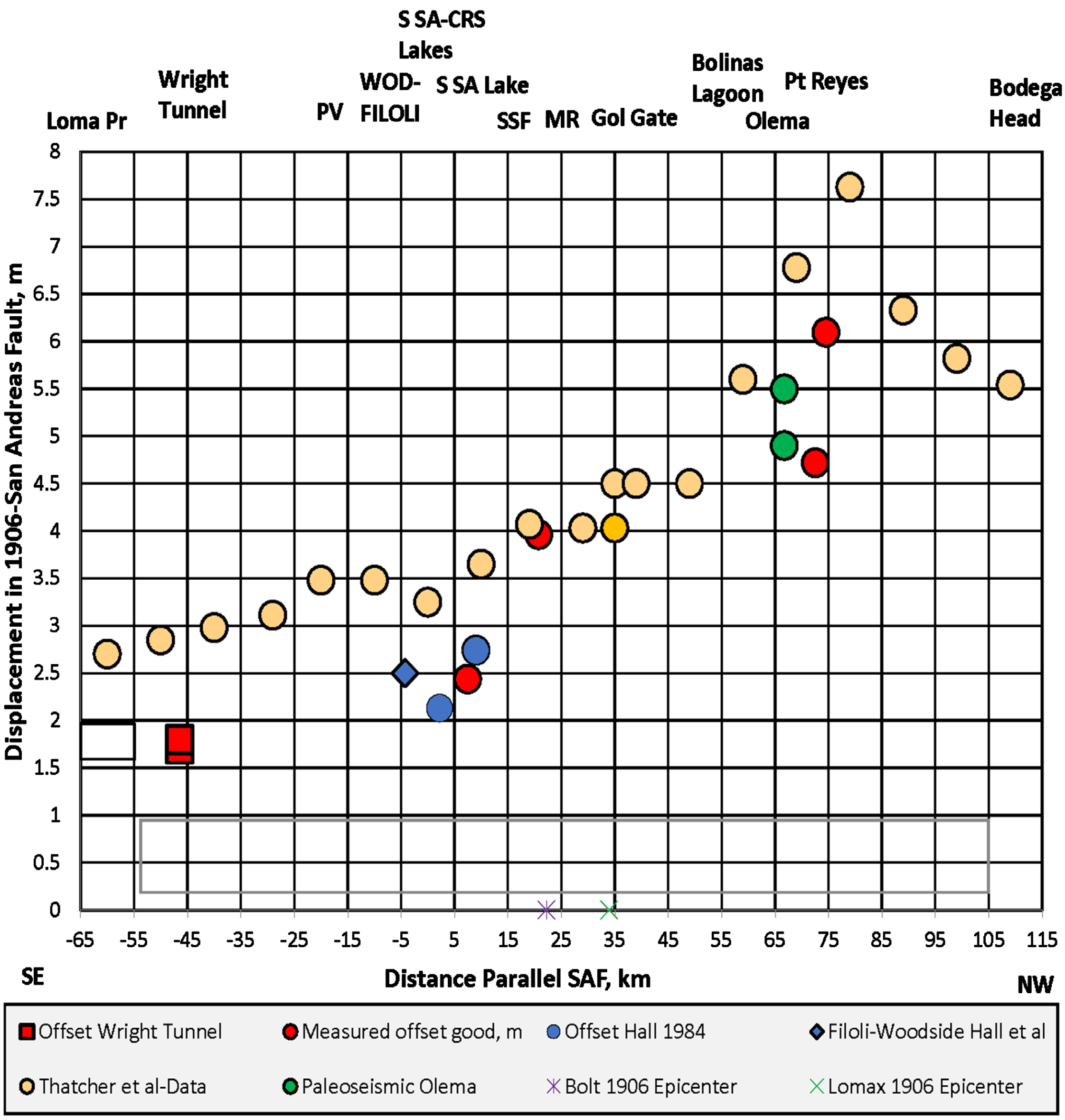

Figure 17. Distribution of computed slip (displacement) in the 1906 earthquake along the San Andreas fault between Wright tunnel at left and Bodega Head at right. The City of San Francisco is just south of the Golden Gate. Slip calculated from geodetic data in yellow is from [27]. Selected surface offsets, such as offset fences, are from [28] in red, and offsets at paleoseismic sites are in blue and green from [29] [30] [31]. Red squares are redeterminations of slip in Wright tunnel by [32].

and the 1989 rupture zone. They increase to the northwest. I selected well-determined surface offsets in red, mainly fences, from photos in [28]. Offsets in 1906 at paleoseismic trenches are shown in blue and green. They are smaller than those calculated from geodetic data.

7. Comparison of Decadal Changes before 1989 Mainshock with Those of the Last 20 Years along the Northern Hayward Fault

Figure 6 shows that a number of shocks of M > 4 occurred before the 1989 mainshock mostly either along East Bay faults or closer in location and time along the Lake Elsman fault. They turned off after 1989. Figure 18 and Figure 19 show sums of seismic moment release in the decades before the 1989 event compared with those from 1990 to 2024.0 along the northern Hayward fault.

While the increase in moment release is dominated by the largest moderate-size event of 1984, it was large in the several years from 1979 to 1989 compared to that from 1968 to 1979.

Moment release in the vicinity of the Hayward fault is dominated by the Mw 5.45 shock of 2007 near the southeast end of Figure 19. It may be an aftershock

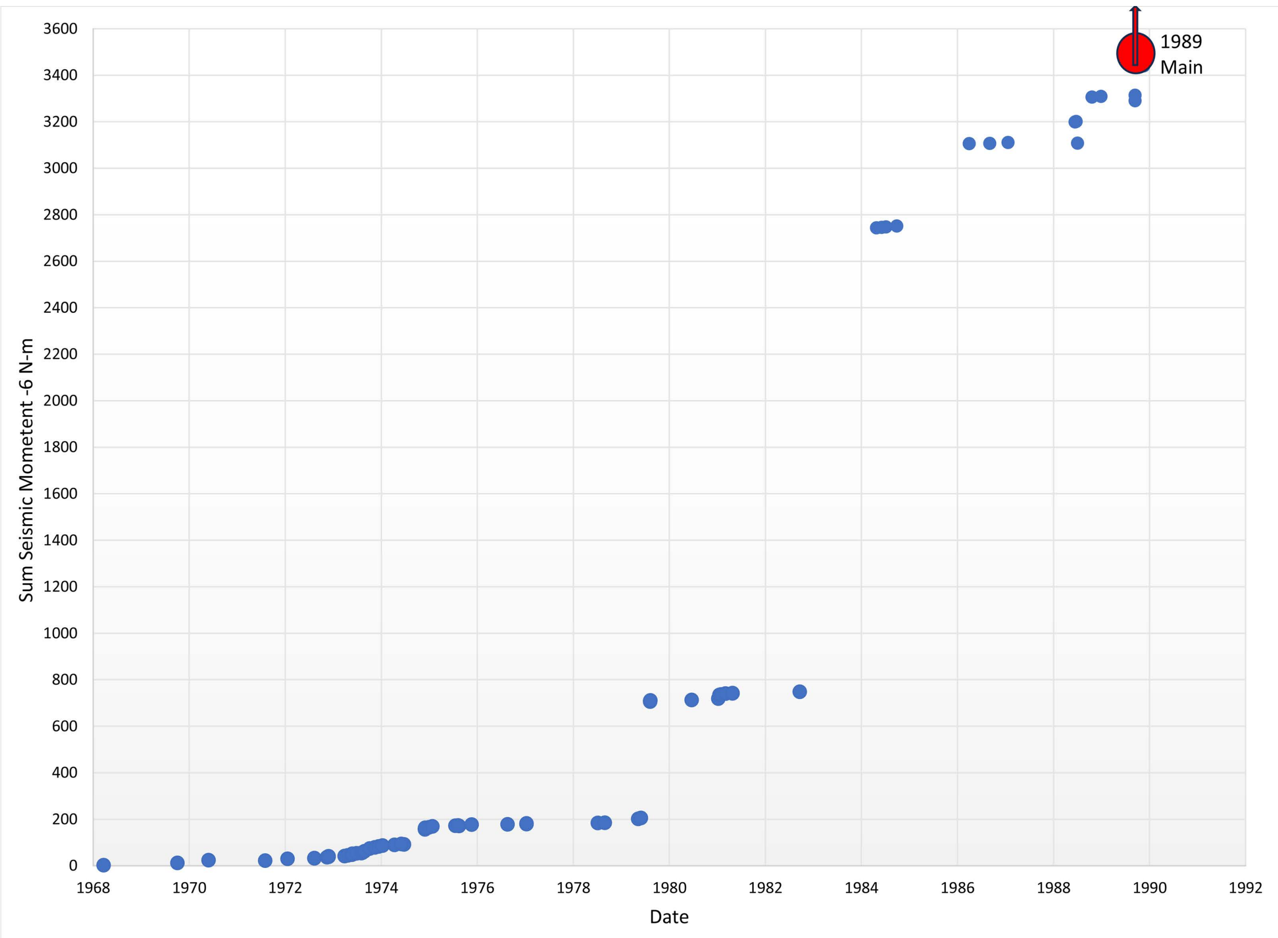

Figure 18. Cumulative seismic moment in area of Figure 6 from 1968 until the 1989 mainshock in red for events of M > 4.0.

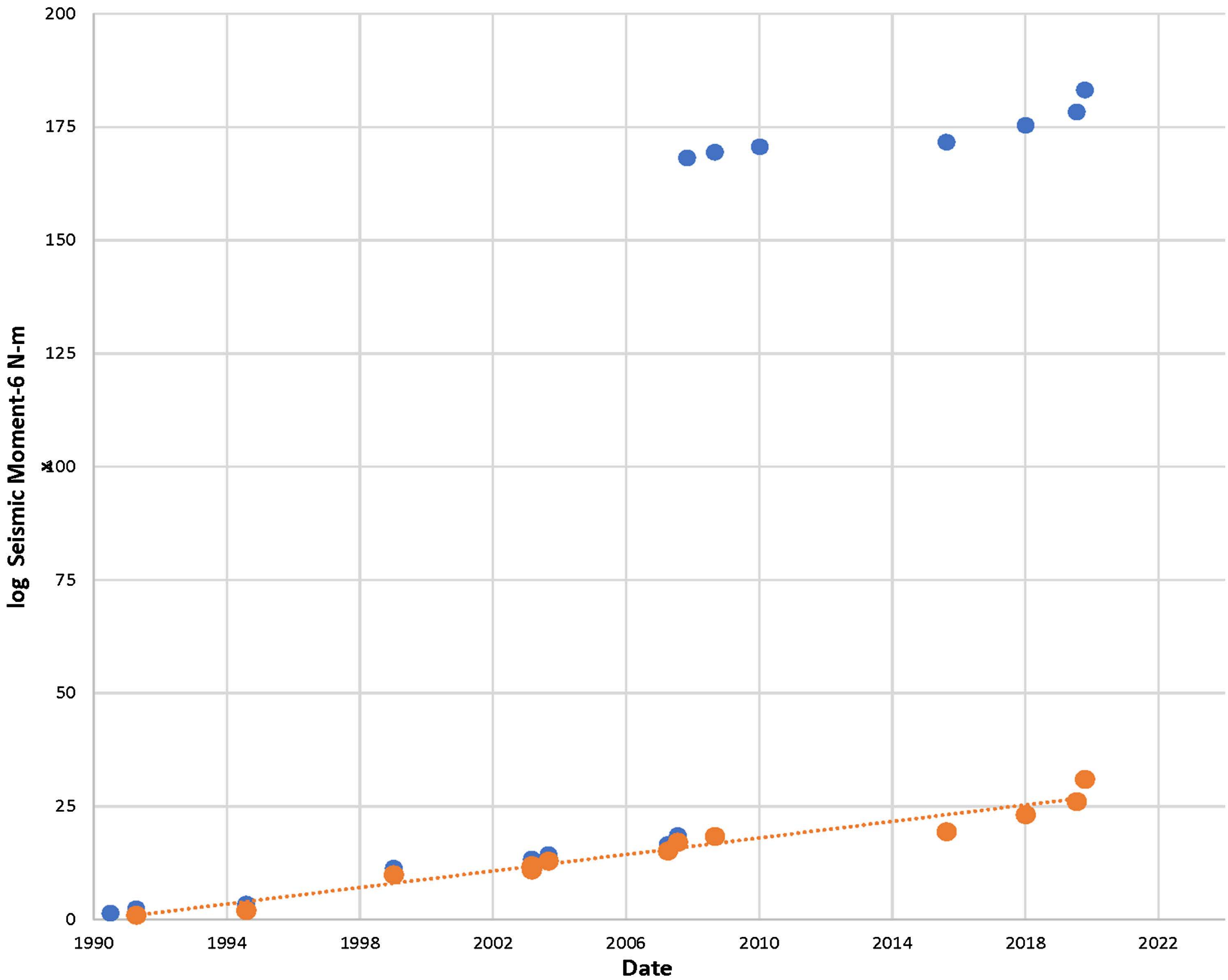

Figure 19. Cumulative seismic moment, Mo, in area near Hayward fault (**Figure 7**) from 1990 to 2024.0 blue dots; red dots exclude lower area between 37.4 and 37.5 N.

of 1989. Excluding it and nearby events leads to a small linear increase in moment release with time (red symbols). More and larger events occurred in the period before the 1868 shock along the Hayward fault. Moment release before the 1989 mainshock was much larger than that along and near the Hayward fault from 1990 until early 2024. Nevertheless, the two faults may well behave differently since the Hayward has a component of creep. While activity accelerated in the 12 years before the 1989 mainshock, it does not appear to have done so along the Hayward fault as of early 2024.

Although the San Andreas fault is the most active in the study area long term, it may not be the site of the next major or damaging shock in the greater San Francisco area. [33] computed probabilities that a number of active faults in the Bay area may break in large earthquakes between 2014 and 2043.

8. Were the 1989 Forecasts Correct?

[34] made a preliminary decadal assessment of an earthquake of magnitude 6.5

for the fault segment that later ruptured in 1989. He based it on small displacements in that area compared to those for other parts of the 1906 rupture zone. [13] proposed that a longer zone could rupture in an event of Mw 7.0. [23] concluded that rupture in a future major event would break the San Andreas from the Black Mountain asperity (**Figure 6**) to the southeastern end of slip in 1906. He stated that the San Andreas fault changed strike at Black Mountain and that it marked a reduction in slip in 1906 from 2.5 to 4 m to its northwest to 1 to 1.4 m to its southeast.

[35] claimed, however, that not enough time had occurred since 1906 for stress to build up along those segments of the San Andreas for a major earthquake to occur during the late 20th Century. Staff of the US Geological Survey stated in their 1990 title [36] that the 1989 event had been "anticipated," to my mind partly a publicity announcement. Other summary scientific papers by USGS authors after 1989 did not use the word anticipated.

Displacements in the main 1989 shock [15], however, were concentrated deeper than anyone had proposed beforehand. [35] stated that the 1989 mainshock was not the one predicted beforehand. I accept their view. It was not anticipated. Forecasters did concentrate on the right general area but not on the rupture depths that occurred in 1989.

This complicates the seismic gap proposal in which it was assumed in the 1980s that slip in the future would be at the same depths as were thought to have broken in 1906. Clearly, assessments of rupture in future large earthquakes need to included depths and as well as distance along strike.

9. Future Directions

What should be done next? Look for additional decadal changes before earthquakes of moderate magnitude. Examine other multi-branched strike-slip faults in New Zealand, Turkey, China and other parts of California for yearly to decadal changes in moderate-size earthquakes and locations of fault creep. Compute false alarm rates for decadal forecasts. Monitor small faults close to the San Andreas with detailed geodetic observations. Understand why fault creep occurs and its physical bases, which have been widely debated.

One of the problems with identifying increased forerunning activity is that it starts out small and then grows. Many scientists and officials will want to wait, perhaps too late, in conveying a forecast to governmental officials and/or the public. More work and thoughts are needed about when, whether and how to present decadal and yearly forecasts to the scientific community and the public. At the present time, yearly to decadal forecasts may not be well known enough for future changes to be conveyed beyond scientific researchers.

[6] concluded that parts of the Sargent fault close to the San Andreas (**Figure 6**) have been sites of repeating earthquakes. [37] reports that parts of it also creep. These factors may well apply to the Lake Elsman fault, which may be an extension of or a part of the Sargent fault. It is faults like it that need to be iden-

tified near the San Andreas and monitored for possible fault creep and changes in seismicity. Additional faults close to the San Andreas and other major faults in the Bay Area are described by [7] [38] [39] and [17]. The distribution of large slip and creep have likely changed with time along Bay area faults as the Mendocino triple junction has moved northwestward during the last 30 million years [40] [41] [42] [43]. Monitoring needs to include regional faults and not to concentrate on just the San Andreas fault itself.

We also need to understand better what controls the maximum depth of large earthquakes in the Bay area [44].

Active faults in the greater Bay Area differ in whether they creep or not. Different strategies are needed to identify decadal forerunning changes for each. Much of the region has not experienced major or great earthquakes since 1906 and by now is highly stressed.

[45] said that improved tests reveal that the accelerating moment release hypothesis is statistically insignificant. I show it is significant for the three largest shocks in the greater Bay area since 1850.

10. Conclusions

This paper addresses long-term forecasts of large earthquakes along the San Andreas fault in the greater San Francisco Bay area. It also studies smaller seismicity of the last 34 years along the northern Hayward fault.

Two major historic shocks along the San Andreas in northern California were preceded in one to two decades by increased activity along nearby regional faults but mostly not along the coming large rupture zones themselves. Increased seismicity of moderate magnitudes was the most reliable decadal forecast. It is clear in retrospect that the increased seismic activity prior to the 1989 mainshock occurred on nearby regional faults and not on the fault that broke in 1989. That activity largely died away after 1989 indicating that it was a decadal forerunner.

The 1989 mainshock, regardless of its depth, did have decadal forerunning activity that was anomalously high (**Figure 6** and **Figure 18**) and was similar to that for the two previous historic large earthquakes of 1868 and 1906. Decadal activity did not increase for several decades after 1920 and 1990.5. Those characteristics, when observed ahead of time, might be useful for scientific and/or governmental actions. The major problem is that preceding decadal activity in northern California is known for only three major to great earthquakes and for two intervals of low activity.

Are decadal forecasts useful? A ten-year assessment that a major shock was coming could have prepared California to consider strengthening or replacing the San Francisco-Oakland Bay Bridge, which failed in 1989. A warning of just a few days beforehand, however, could lead people to try to escape, perhaps resulting in many deaths in car accidents. Similar decadal patterns occurred before great earthquakes along subduction zones and other transform faults. We may be able to make decadal forecasts when short-term predictions are not possible.

Much of the decadal preceding activity before large shocks along the northern San Andreas fault occurred along nearby active East Bay faults such as the Calaveras. They differ from the northern San Andreas by creeping near the surface and having many small repeating earthquakes. The San Andreas itself between San Francisco and Wright tunnel differs in that it is locked, is not creeping and it has not been the site of repeating earthquakes in the study area. Sites of repeating events represent strong fault patches surrounded by creeping regions.

Different behaviors of the northern San Andreas and East Bay faults are illustrated in **Figure 6**. In addition to decadal increases in activity along regional faults to its northeast, the 1989 mainshock also was preceded one to two years ahead of time by shocks larger than magnitude 5 along the sub-parallel Lake Elsman fault only 3 km away.

A physical basis of these two types of forerunning activity indicates that stresses were dropped in the region in 1906 and they extended out to East Bay faults. Stresses were restored during one to two decades along parts of East Bay faults. Stress was restored just three kilometers from the San Andreas fault in one to two years before the 1989 shock along the Lake Elsman fault.

The detailed distribution of precisely located small earthquakes indicates that the San Andreas fault zone consists of multiple nearby faults. They need to be monitored frequently for possible increases in moderate-size earthquakes. Geodetic observations should focus on whether any of them are creeping that are close to the San Andreas. Examining small faults close to the San Andreas offers the possibility of moving from decadal forecasts to those of several years. We need to know if the determination of magnitude changed much in the last 60 years with respect to estimating decadal changes for shocks of magnitude ≥ 4.

I have long argued that we need to work on decadal forecasts. Some in the scientific community have stated that earthquake prediction is impossible since, as they argue, stress release in large shocks is a very chaotic process. Some others say that since accurate predictions of a few days cannot be made, the subject is not worth either studying or funding. Many statements about earthquake prediction today resemble those made from 1920 to 1965 that continental drift was impossible. Working on earthquake forecasting is not for the faint hearted given considerable scientific opposition to it and the likelihood of being wrong at least some of the time. We still have much work to do with forecasts of earthquakes on various time scales and to understand their physical bases.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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