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Major Asperities that Ruptured in Large California Earthquakes, Surrounding Pre-Shocks, and Some Yearly to Decadal Precursory Changes in Seismic Activity

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Abstract

Double-difference locations of forerunning shocks of seismic magnitude, M, 2 to 6 are examined in the months to decades before 11 mainshocks in California of magnitude 6 and larger. Each of the 11 had large quiet zones beforehand, which are called asperities, that break nearly entirely in large mainshocks. Their surrounding 11 zones were all sites of small to moderate-size shocks that define the approximate magnitudes of the coming large event. The latter, donuts of activity, are places to examine for precursory changes years to decades before larger earthquakes. The quiet asperities and many sites at the earth's surface are not good places to monitor precursory changes before large mainshocks. Detecting forerunning events to large future earthquakes requires monitoring the right places. A few possible precursory changes are identified and discussed.

Keywords

Active Faults, Plate Boundaries, California, Double-Difference Locations, San Andreas Fault, Asperities, Forecasts, Predictions, Seismology

1. Introduction

My colleagues and I [1]-[11] examined seismic activity prior to a number of large global earthquakes. Most involved decadal changes rather than shorter-term predictions of days, which are discussed more often in the literature and by the public.

In this paper, I emphasize seismic and other data from the weeks to decades before 11 earthquakes of magnitude 6.0 to 7.3 in northern and southern California. I try to let the data "speak" for themselves for those times instead of emphasizing particular models. My goal is not to predict all large global shocks but merely to see if some are preceded by changes that may or may not be useful to either the scientific community or society.

Since the occurrence of the great shock of 1906 along the San Andreas fault, many authors have proposed dates of future major earthquakes in northern California. Most of the 1906 rupture zone has not rebroken in large to great earthquakes. Most of it is considered to be a major seismic gap that has not ruptured for a long time. It broke to the southeast of San Francisco and for about 450 km to the northwest. Most of it is locked and is currently building up stresses that were reduced in 1906. A small part of it broke in 1989. Great shocks occurred in southern California in 1857, 1812 and about 1680 [7]. Hence, it has been a long time since the San Andreas fault ruptured in a great earthquake. Most of the preceding activity I describe here was located off of the main San Andreas fault itself.

I describe great events by their very long-period seismic magnitudes, Mw ≥ 7.8 and major shocks of 6.8 < Mw < 7.8. Mw is reported by [12]. I use M for events smaller than Mw 5.5. For smaller shocks, M is generally used to measure either body waves, surface waves, or local magnitudes as determined by Berkeley.

The main topic of the paper is the use of precise locations of small to large shocks, so-called double-difference solutions with precisions of about 30 m [13] [14] for all of the 11 large earthquakes studied here and their preceding smaller shocks. These 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 merely using the distribution of active faults at or near the earth's surface. The use of double-difference locations permits small forerunning activity to be examined in detail prior to shocks as small as magnitude 6.

Many seismologists have assumed incorrectly that forerunning shocks occur along the same fault as a future major or great earthquake. Evidence shows that moderate-size forerunning events often have taken place one to a few decades ahead of time on surrounding regional faults, what was called a donut pattern by Mogi [15]-[17]. He and colleagues [18] showed that the great and damaging Tokyo earthquake of 1923 had a similar pattern of decadal pre-shocks surrounding its rupture zone. A similar pattern was described [2] [4] for the decades preceding the great 1906 and the major historic earthquakes in northern California of 1868 and 1989.

The main conclusion of this paper is that a donut pattern of moderate-size earthquakes surrounds each of the 11 large events studied here. I refer to each of the holes in those donuts as a large asperity. The search for precursory changes needs to focus on the donuts where small events and aftershocks occur and not just on the asperities. Some forerunning activity has taken place on nearby active faults, especially ones where parts of them are known to move by creep.

When a major or great earthquake occurs in the study area, it likely will cause much damage and perhaps loss of life. These are not the main focus of this paper.

The eleven large earthquakes examined here are shown in **Figure 1** and **Figure 2**.

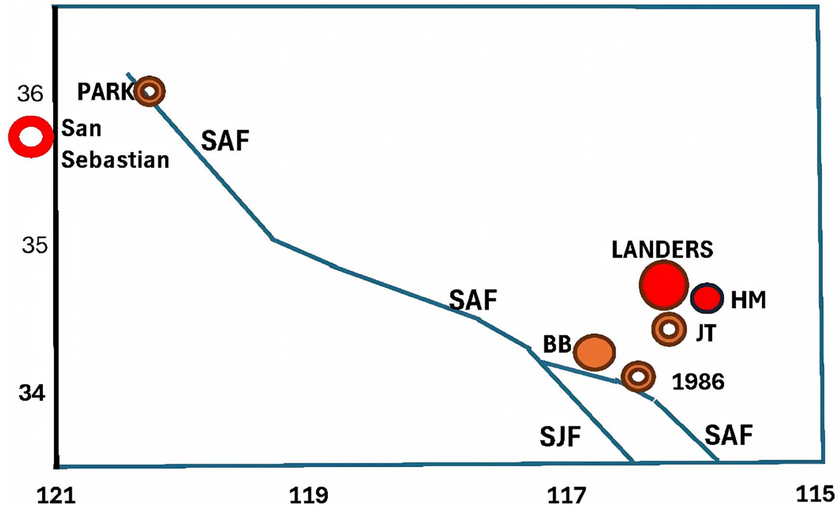

Figure 1. Large earthquake studied in southern California. BB denotes Big Bear, HM Hector Mines, JT Joshua Tree, PARK Parkfield, SAF San Andreas fault, SJF San Jacinto fault.

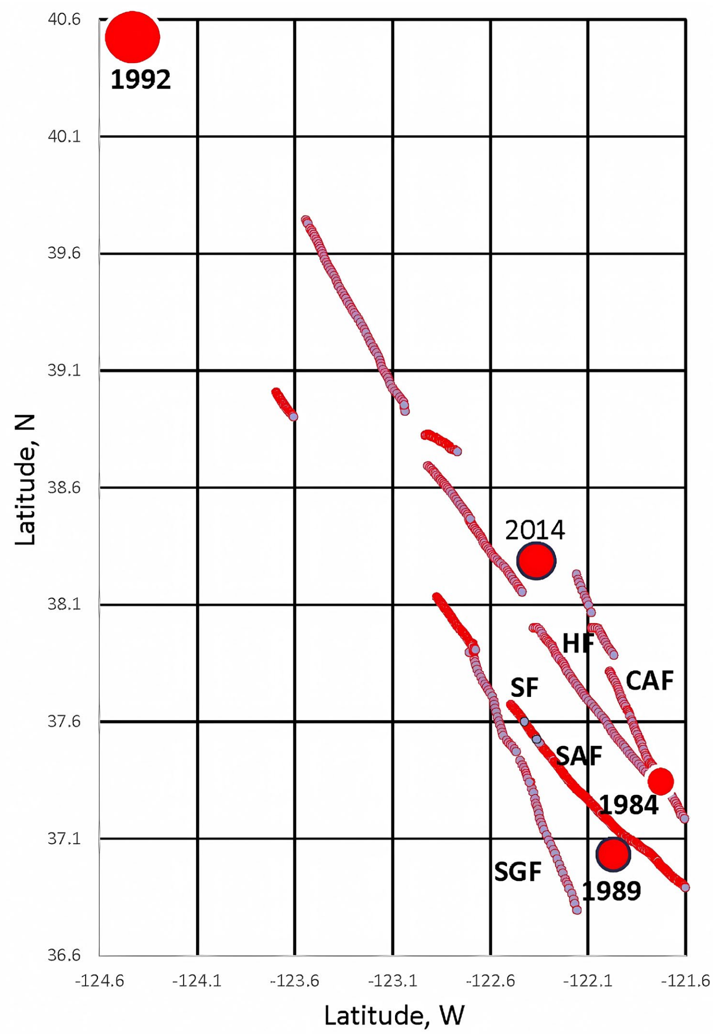

Figure 2. Large earthquake studied in northern California (in red). CAF = Calaveras fault, HF = Hayward fault, SAF = San Andreas fault, SGF = San Gorgonio fault, SF = San Francisco.

Pertinent data are in Table 1. I discuss them starting with Parkfield in central California.

Table 1. Earthquakes studied (Mw > 6.0).

Date	Latitude	Longitude	Place	Depth (km)	Magnitude (Mw)
1966	35.95	−120.5	Parkfield	9	6.0
1984	37.31	−121.68	Calaveras fault	8	6.2
1986	34.01	−116.61	North Palm Springs	10.9	6.0
1989	37.04	−121.89	San Andreas fault	18.5	6.9
1992	40.45	−124.44	Thrust-north Mendocino	11	6.9
1992	33.97	−116.316	Joshua Tree	11.9	6.2
1992	34.201	−116.436	Landers	2.5	7.3
1992	34.204	−116.82	Big Bear	9.68	6.3
1999	34.60	−116.28	Hector Mines	10.3	7.1
2003	35.712	−121.805	San Sebastian	13	6.6
2004	35.819	−120.368	Parkfield	8.4	6.0
2014	38.205	−132.32	South Napa	12	6.02

2. Parkfield

2.1. Major Asperity, Surrounding Forerunning Activity, Aftershocks

Figure 3 shows seismic events from 1984 to the main Parkfield shock of 2004 as a function of depth and distance parallel to the San Andreas fault. It is a projection onto the San Andreas fault itself. I draw lines in blue connecting red circles so as to define a quiet region within them. Most aftershocks in yellow also lie on the same boundaries of the quiet zone. The quiet zone, which is here called an asperity, broke in the main 2004 earthquake and likely in the mainshock of 1966. The forerunning activity is a good place to search for changes that may represent precursors. The Earth's surface and the asperity, being very quiet, are not good places to seek precursors. I go on to define similar asperities for 10 other large earthquakes in California. Some asperities are not as well defined as they are for Parkfield.

Figure 4 shows activity near Parkfield from 1969 until the 2004 mainshock. That activity and 2004 aftershocks were concentrated along a zone 1 to 2 km wide. Some shocks from 1969 to 1984 were not as well located.

Figure 5 expands upon Figure 3 so as to add the time from the 2004 mainshock to mid-2024. The thin red lines enclose a similar area to that identified prior to 2004, except that they extend somewhat farther to the northwest and southeast. They indicate the next Parkfield mainshock likely will break the 2004 rupture zone and maybe somewhat longer zones along strike. It took double-difference locations to resolve these. [19] and [20] identified quiet zones at depth but not

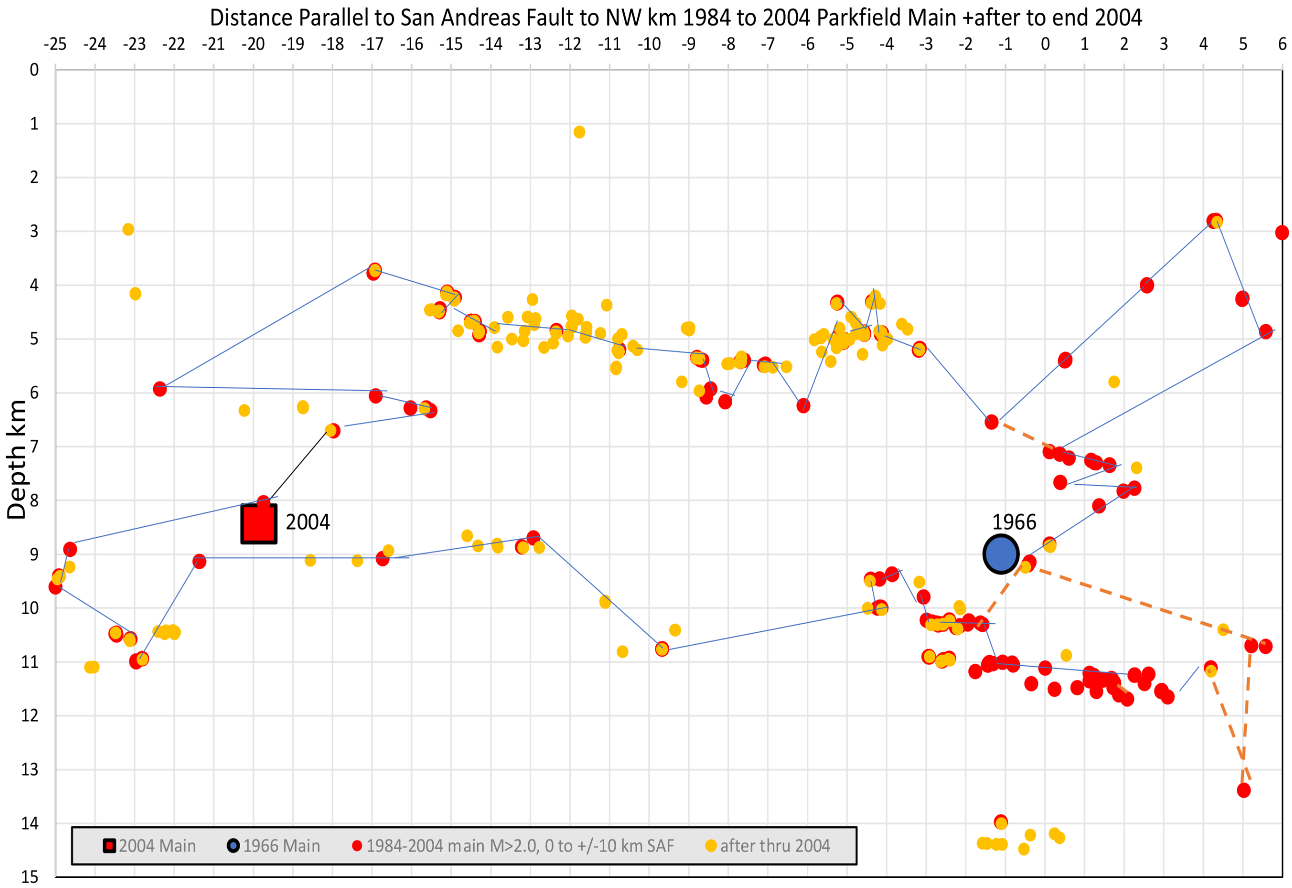

Figure 3. Preceding earthquakes and aftershocks to the main Parkfield shock of 2004 as a function of depth and distance parallel to San Andreas fault. Note the quiet zone from depths of about 5 to 9 km. Event locations are double-difference solutions.

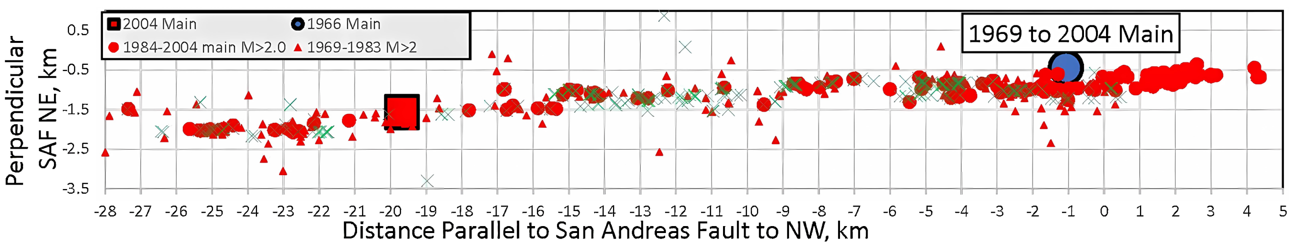

Figure 4. Preceding earthquakes near Parkfield as a function of distances parallel and perpendicular to the San Andreas fault from 1969 until the mainshock of 2004.

with the distinctiveness shown in Figure 3 and Figure 5. Pre-shocks to 2004 extend to mid-2024 (Figure 3 and Figure 5).

Geodetic data and seismic modelling of the 2004 mainshock [20] also give a measure of the length along strike of rupture in 2004. It includes the distance between the 2004 and 1966 mainshocks and somewhat beyond each of them. These and the precursory events in Figure 3 and Figure 4 indicate that the surrounding donut is quite narrow for Parkfield.

Felt areas of earlier Parkfield mainshocks indicate [21] that they ruptured somewhat different zones in the 1934 and 1966 mainshocks. Assuming they were the same, however, [22] made a misprediction of the next mainshock for 1983 to

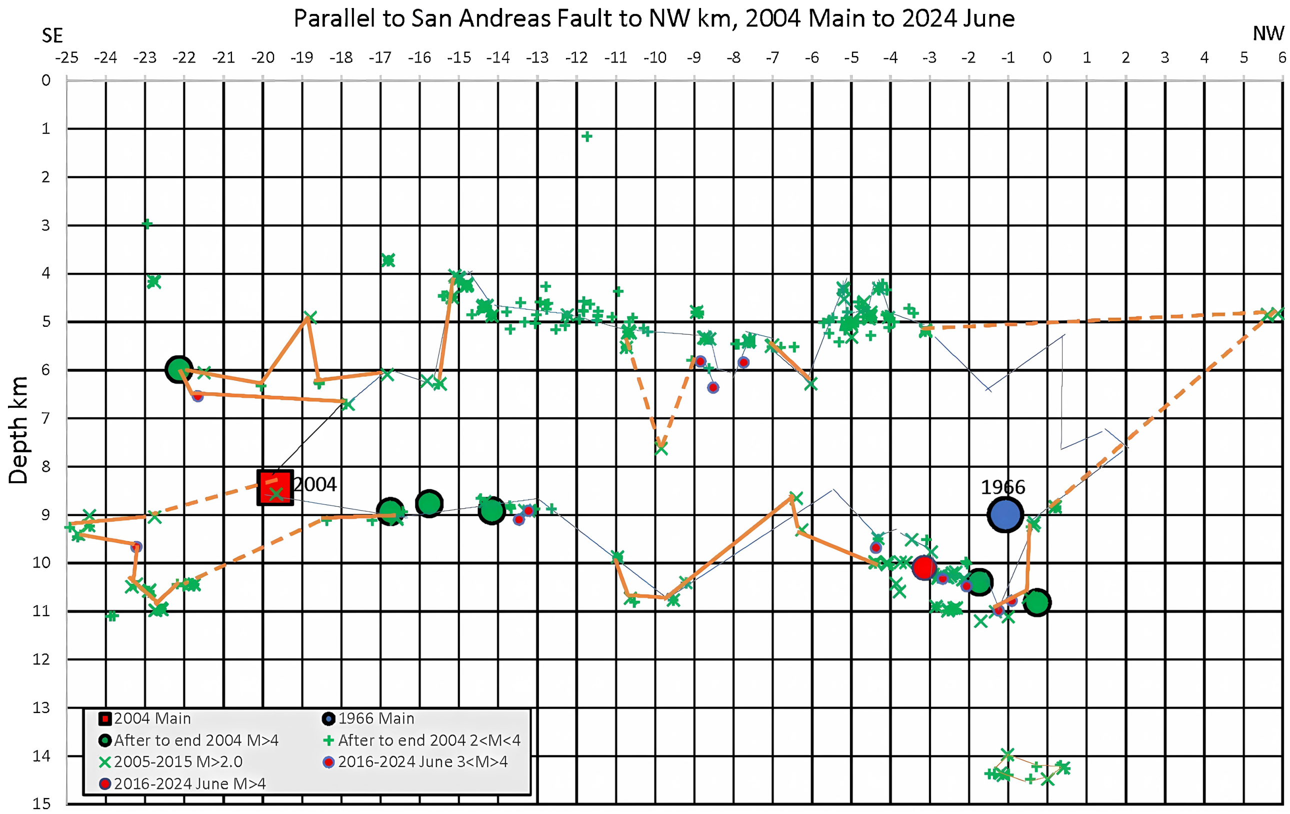

Figure 5. Parkfield earthquakes from the 2004 mainshock to 2024 as a function of depth and distance parallel to the San Andreas fault. Thin blue lines are activity before 2004 mainshock from **Figure 3**. Red lines denote shocks from 2004 mainshock to June 2024.

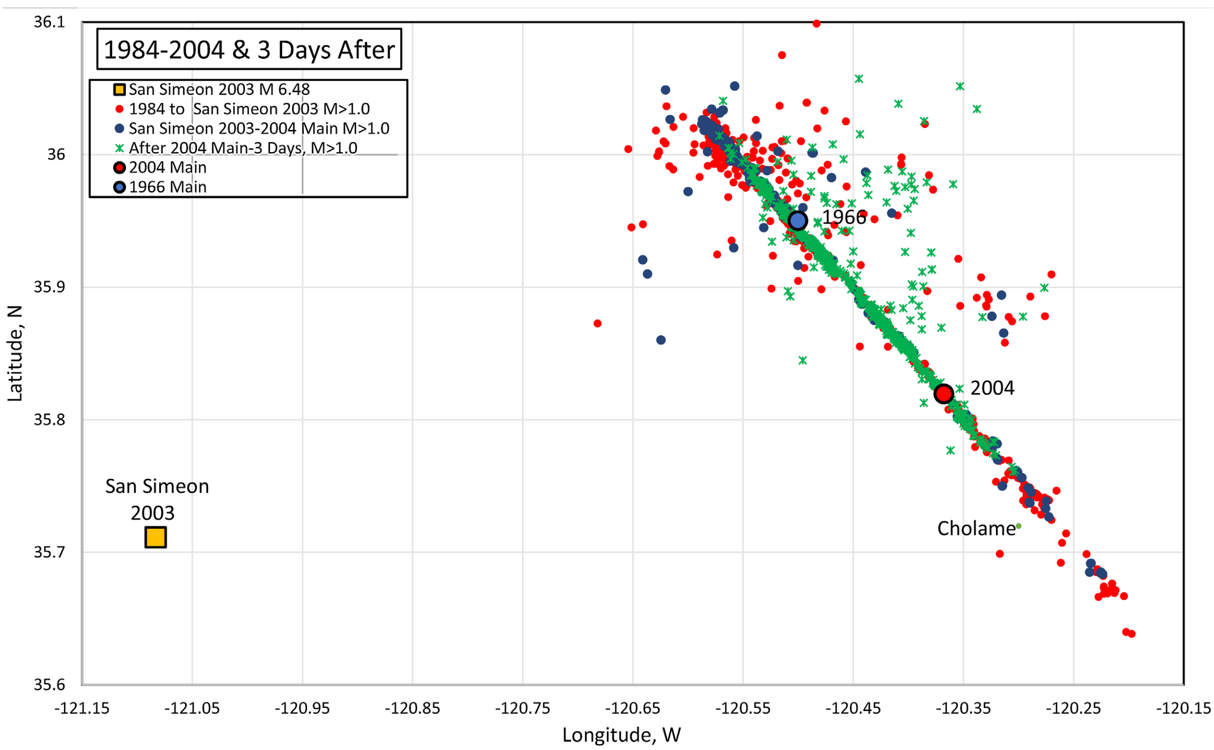

Figure 6. Activity near the Parkfield region at right between 1984 and the San Simeon shock of M 6.5 of 2003, between it and the Parkfield mainshock of 2004, and three days of 2004 aftershocks.

1993, well before its actual occurrence in 2004.

Figure 6 and Figure 7 indicate seismicity in the vicinity of Parkfield prior to the 2003 M 6.5 San Simeon mainshock, between it and the 2004 main event, and aftershocks. Much pre-activity was concentrated northwest of the 1966 epicenter and near Cholame to the southeast. Aftershocks and geodetic data indicate that the Cholame segment likely did not rupture in the 2004 mainshock. Little pre-activity occurred on the San Andreas fault between the 1966 and 2004 main events (as in Figure 3).

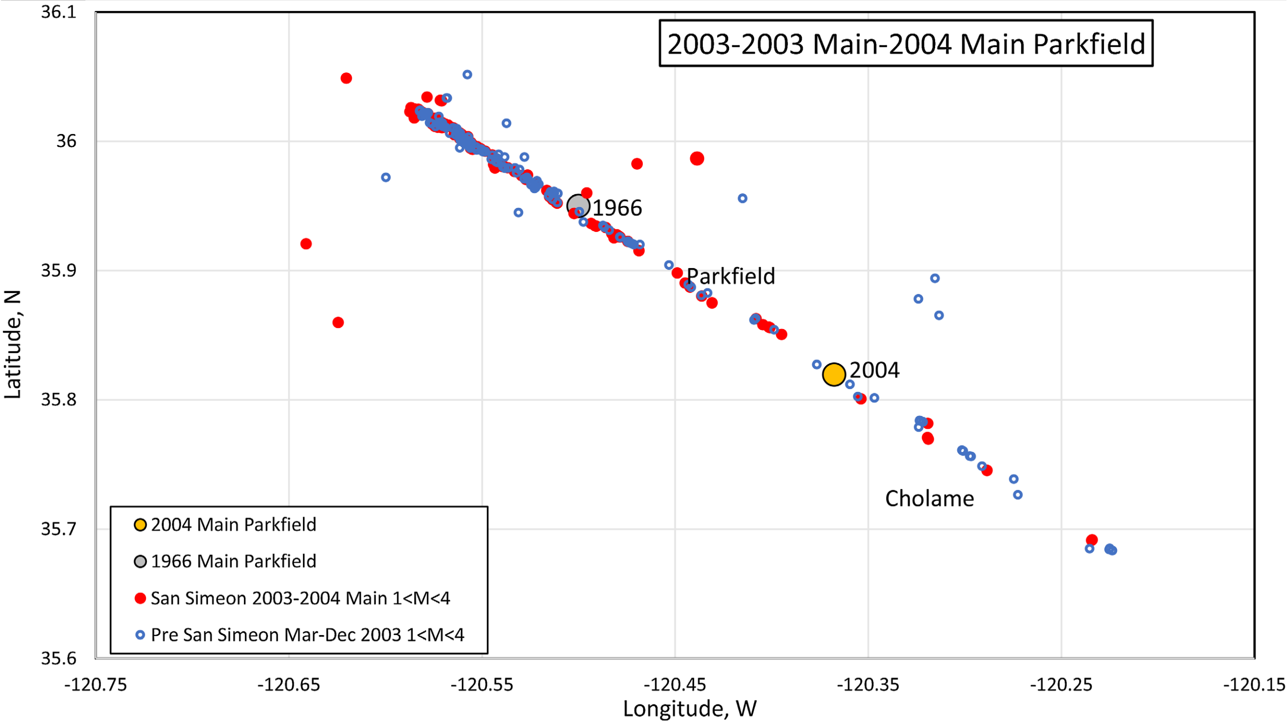

Figure 7. Activity along the Parkfield region between the San Simeon shock of M 6.5 of 2003 and the Parkfield mainshock of 2004.

2.2. Search for Precursors to Parkfield Mainshocks

In this subsection, I pose the question of whether changes in seismic activity preceded the 2004 mainshock. I only did a limited search for possible decadal and shorter changes. One possibility is shown (Figure 8) where seismic moment release is computed as a function of time prior to the 2004 Parkfield mainshock. Moment release increased after a larger event in 1999 and another in 2002. Moment release then increased between 2003 and the 2004 mainshock. The latter increase may have been either a precursor or additional aftershock activity. Pre-activity was more numerous closer to the 1966 epicenter than to the 2004 event, where rupture was initiated in 2004.

[23] [24] and others found tremor and slow-slip seismic events at depths near 20 km below the fast-slip forerunning events of Figure 3 and Figure 5. Many near 20 km were triggered by the nearby San Simeon shock of 2003 and the 2014 South Napa event of M 6.0 well to the north. Deeper shocks are not used in examining

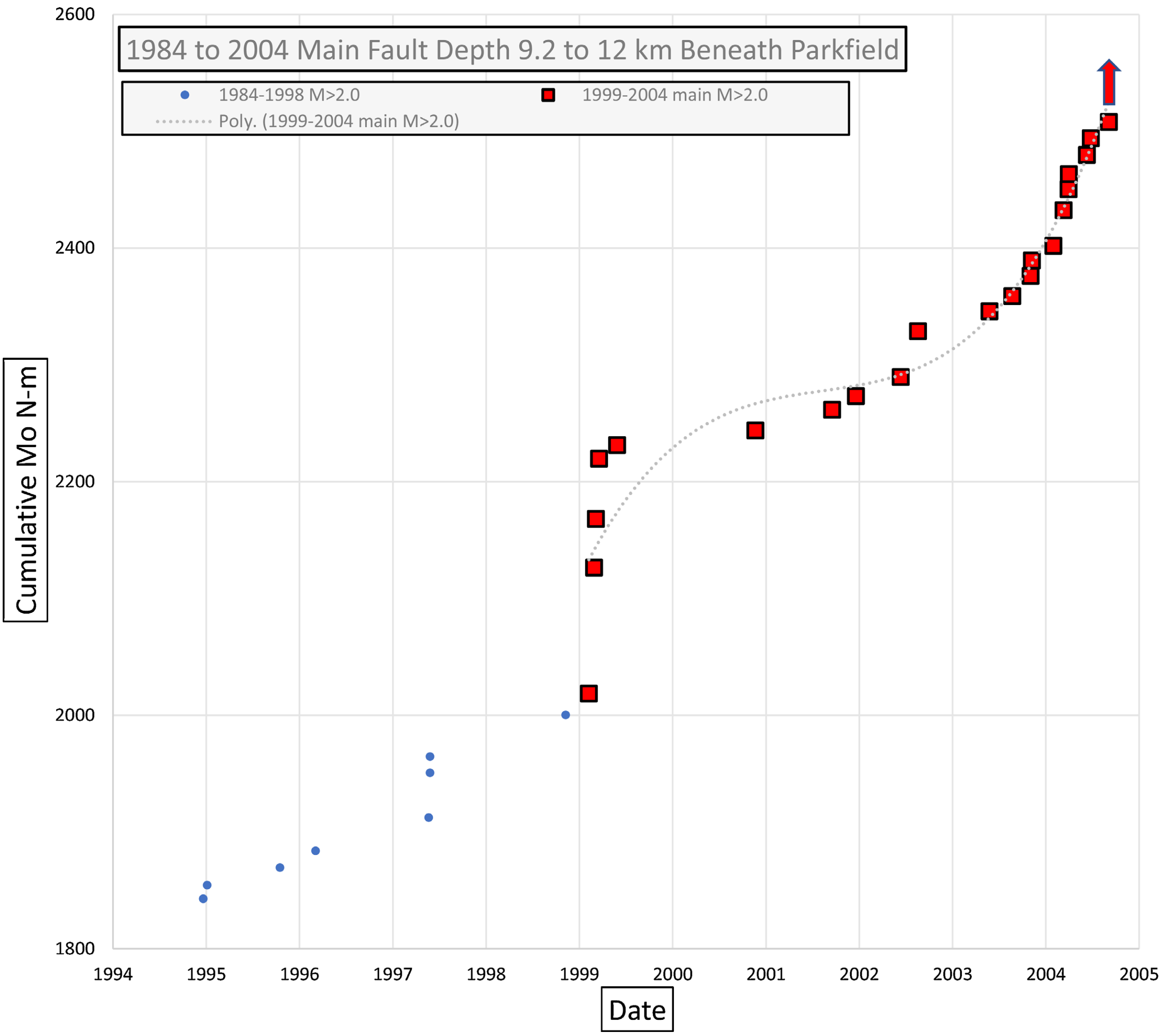

Figure 8. Cumulative seismic moment release as a function of time prior to the 2004 Parkfield mainshock (red arrow).

precursors to the Parkfield and other large shocks since I seek closer triggering events. These slower events were concentrated near Cholame along a part of the San Andreas that likely did not rupture in 2004 (**Figure 6**).

Sieh [25] found several shocks hours prior to the giant 1857 earthquake. He called the two largest the Dawn and Sunrise foreshocks. While other locations are compatible with the sparse felt reports, his two likely epicenters occurred near Parkfield and just to its south. He states, "These later two shocks were $5 \le M \le 6$ and probably... includes the southeastern 100 km of the historically creeping segment of the San Andreas fault."

Slip at the surface in 1857 was measured more than 100 years later. It includes 1 to 2 m of displacement close to Cholame and 2 to 4 km [26] farther southeast. One interpretation of the observations is that slip occurred in the Dawn and Sunrise shocks near Parkfield and Cholame prior to the great rupture later the same day to the southeast of Cholame.

The quiet zone in Figure 9 extends deeper southeast of Cholame. It may not

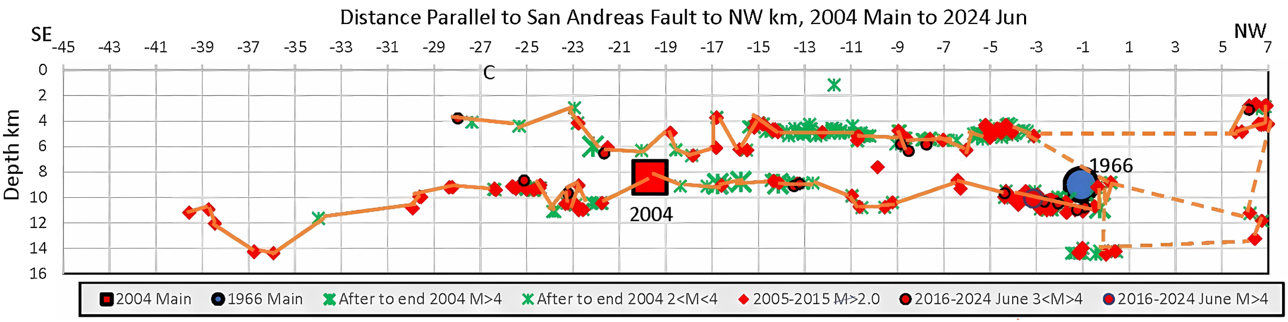

Figure 9. Parkfield earthquakes from the 2004 mainshock to 2024 as a function of depth and distance parallel to the San Andreas fault. Red lines connect events between the 2004 mainshock and June 2024. The figure is extended farther southeast to include Cholame (C) and that farther southeast that broke in the great 1857 mainshock.

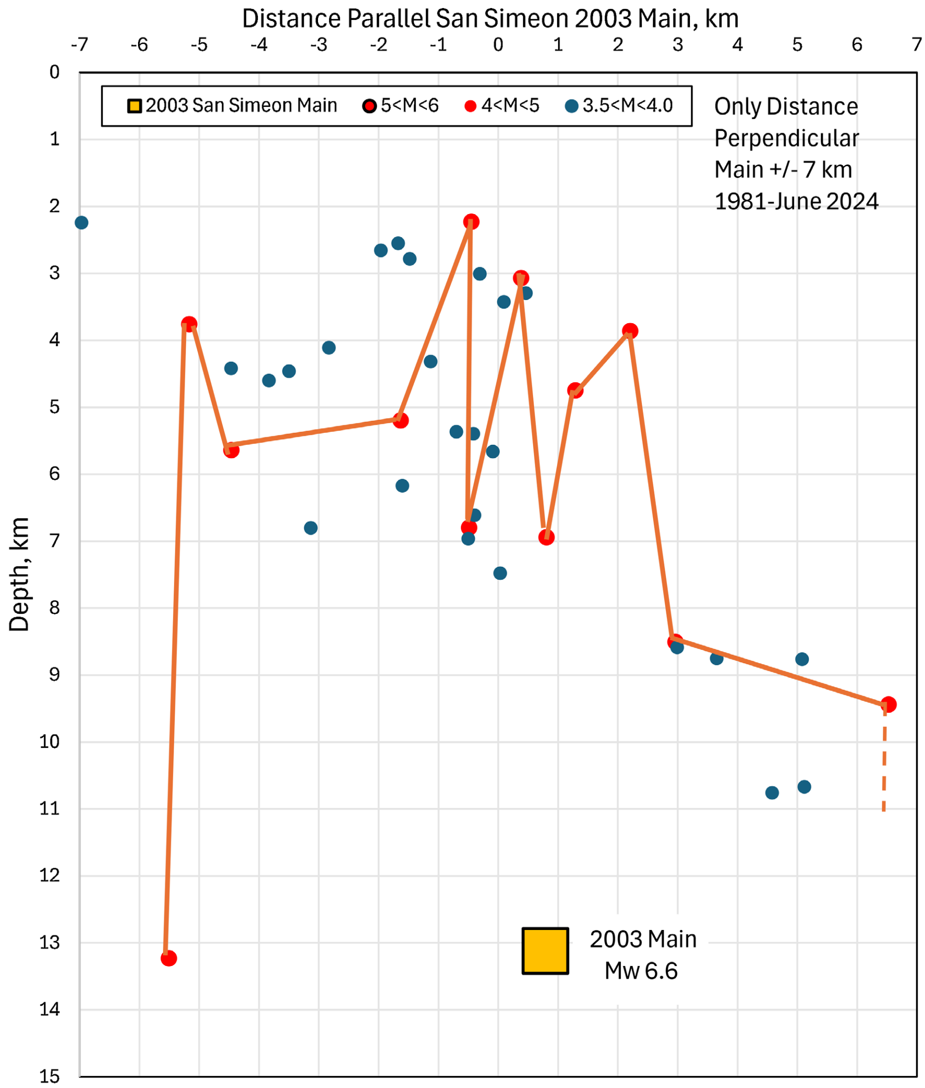

Figure 10. Earthquakes at a function of depth and distance parallel to the San Simeon mainshock of 2003.

have ruptured since 1857. Its deeper asperity may rupture less frequently than the Parkfield zone. Hence, it is a good place to monitor since it may break in conjunction with either the next or a subsequent Parkfield mainshock. Its next rupture may signal a coming great shock like that farther southeast in 1857.

3. San Simeon Asperity

An asperity prior to the 2003 San Simeon shock is evident in the data for more than 20 years prior at depths from about 6 km to the 13 km depth of the mainshock (**Figure 10**).

4. Asperities that Broke the northern San Andreas Fault in 1989

Sykes *et al.* [10] examined shocks as small as magnitude 1.0 before and after the M 6.9 1989 Loma Prieta earthquake (**Figure 11**) in northern California. All of the events shown were precisely located, double-difference solutions. The two shocks of M > 5 and several other previous events beneath nearby Lake Elsman (in red) occurred on what they called the Lake Elsman fault. Its dip was nearly the same as that defined by small aftershocks of the main 1989 earthquake but displaced

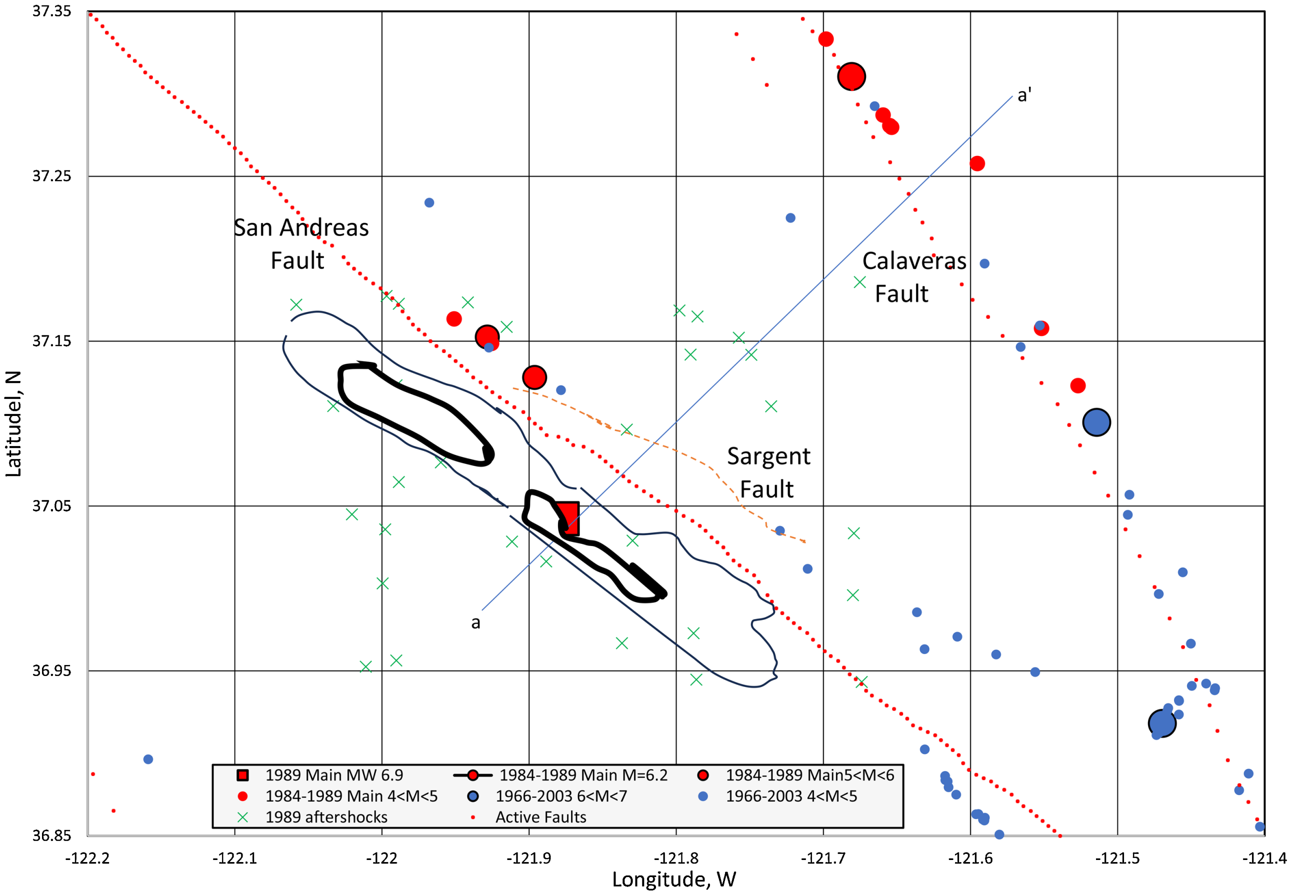

Figure 11. Forerunning earthquakes to the 1989 Loma Prieta mainshock. Two slip contours for the 1989 mainshock from [27]. Figure published in [10].

from the latter by about 3 km and located at depths of about 10 to 16 km. In retrospect, they regarded the two largest red events as yearly forerunners to the 1989 mainshock.

Figure 12 shows a large aseismic region or asperity prior to the 1989 mainshock. Figure 11 indicates it ruptured two large asperities [27]. The southeastern region to the right of the mainshock (Figure 12) defines two asperities at shallower depths greater than about 10 to 12 km. Displacement in the main 1989 shock [27], however, was concentrated deeper than anyone had proposed before it occurred. This complicates the seismic gap proposal in which it was assumed that slip in the future would be at the same depths as were assumed to have broken in 1906. Stresses released deeper in 1989 may have been accumulated earlier than 1906. Nevertheless, the distribution of one or more asperities is clear in Figure 12.

Asperity Prior to 1984 Earthquake of M 6.2

The 1984 shock of M 6.2 was the largest between 1984 and the 1989 mainshock, as shown in Figure 11. Its location on the creeping Calaveras fault indicates it was a large precursor to the 1989 main event [10]. A large aseismic region or asperity broke in the 1984 mainshock (Figure 13).

5. Earthquakes Defining Current Asperities on or Near the San Andreas Fault between San Francisco and the 1989 Rupture Zone

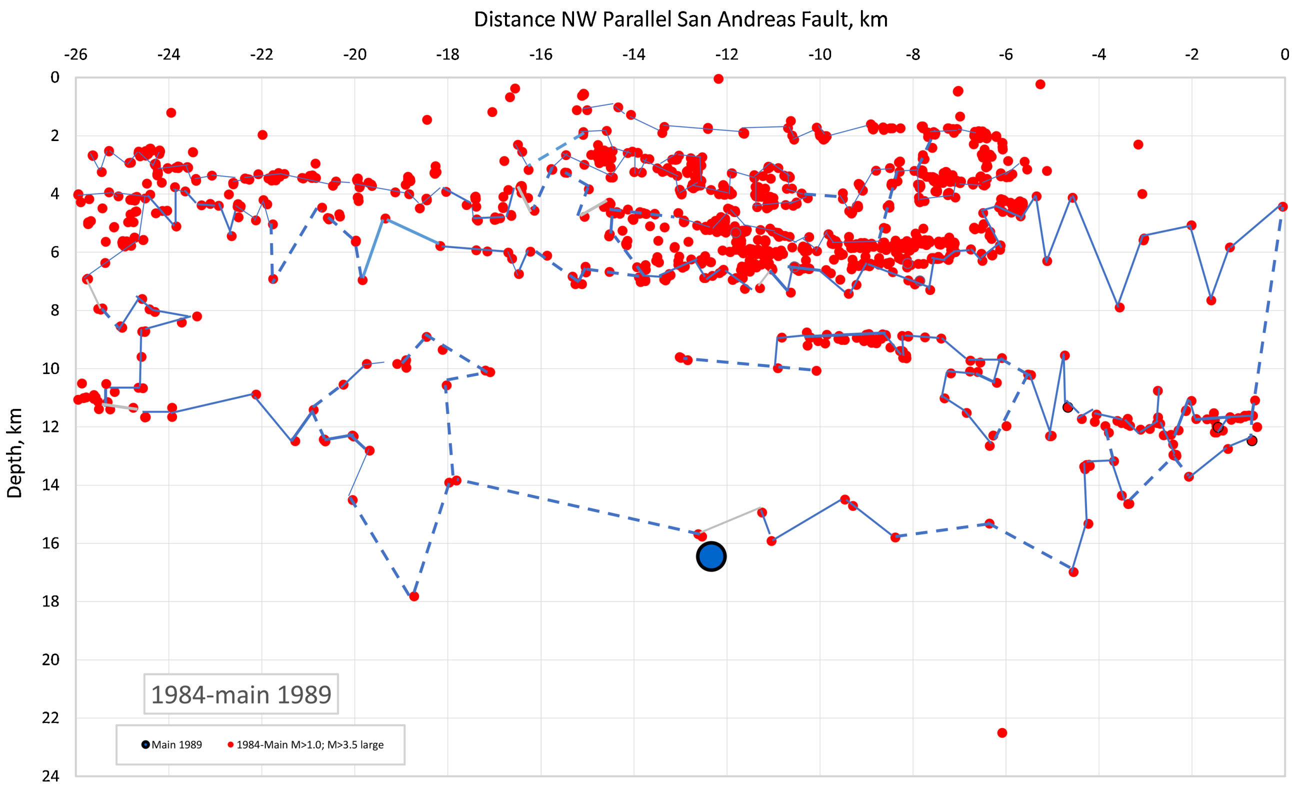

Figure 12. Earthquakes prior to the 1989 Loma Prieta Mainshock (large blue circle). Blue lines enclose two or three asperities (see Figure 11).

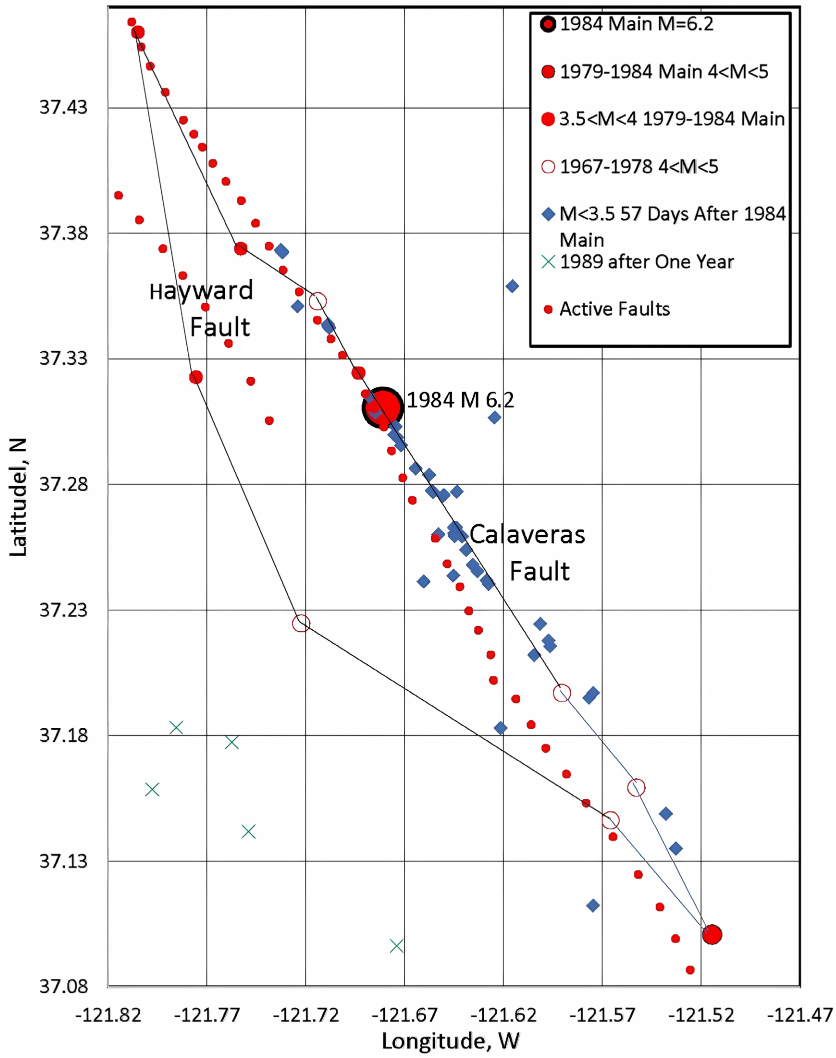

Figure 13. Earthquakes in red prior to 1984 shock of M 6.2 along the Calaveras fault and its aftershocks. Thin blue lines enclose asperity defined by lack of preceding shocks.

Double-difference locations differ greatly along the northern San Andreas fault. There were numerous places near San Francisco (**Figure 14**), between Woodside (WOD), and at the northwestern end of the 1989 Loma Prieta earthquake (**Figure 15**) near Wright tunnel (WT). Most activity was located on either side of the San Andreas fault, and quiet asperities were defined inside them.

The distribution of shocks appears to define five segments of the San Andreas fault between San Francisco and the southeastern end of the 1989 rupture zone. They are discussed more in [10]. They may break separately or together as in 1906 and 1838. Note the donut-patterns of activity on regional faults surrounding the San Andreas and near lack of activity along it between San Francisco and Wright tunnel.

[2] and [4] studied moderate and small earthquakes in the decades preceding the three largest shocks in northern California since 1860—the great 1906 event of Mw 7.9, the Hayward fault earthquake of 1868 of Mw 6.8 and the1969 Loma Prieta shock of Mw 6.9. Only a summary of their findings is repeated here.

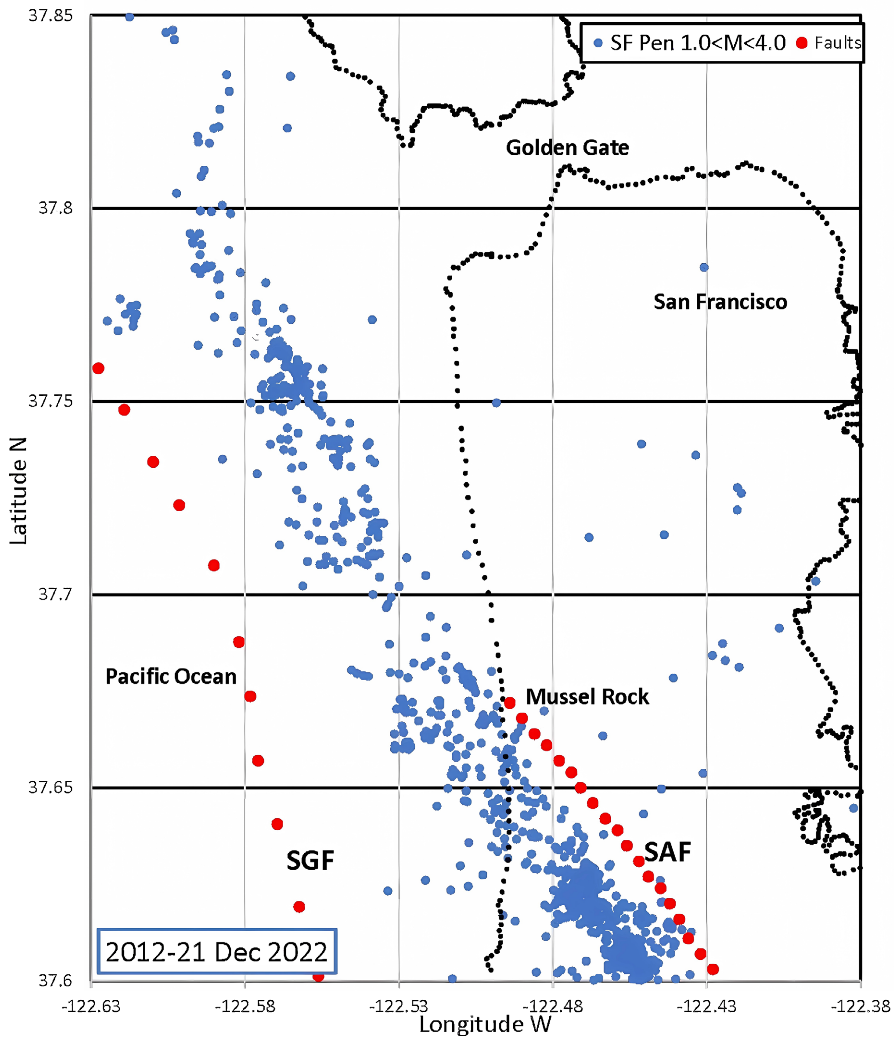

Figure 14. Earthquakes from 2012 to 2019 near San Francisco.

The number of moderate-size earthquakes was much higher from 1872 until the 1906 Great Shock than it was from 1920 to 1954. By 1912, activity had died down after the 1906 event. [28] noted the re-emergence of events of magnitude M 5.0 to 5.9 from 1955 to 1980 after a long quiescence and 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. [1] found that 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. This suggested that the next major earthquake would not be as large or its rupture zone as long as in 1906. Those conclusions were correct for the 1989 event.

[2] and [4] showed that seismic moment Mo accelerated prior to those three large historical earthquakes. Mo is the product of the average slip and the shear modulus. They calculated seismic moments from $\log_{10}\text{Mo} = 1.5\text{M} + 9.0$. The exponential fit 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. That time

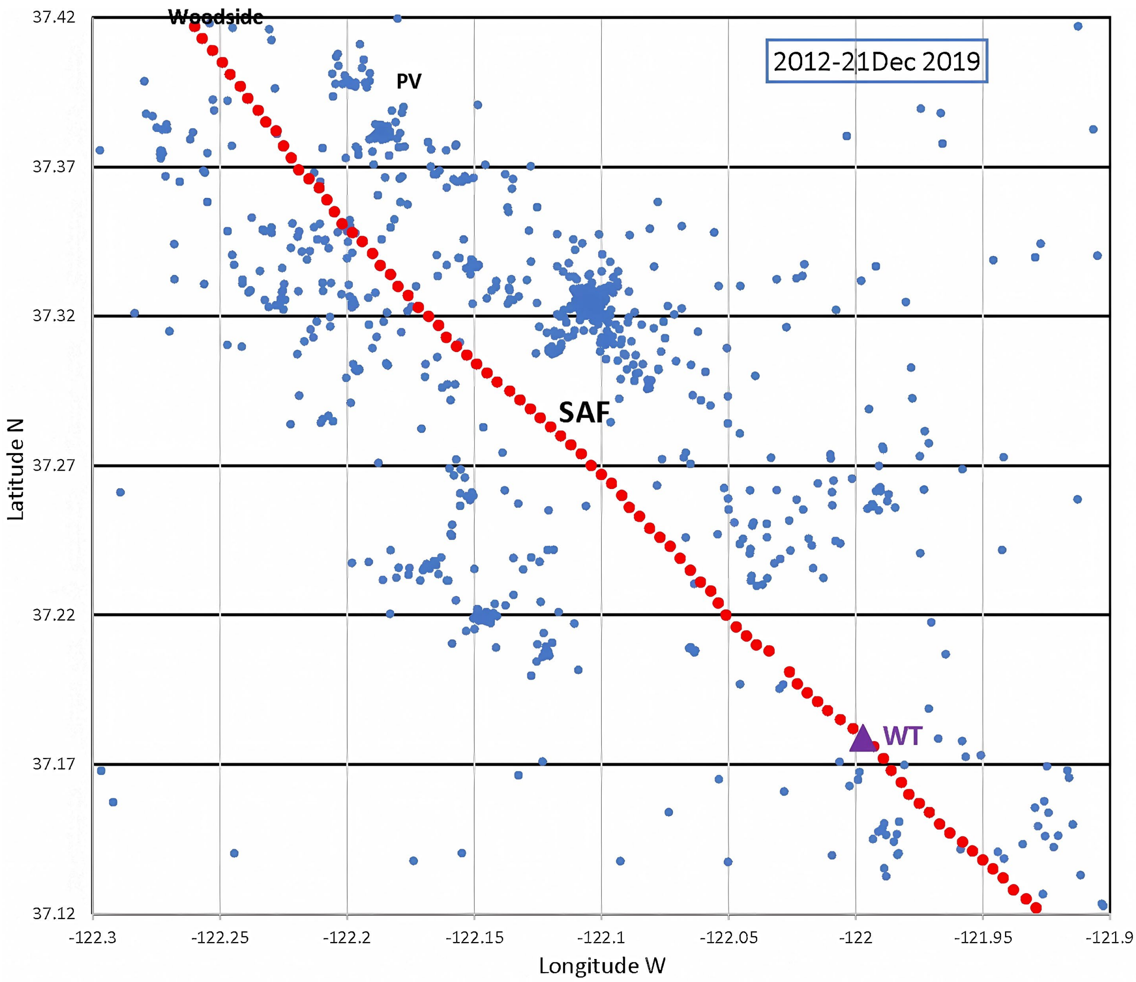

Figure 15. Earthquakes from 2012 to 2019 between Woodside (WOD) and Wright tunnel (WT) along the San Andreas fault.

constant for 1868 is poorly determined since it was based on a preceding shorter interval and more uncertain data.

A shock in 1838 along the San Andrea fault between South San Francisco and the southeastern end of rupture in 1906 was estimated to be at least M 7.4 [3]. Data for it are poorer than those for shocks since the California gold rush of 1848-49. They also estimated that an earthquake of about M 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 compared to those north of the city. Little is known about the 1838 earthquake to the north of San Francisco. It was occupied then by the Russian Empire.

The 1989 mainshock, regardless of its depth, did have a forerunning activity that was anomalous [8] and similar to that in previous major and great earthquakes. Those characteristics, when observed ahead of time, could be used for governmental actions, including decadal predictions for earth and environmental scientists.

I propose that we frequently search for future activity on faults close to but not on parts of the San Andreas fault between San Francisco and Wright tunnel for possible sites of forerunning activity to future major and great events on the San Andreas itself.

6. Earthquakes Defining Asperities in Southern California—The Landers and Hector Mines Sequences

A series of earthquakes of 6.2 < M < 7.3 constitute the Landers-Hector Mines series in the Mojave area to the east of Los Angeles and northeast of the San Andreas fault (Figure 1 and Figure 16; Table 1). They occurred in a broad area between 117.3 and 116.2 West that was active from 1976 to 1999 (Figure 16). They are associated with a bend in the San Andreas fault where activity occurred to the northeast of the San Andreas (Figure 1). Displacements along them were

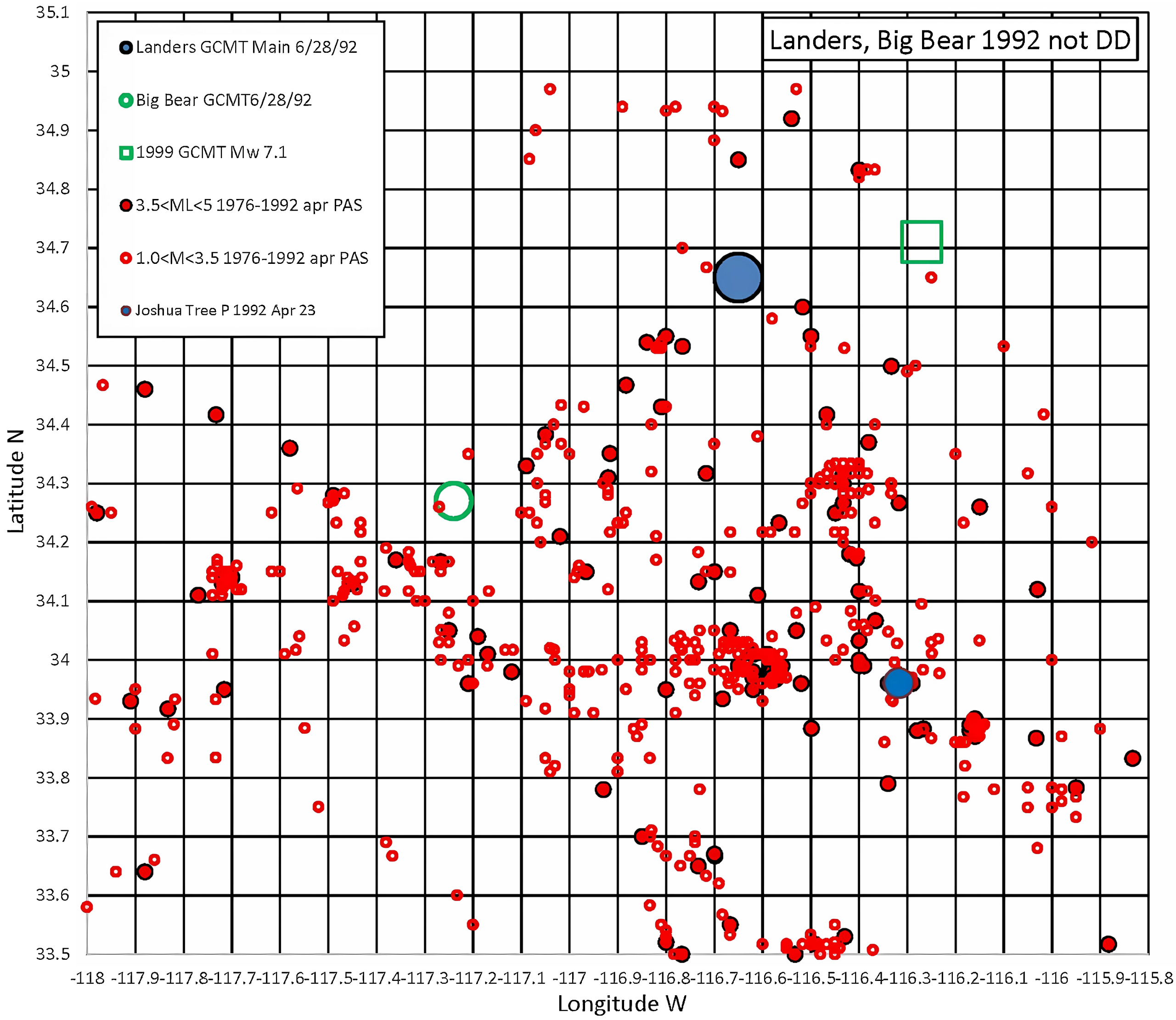

Figure 16. Earthquakes in a broad area to the east of Los Angeles (1976 to 1999).

not parallel to the overall plate motion. More detailed figures help to define asperities and donuts.

The Landers mainshock of Mw 7.3 was preceded two months earlier by the Joshua Tree event of Mw 6.2 just to its south. The Big Bear shock of Mw 6.3 occurred later on the same day as Landers.

Pre-activity to Joshua Tree (Figure 17) defines a major asperity that broke in the April mainshock along a fault of northerly strike.

Figure 18 illustrates broad zones of no pre-activity before the Landers and Big Bear mainshocks. Aftershocks to the end of April of the Joshua Tree main event define its main rupture zone between 33.88° and 34.09° N.

Rupture in the larger Landers event two months later propagated northerly from the northern end of the Joshua Tree zone.

The Landers mainshock itself ruptured several quiet zones (Figure 18 and Figure 21) of differing strikes [29] [30]. The results might be improved by taking into account the three different strikes for Landers displacements in Figure 19.

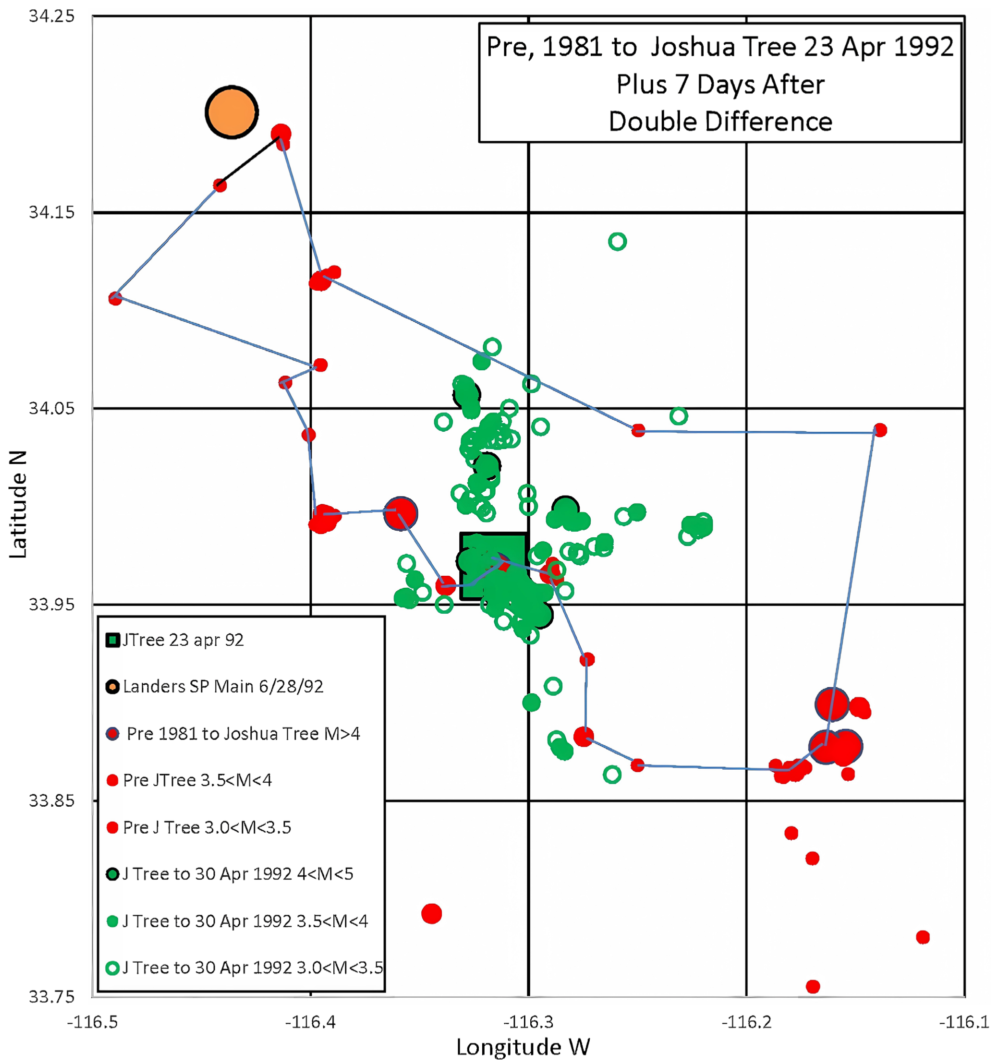

Figure 17. Earthquakes from 1981 to Joshua Tree mainshock of April 1992 and its aftershocks.

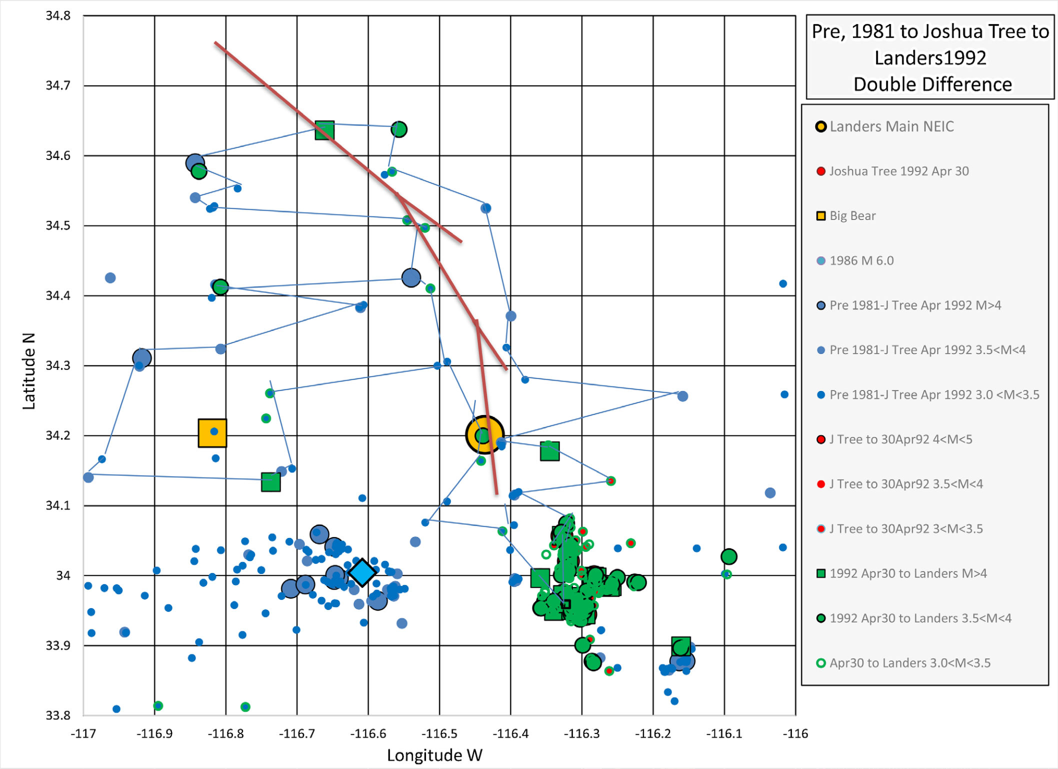

Figure 18. Earthquakes from 1981 to Joshua Tree mainshock of April 1992 and its aftershocks through the start of the Landers mainshock of June 1992 (solid yellow circle). Three red lines represent displacements mapped by [29] [30].

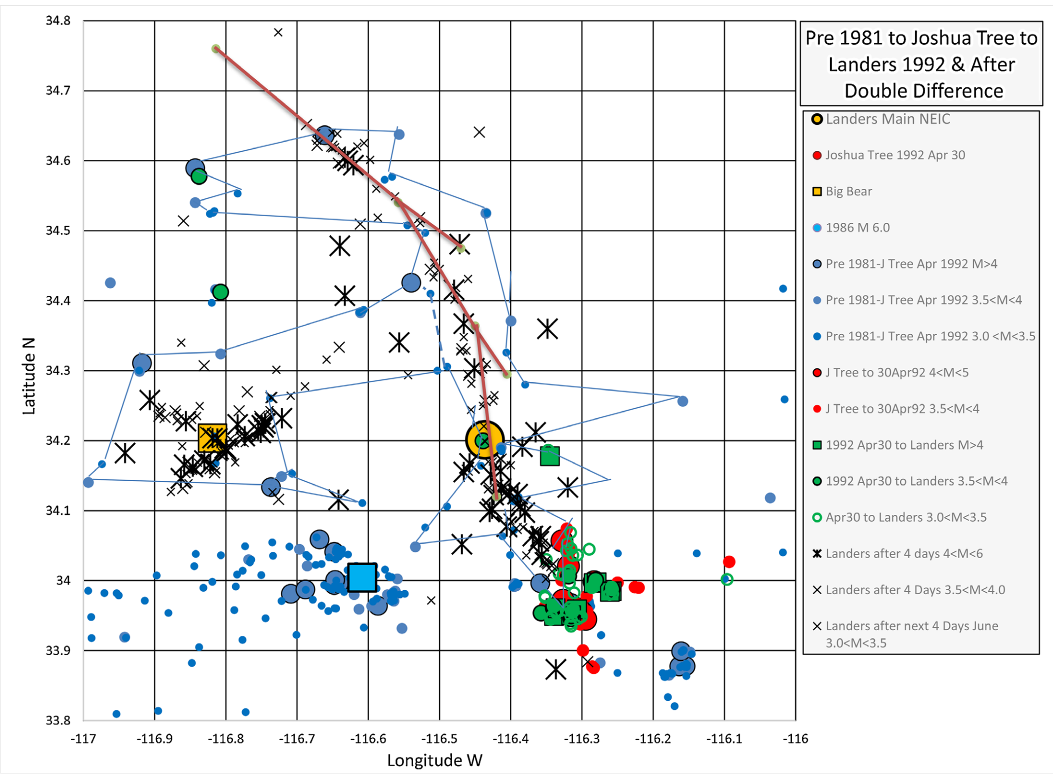

Figure 19. Earthquakes as a function of latitude and longitude from 1981 to the Joshua Tree mainshock of April 1992 and the Landers mainshock of 28 June 1992. Four days of Landers aftershocks are shown as x's. Red lines denote previous faulting at surface [29] [30].

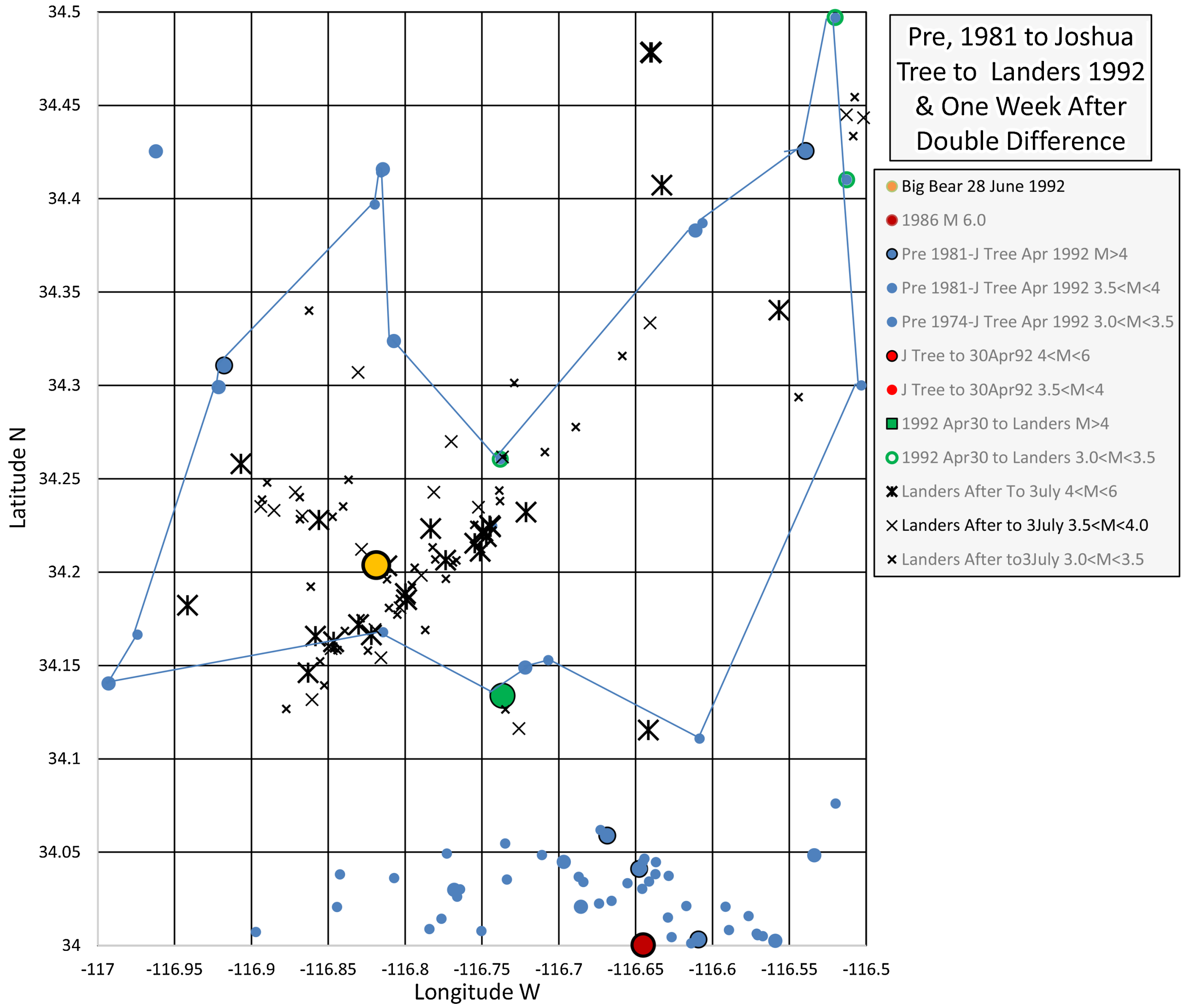

Figure 20. Earthquakes from 1981 to aftershocks of Landers.

What is surprising is that smaller shocks from Joshua Tree in April until Landers in late June (Figure 18) occurred well north and northwest of the start of rupture in Landers. They might be interpreted as precursors to Landers. They are an indication that Landers would break in a large event as far north as it did.

6.1. Rupture Zone of 1986 Event

A shock of Mw 6.0 is illustrated in Figure 22 to the south of the Landers sequence (Figure 1). It too was surrounded by a prior quiet zone of seismicity, i.e., an asperity. It appears to have been located on a separate seismic zone from the Landers sequence of 1992 (Figure 18 and Figure 20).

6.2. Rupture Zone of 1999 Hector Mines Event, Mw 7.1

A major asperity is seen in Figure 23 before the 1999 mainshock. Its strike NNW is similar to that mapped by [31].

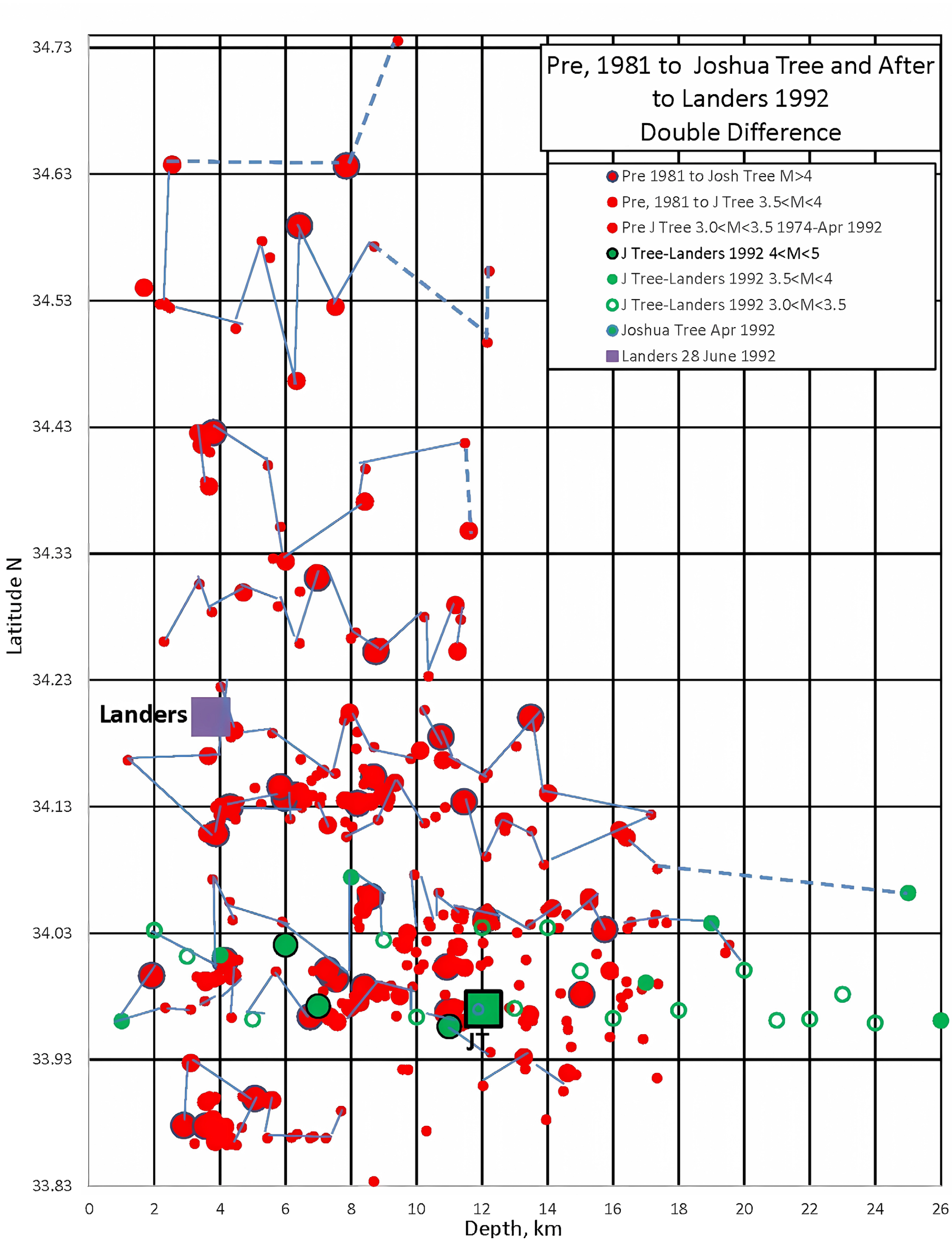

Figure 21. Earthquakes as a function of latitude and depth from 1981 to Joshua Tree mainshock of April 1992 and its aftershocks and through the start of Landers on 28 June 1992.

Two quiet zones (asperities) and three regions of prior activity constitute the 1999 Hector Mine sequence in **Figure 24**. It is similar to that by [31] and for Landers in **Figure 21**. Thus, Landers and Hector Mines—each larger than M 7—each broke several adjacent asperities.

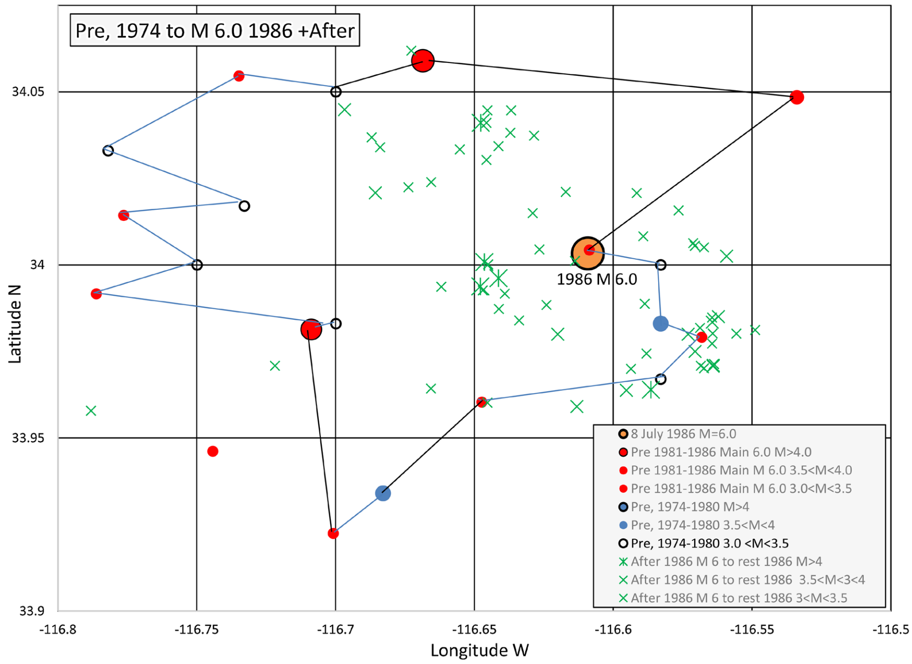

Figure 22. Earthquakes from 1981 to 1986 mainshock of M 6.0 and its aftershocks.

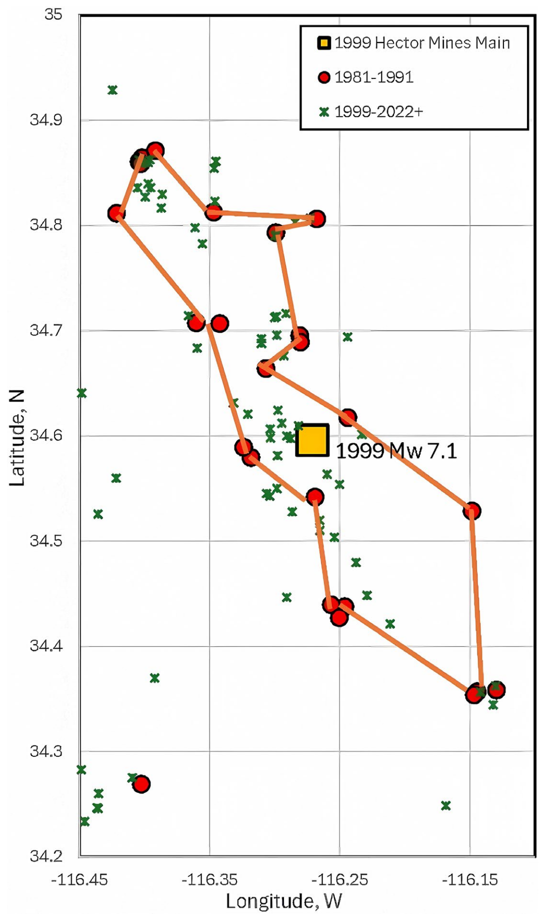

Figure 23. Earthquakes from 1981 to 1991 define a major quiet zone prior to the 1999 mainshock.

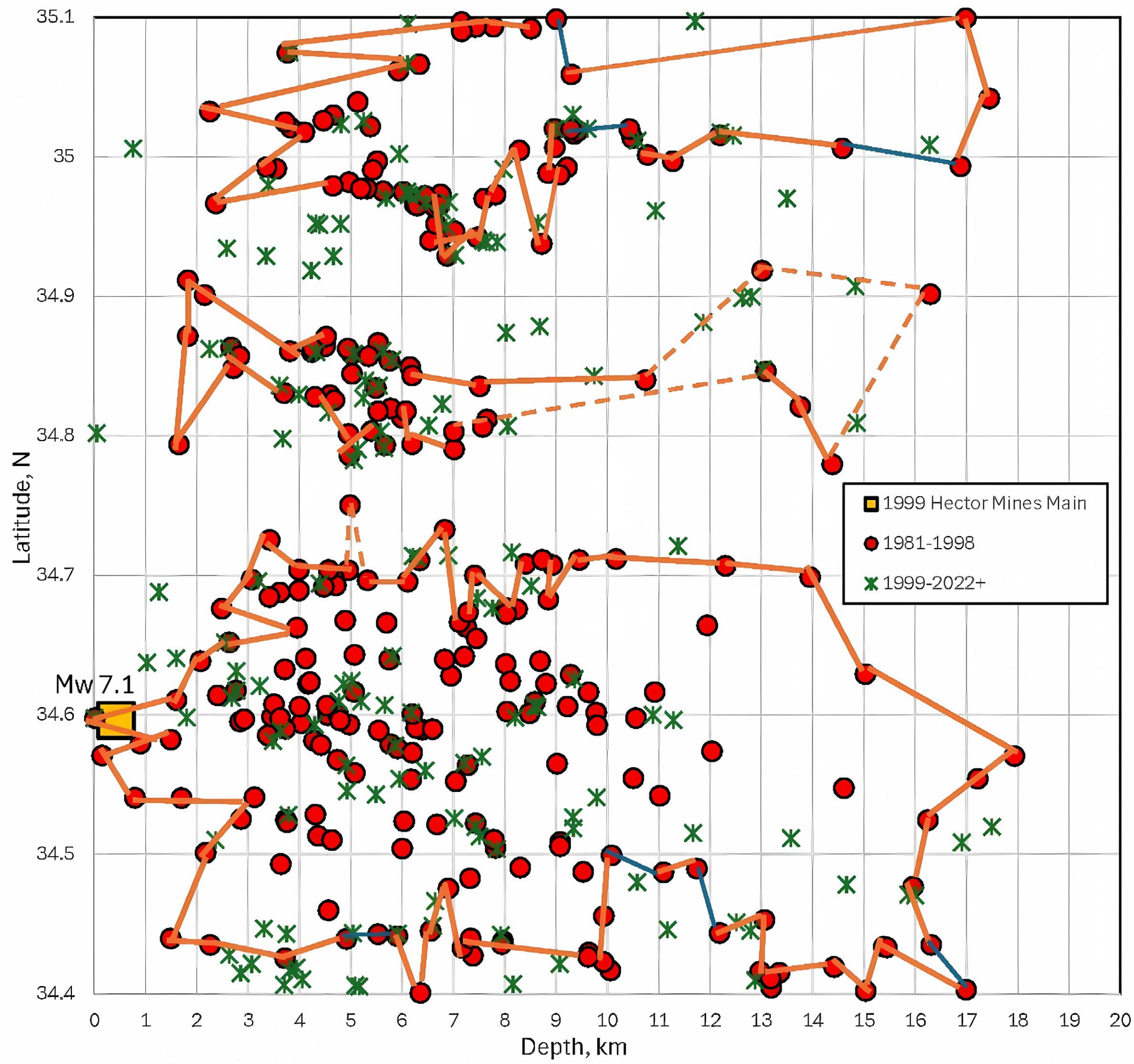

Figure 24. Earthquakes from 1981 to Hector Mine mainshock 1999 and aftershocks.

7. South Napa Mainshock to Northeast of San Francisco in 2014

The quiet zone (asperity) prior to the 2014 South Napa mainshock in **Figure 25** was much longer than its aftershocks, suggesting that the actual rupture length was shorter.

A number of moderate-size earthquakes occurred in the last 20 years near Berkeley (UCB) on the northern Hayward fault. Since that part of the Hayward likely did not rupture in 1868, many seismologists in the Bay area thought the events foretold a coming large event near Berkeley. Some parts of the Hayward fault have experienced creep.

The South Napa mainshock triggered deep, slow events near Parkfield. Hence, the activity near Berkeley may have occurred as stresses built up to the South Napa mainshock. The presence or lack of much activity on the northern Hayward fault during the next decade may well favor one of the two hypotheses—slip

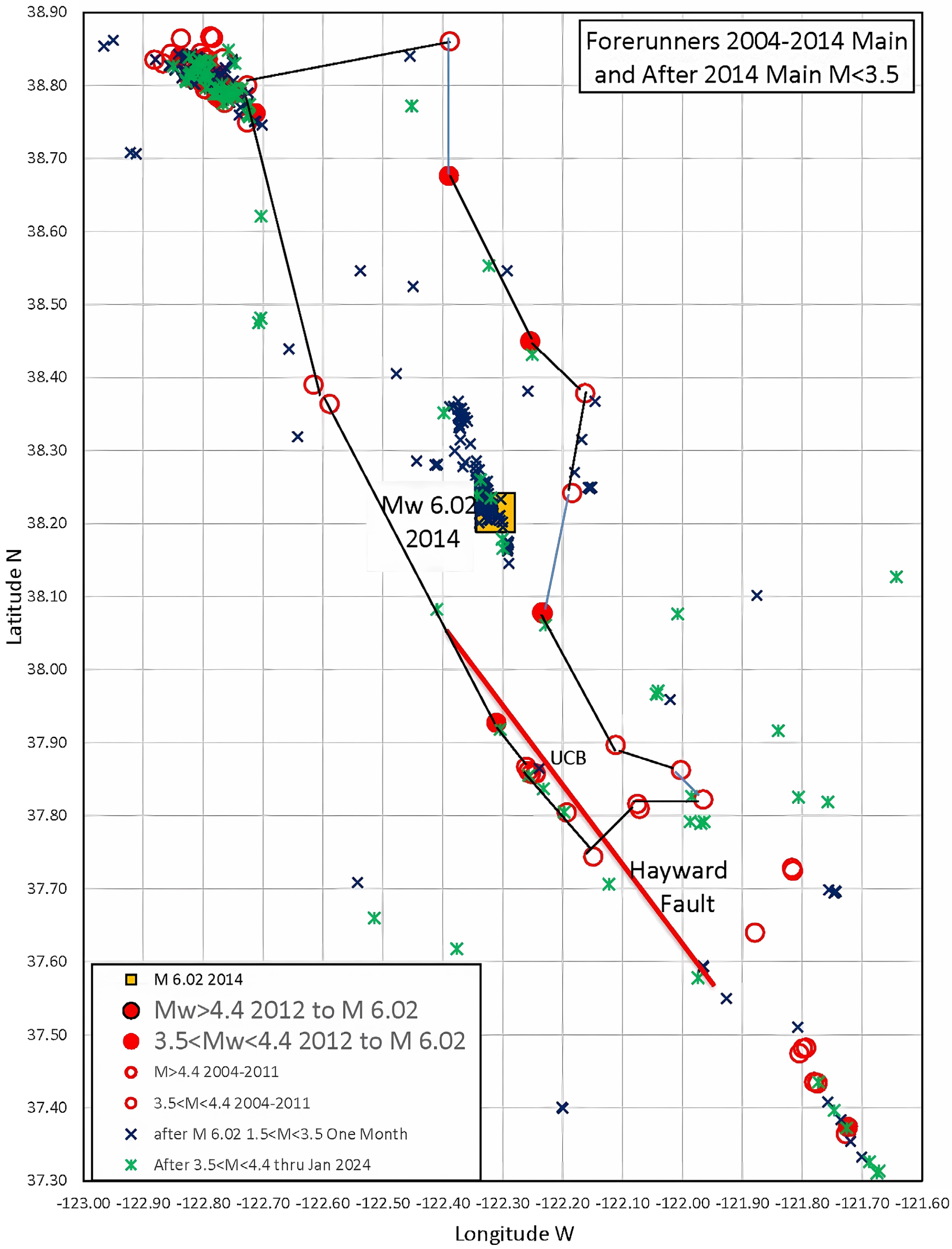

Figure 25. Earthquakes in vicinity of South Napa Mainshock of 2014 from 2004 to its aftershocks. UCB = University California Berkeley.

triggered by the 2014 event or a coming large earthquake. The Hayward fault is close enough to many people and assets that the region needs to be carefully monitored and studied.

8. Mendocino Triple Junction

The area near the triple junction, which involves the Gorda plate to the north, the

North American plate to the east, and the Pacific plate to the southwest (**Figure 26**), is one of the most active in the United States. [11] and [32] examined activity before the 1992 mainshock and its 1991 large forerunner.

Most events in the area had strike-slip mechanisms (yellow). The 1991 and 1992 large events involved thrust faulting instead. It and the other red events in **Figure 26** occurred outside of what is taken to be a quiet region or asperity for thrust shocks (but not for strike-slip). Great thrust events are likely to occur along the longer Pacific-Gorda plate boundary to the north.

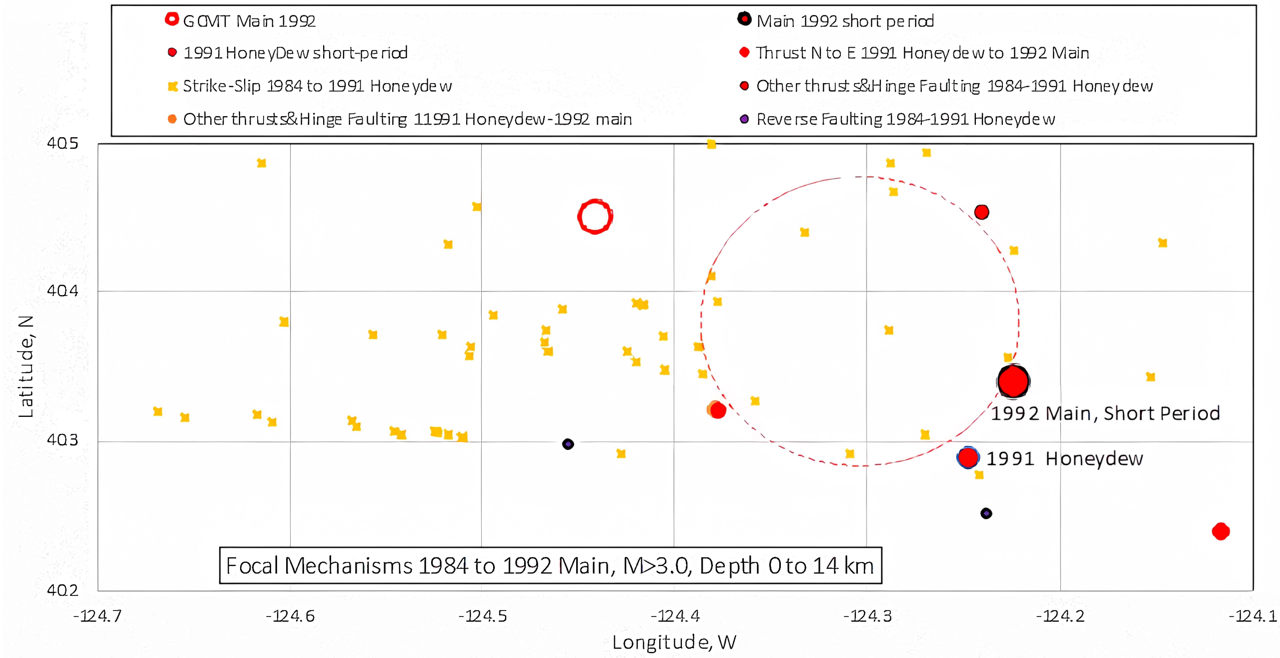

Figure 26. Earthquakes near Mendocino triple junction of depths from 0 to 14 km from 1984 to 1992 mainshock. Republished from [11].

9. Discussion and Conclusion

For the 11 larger earthquakes examined (of very long-period magnitudes Mw 6 to 7.3), quiet zones of preceding smaller shocks are identified. They are called asperities and are surrounded by donut patterns of moderate-size shocks. Each of them could be used ahead of time to estimate the size of the next large event that will rupture that asperity. The search for long-term precursors to it should focus on the donut and not on either the asperity or measurements at the Earth's surface. Double-difference locations of small earthquakes provide structural geological information about faults, especially their depth distribution. This is another method to estimate the size of at least some future large earthquakes.

Multiple asperities are defined ahead of time as those that broke in shocks of Mw ≥ 6.8, such as Loma Prieta and Landers. Moderate-sized earthquakes in the two months before the Landers mainshock indicate that it was likely to break several asperities to the north of the Joshua Tree event, resulting in a forecast for Landers being Mw > 7.

The physics of asperities that break in large shocks must be very different from their surrounding zones (donuts) that repeatedly rupture in moderate-size earthquakes. The buildup of stress in asperities can be called velocity weakening [33] [34]. Since the rate of activity in Parkfield donuts is nearly constant, it is not clear if it involves velocity strengthening.

Some wonder if long-term forecasts might be useful. The 1989 Loma Prieta shock south of San Francisco was preceded two years before by two unusual nearby events of magnitude M > 5. The San Francisco-Oakland bridge was heavily damaged in the Loma Prieta event. More than a year was needed to repair it. If work had been done to fix it in the previous year, it might have withstood the main 1989 earthquake. Fixing it ahead of time, however, would have involved considerable political debate and financial decisions.

We may be able to make decadal forecasts when short-term predictions are not possible. I propose designating "earthquake alerts" that would be somewhere between clearly defined predictions and no actions at all. They could be made starting soon but likely would be of varying specificities. Initially, they might be discussed by scientific communities.

Many colleagues in California are repeatedly asked, "When is the next Big One going to occur?" Some have responded, "We don't know; earthquake prediction is impossible since shocks are a chaotic process." Weather is also a chaotic process. Nevertheless, forecasts are now being made 10 days ahead, which is as good as those made 30 years ago for 3 days ahead of time. This improvement was, in part, due to the use of global satellite observations and computer processing. Forecasting earthquakes should be cast in a similar manner. They might be easier than weather forecasts since the atmosphere, unlike the solid earth, moves a lot over a period of days.

Many statements about not working on prediction today resemble those made from 1920 to 1965 that continental drift was impossible. We still have much work to do with forecasts of earthquakes on various time scales and understanding their physical bases. The physical mechanisms of regional faults like the Calaveras and Hayward in northern California, which exhibit creep, differ from those of the northern San Andreas, which is currently locked and is not creeping. Moderate-size earthquakes along some of those creeping faults slowly increase in numbers as stresses in the region are restored in the latter part of the cycle of stress restoration to major and great earthquakes along the San Andreas. Better mapping of creep is needed.

Much remains to be learned about the physics and predictability of large and great earthquakes on faults like the San Andreas, those in Türkiye, Japan and South America.

The Gofar oceanic transform fault complex near 4˚ S along the fast-spreading East Pacific Rise has one of the best recordings of seismic cycles [35] [36]. Several of its segments have experienced Mw > 5.5 shocks. The 160-km long Gofar system was divided [34] into three major segments with six asperities over the past 30 years. Most of those asperities broke about every 3 to 5 years. These short intervals for breakage of asperities make them ideal for understanding repeat times of large events.

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Conflicts of Interest

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

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