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Decadal and Yearly Forerunning Earthquakes to Cape Mendocino, Northern California, Mainshock of 1992 Magnitude 6.9

Lynn R. Sykes

Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York, USA
Email: SYKES@LDEO.COLUMBIA.EDU

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Abstract

The area near the Cape Mendocino earthquake of 1992, magnitude 6.9, was the site of many moderate to large shocks during the previous decades. It and the Honeydew event of 1991, however, are distinguished from most earthquakes in the region by their thrust-fault mechanisms. The magnitude of the 1991 shock was also unusually large for the preceding decades, Mw 6.1. The mechanisms of most other large events involved strike-slip faulting. The 1992 mainshock occurred in a volume of space characterized by few decadal forerunning earthquakes of moderate to large size. Most of those forerunners took place on the periphery of that volume. The presence of that zone suggests that it broke previously in a large to great earthquake. Precise locations indicate that slip in the 1991 and 1992 earthquakes occurred on faults dipping shallowly to the NE and ENE. They likely took place within the North American plate above the subduction plate boundary. Their implications for earthquake forecasting using sparse precursors are discussed.

Keywords

Earthquakes, California, Prediction, Precursors, Subduction, Cascadia, Gorda Plate

1. Introduction

The triple plate junction near Cape Mendocino in northern California is the most seismically active region in the contiguous United States (**Figure 1**). The Pacific, North American and Gorda plates interact seismically onshore and off the coast. A mainshock on 25 April 1992 of revised long-period magnitude Mw 6.91 [1] ruptured the southern end of the Cascadia subduction zone (**Figure 1**).

This paper describes the 1992 mainshock and an intermediate-term precursor called the Honeydew event of Mw 6.05 that occurred eight months earlier. Each was unusual for the region since their mechanisms involved thrusting on shallow-dipping fault zones (**Table 1**), likely above the plate boundary. Little work has been done to study either decadal forerunning events, shorter-term precursors or possible implications for earthquake forecasting.

This paper emphasizes decadal and yearly forerunners to the 1992 mainshock after separating various events by depth, latitude, longitude, magnitude and mechanism. I pay particular attention to the detailed geometry of preceding seismic activity from 1984 to the 1991 and 1992 events using a catalog where hypocenters are located with respect to one another with precisions of 10 s of meters or better [2] [3] [4]. 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. This was typically a 50-times increase in precision compared to those of routine locations in the area.

1.1. Tectonic Setting

Figure 1 shows earthquake activity along the three plate boundaries studied as well as within the Gorda plate. The three meet at what is called the Mendocino triple junction. The region is dominated by earthquakes with strike-slip mechanisms (yellow symbols). They occurred along the Mendocino transform fault near and to the northwest of the 1992 mainshock as well as along the Blanco transform fault. Shocks along the spreading Gorda ridge involve a predominance of normal faulting. Other earthquakes occurred within the downgoing Gorda plate where it is being subducted beneath the North American plate.

The southern Gorda plate is unusual in that many earthquakes occur within it with strike-slip mechanisms. It has been known since the early days of plate tectonics that the Gorda plate has been deformed during the last 10 million years [6] [7]. The deformed seafloor magnetic anomalies on the southeastern side of the Gorda plate result from compression as the Pacific plate converges upon it along the Mendocino transform (**Figure 1**). That transform has been moving northward for about the last 30 million years. The Gorda plate shrinks in size as the San Andreas fault system continues to grow to the northwest [6] [7]. Some North American-Pacific plate motion occurs to the east of the San Andreas fault (southeast of **Figure 1**) especially along the Maacama and Bartlett Spring faults.

Table 1. Revised mechanisms for Mendocino earthquakes of 1991 & 1992 [1].

Date	Latitude, N	Longitude, W	Depth	Magnitude	Nodal Plane1	Nodal Plane2
GCMT	GCMT		Fixed	Mw	Strike/Dip	Strike/Dip
1991 Aug. 17	40.33	124.30	12.0 km	6.06	317/31	162/62
1992 April 25	40.45	124.44	12.0 km	6.91	334/16	172/74

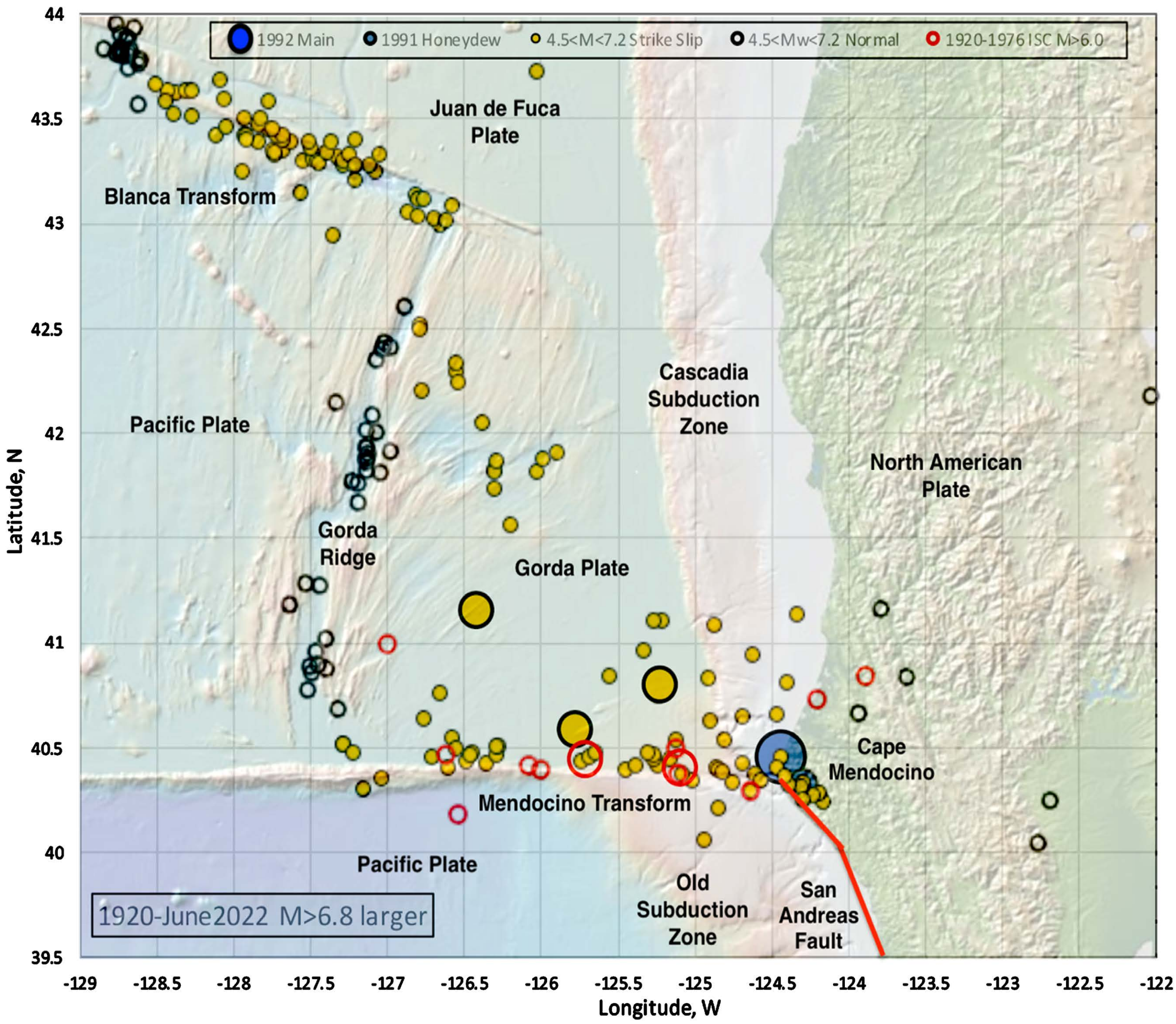

Figure 1. Earthquakes of magnitude M > 4.8 and their mechanisms on the periphery of and within the Gorda plate from 1920 to June 2022. Larger symbols denote shocks of M ≥ 6.8. Blue circles denote the centroids of the 1992 Cape Mendocino mainshock of Mw 6.91 and the 1991 Honeydew event of Mw 6.06. Later figures are from a smaller area near those two events. Bathymetry and topography from [5].

Much of the northernmost San Andreas fault, described later, has been remarkably quiet even for microearthquakes.

Only the southernmost 100-km extent of the Cascadia subduction zone off the northwestern United States has been seismically active for large shocks during the last 100 years (**Figure 1**). It and the entire plate boundary farther north broke in a giant subduction zone shock in 1700 and in earlier events that were detected by paleoseismic studies [8]. Work on the 1992 Cape Mendocino earthquake may have the potential to understand better great shocks along that subduction zone to the north as far as British Columbia and possibly the norther end of the San Andreas fault. Separating earthquakes by their mechanism is a major step in identifying precursors to the 1992 mainshock.

1.2. Previous Studies of 1992 Earthquake

In 1993 [9] published a description of several data sets for the 1992 mainshock. Rupture initiated onshore at a depth of 10.5 km and propagated up-dip and seaward. It damaged local towns, generated coastal uplift and produced a tsunami. Figure 2 shows the rupture zone inferred by [9] from changes in vertical deformation as a dashed rectangle.

The recomputed centroid moment-tensor, CMT, [1] places it near the northern end of the rupture zone as inferred by [9] and 30 km to its west (Figure 2). The original CMT produced in 1992 was located about 20 km to the south and 10 km to the east of the recomputed one [10] [11]. The revised dip of the CMT was increased from 9˚ to 16˚, resulting in Mw being revised downward from 7.15 to 6.91 [1]. Each CMT indicates a predominance of thrust faulting of shallow dip. That distinguishes the 1992 shock from the many of the strike-slip solutions in the region.

While the absolute location of the revised CMT is uncertain, its location suggests that rupture extended farther west than that deduced from geodetic data by

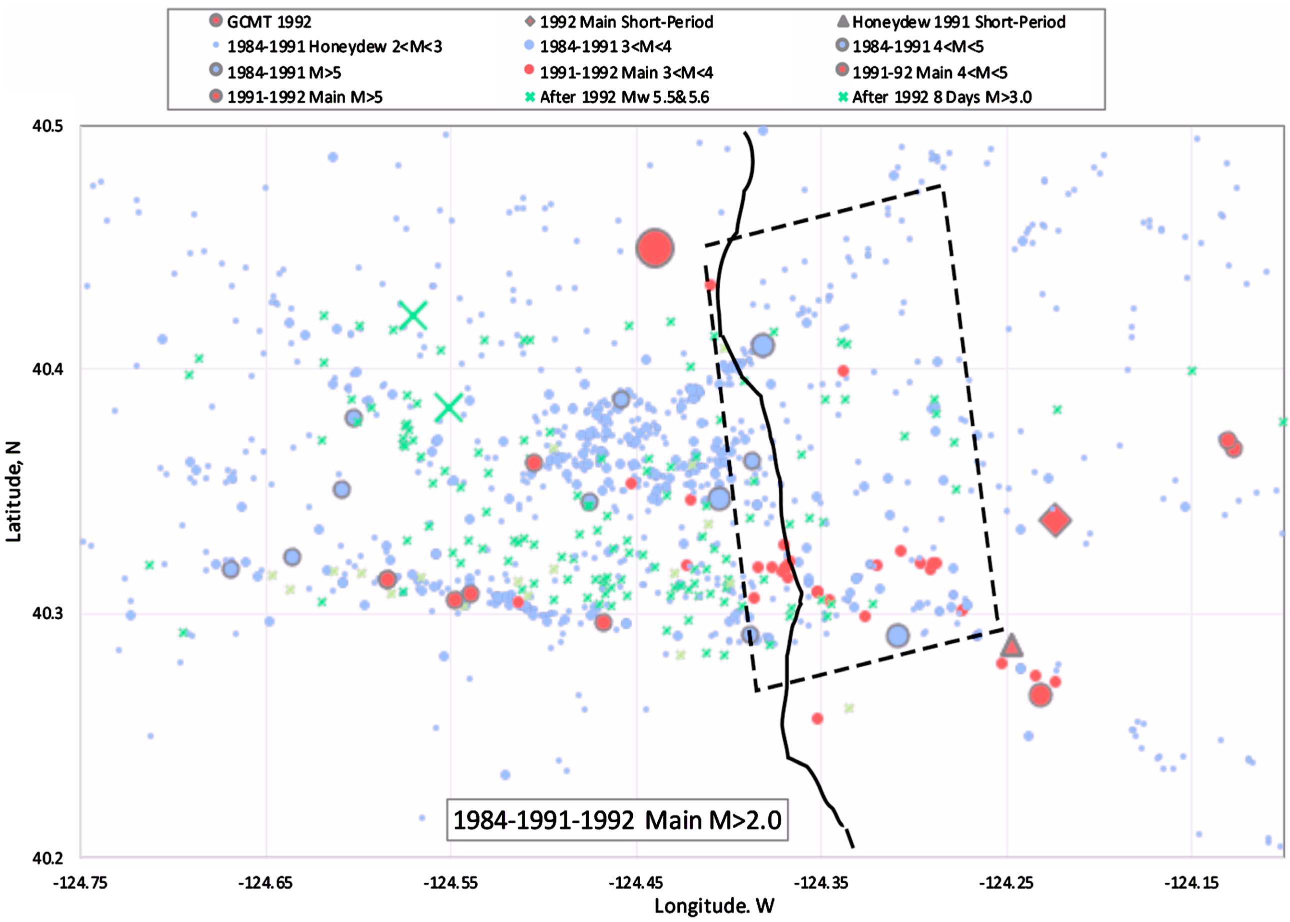

Figure 2. Earthquakes of magnitudes M>2.0 from 1984 until the 1991 Honeydew shock (blue), from it until the 1992 mainshock (red) and aftershocks of 1992 for 8 days (green). The Centroid Moment Tensor (CMT) for 1992 and short-period locations for the 1991 and 1992 events are in red. Large green crosses are aftershocks of Mw 6.5 and 6.6 during the day of the 1992 mainshock. Dashed box is rupture zone of 1992 shock deduced from geodetic data and sea level changes [9].

[9]. [12] used long-period seismic waves to deduce that the 1992 mainshock ruptured WSW from the initial short-period hypocenter. They place the rupture zone as far west as that determined from geodetic data as well as 5 km to its south but only in its southern half. I later discuss the volume of the zone that was largely quiet before the 1991 and 1992 earthquakes as another measure of the approximate size of the 1992 event.

2. Methods

I use hypocentral locations from 1984 to 2014 of earthquakes from the catalog for northern California, NCAeqDD.v202112.1, http://ddrt.ldeo.columbia.edu [2] [3] [4]. It consists of updated high-resolution double-difference solutions. It contains local magnitudes and short-period solutions indicative of where rupture initiated in those events. I emphasize events since 1984 as digital waveforms were not available previously for very many events.

The very long-period magnitude, Mw, and its corollary seismic moment, Mo, are needed to quantify the large dimensions and magnitudes of major earthquakes such as the 1992 mainshock. Seismic moment, Mo in N-m, is related to Mw by

$$\log Mo = 1.5\ Mw + 9.1 \quad (1)$$ [13] [14]

I also examined earthquakes of Mw 5.0 and greater since the Global Centroid Moment Tensor (GCMT) catalog started in 1976 [10] [11] [15] [16]. GCMT solutions improved over time and were extended to events as small as Mw 5.0. Pre 1976 solutions are from the *Bulletin of the International Seismological Centre*, the U.S. Geolological Survey and [17]. The computer program GeoMapApp [5] was used for bathymetry and topography.

3. Results

3.1. Forerunning Earthquakes to 1992 Mainshock

Figure 2 illustrates patterns of forerunning and aftershock activity in an enlarged view near the 1992 mainshock. Forerunning activity from 1984 to the 1991 Honeydew earthquake in blue is largely concentrated either to the south or north of most of the 1992 aftershocks (green). Most activity between the 1991 Honeydew shock and the 1992 mainshock (red) occurs either along the Mendocino transform or within the Gorda plate but only up to 11 km west of the 1991 short-period hypocenter. Some of those events are aftershocks of the 1991 mainshock. Others are far enough west, however, that they can be interpreted as earthquakes triggered by the final stress buildup to the 1992 shock. It Is clear that the 1991 shock occurred very close to the 1992 rupture zone. Various events are portrayed separately later by their depth of focus.

3.2. 1992 Cape Mendocino Mainshock

Figure 3 illustrates the same earthquakes as in **Figure 2** but as a function of

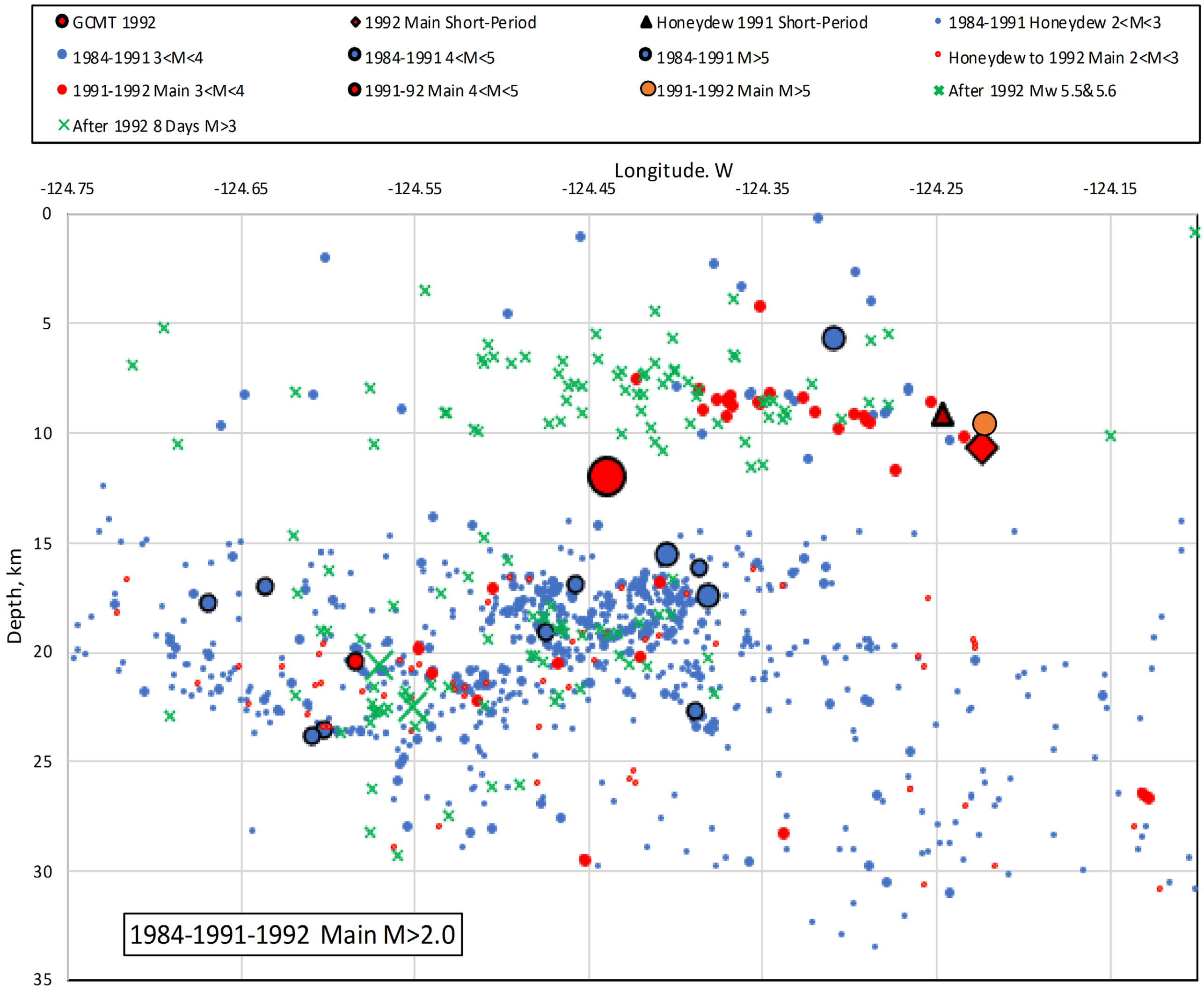

Figure 3. Earthquakes as a function of longitude and depth for M > 2.0. Symbols same as Figure 2.

depth and longitude. The aftershocks fall largely into two groups—those shallower than 11 and ones deeper than 15 km. The aftershocks in red for the 1991 Honeydew earthquake define a plane dipping shallowly, which is consistent with its revised CMT solution (Table 1). Its aftershocks indicate that it ruptured westerly and up dip. Likewise, events after the 1992 mainshock indicate a similar rupture pattern but one that extended farther west and north as discussed later. The 12-km depth of the 1992 main event is the shallowest permitted by CMT processing. Its short-period depth was 10.5 km. The mainshock likely ruptured somewhere between depths of 6 and 11 km.

Figure 4 expands a similar view for depths only between 0 and 15 km. Aftershocks of the 1992 mainshock extended farther west than those for the 1991 event. The 1991 ones are also more concentrated in depth. Little activity occurred between depths of 0 and 4 km.

It is difficult to tell how far westerly rupture took place in the 1992 mainshock since the two largest aftershocks of Mw 6.5 and 6.6 occurred within one day.

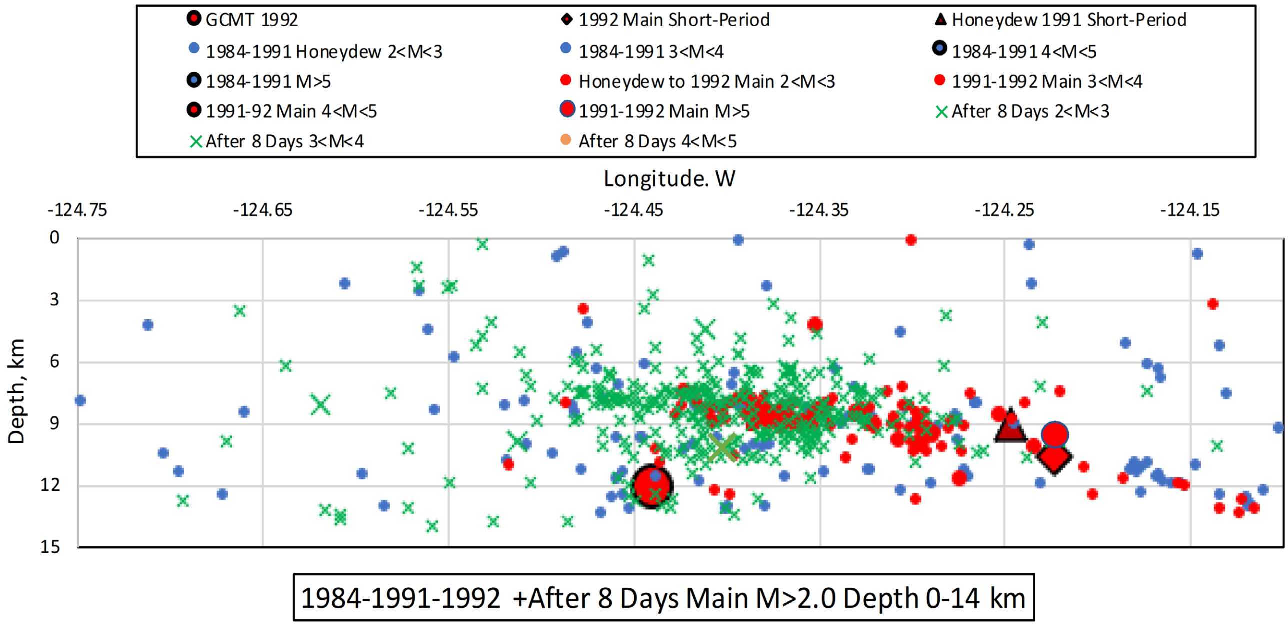

Figure 4. Earthquakes of magnitudes M > 2.0 for depths of 0 to 14 km from 1984 until 1991 Honeydew shock in blue, 1991 to 1992 mainshock in red and eight days of aftershocks in green.

Their depths (Figure 3), however, place them within a deeper zone of activity in the downgoing Gorda plate. Their mechanisms and rupture modelling [12] indicate one involved strike-slip motion on a northeasterly-striking zone and the other strike slip on a northwesterly-trending zone. While they were triggered by the1992 mainshock, their mechanisms and depths were decidedly different.

3.3. Size of the Asperity that Ruptured in the 1992 Mainshock

Figure 5 shows activity for depths of 0 to 14 km as a function of latitude and longitude. Aftershocks shallower than 14 km occurred between the Mendocino transform to the south and the CMT solution for the 1992 mainshock 17 km to the north. Aftershocks of 1992 were largely delimited to the north by the Bear River fault (BRF of Figure 5).

Most of the activity shown between those latitudes in Figure 2 was deeper than 14 km. It is clear that few forerunning shocks to 1992 of those depths took place north of the 1991 aftershocks and south of the 1992 CMT solution. That region can be described as a large asperity that broke in the 1992 mainshock. It denotes a region that probably slipped previously as a large thrust mainshock at an unknown date.

Very large mainshocks and their forerunning events are described in terms of the rupture of asperities of various sizes, *i.e.*, relatively strong, well-coupled portions of plate interfaces. The term asperity is used extensively in the seismological and rock mechanics literatures. Some parts of plate boundaries consist of great asperities that are well coupled, *i.e.*, largely locked, during the slow process of stress buildup to large earthquakes. Other parts, so called low-coupling zones (LCZ), often are identified as the sites of either moderate-magnitude forerunning

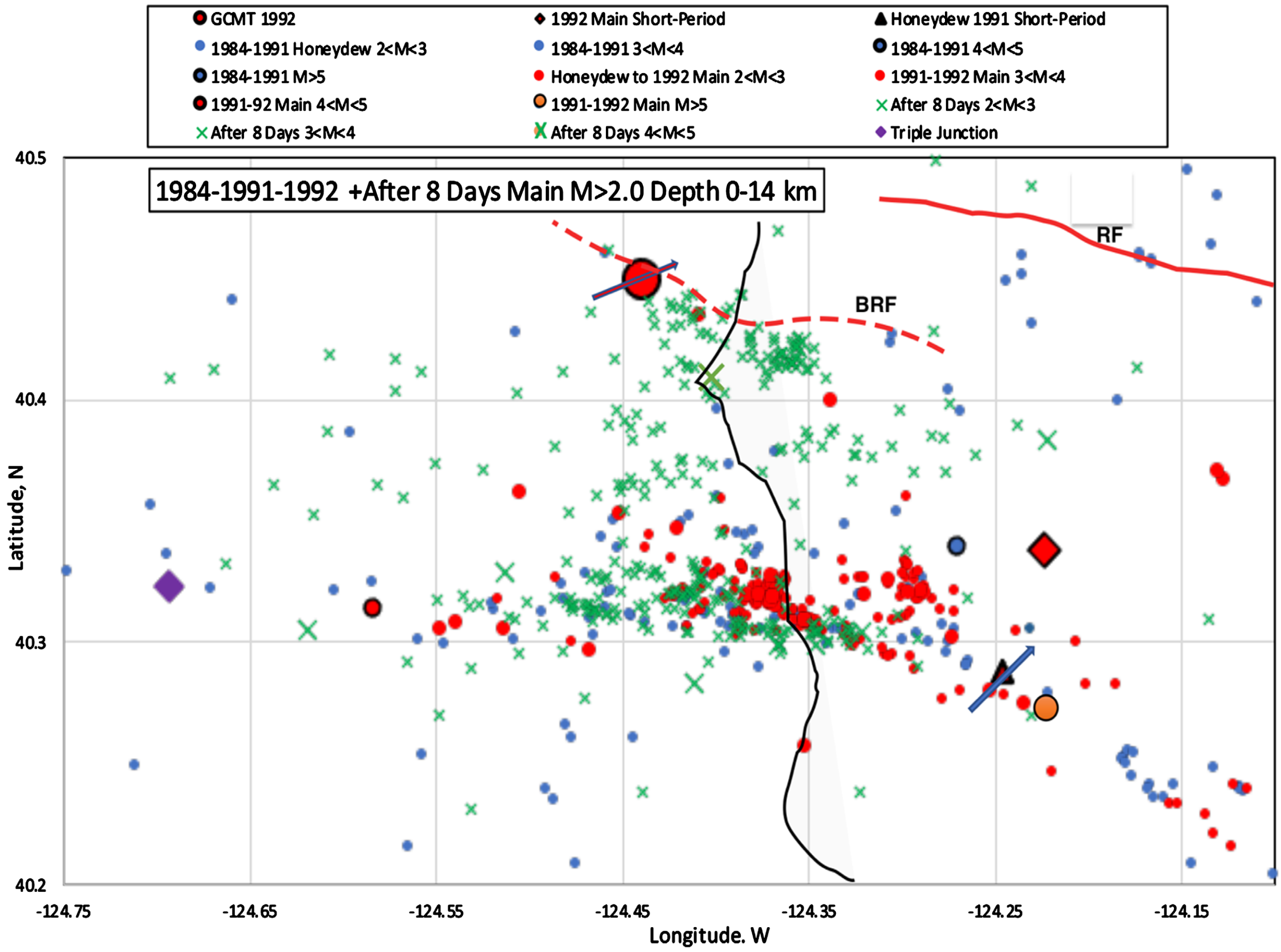

Figure 5. Earthquakes of magnitudes M>2.0 for depths of 0 to 14 km. Two arrows indicate slip vectors of 1991 and 1992 earthquakes for movement of Gorda plate with respect to a fixed North American plate. Other symbols same as Figure 2. RF (Ross) and BRF (Bear River) are large surface faults reported by [13].

activity, smaller asperities or fault creep. Much forerunning activity as well as several slow-slip events described in the literature occurred in LCZ's on the peripheries of great asperities world-wide [14] [15]. The pattern of forerunning activity to the 1992 mainshock was similar even though it likely occurred above the plate boundary.

Many of the larger forerunning shocks in Figure 2 occurred at depths below 14 km, *i.e.*, deeper than that of the rupture zone of the main 1992 earthquake. Many other smaller forerunning events shown in Figure 6 took place at depths deeper than 14 km. Thus, they and all but one of the larger forerunning earthquakes occurred below the large asperity that broke in 1992. The quiet zone and its inferred large asperity were three-dimensional in shape.

Figure 7 shows known mechanisms of earthquakes with depths between 0 and 14 km from 1984 until the 1991 Honeydew shock plus three thrust mechanisms (two close together) from it in 1991 until the 1992 mainshock. An ellipse in red is drawn around the region of few forerunning thrust and reverse faulting events to approximately define the size of the coming 1992 mainshock. It is

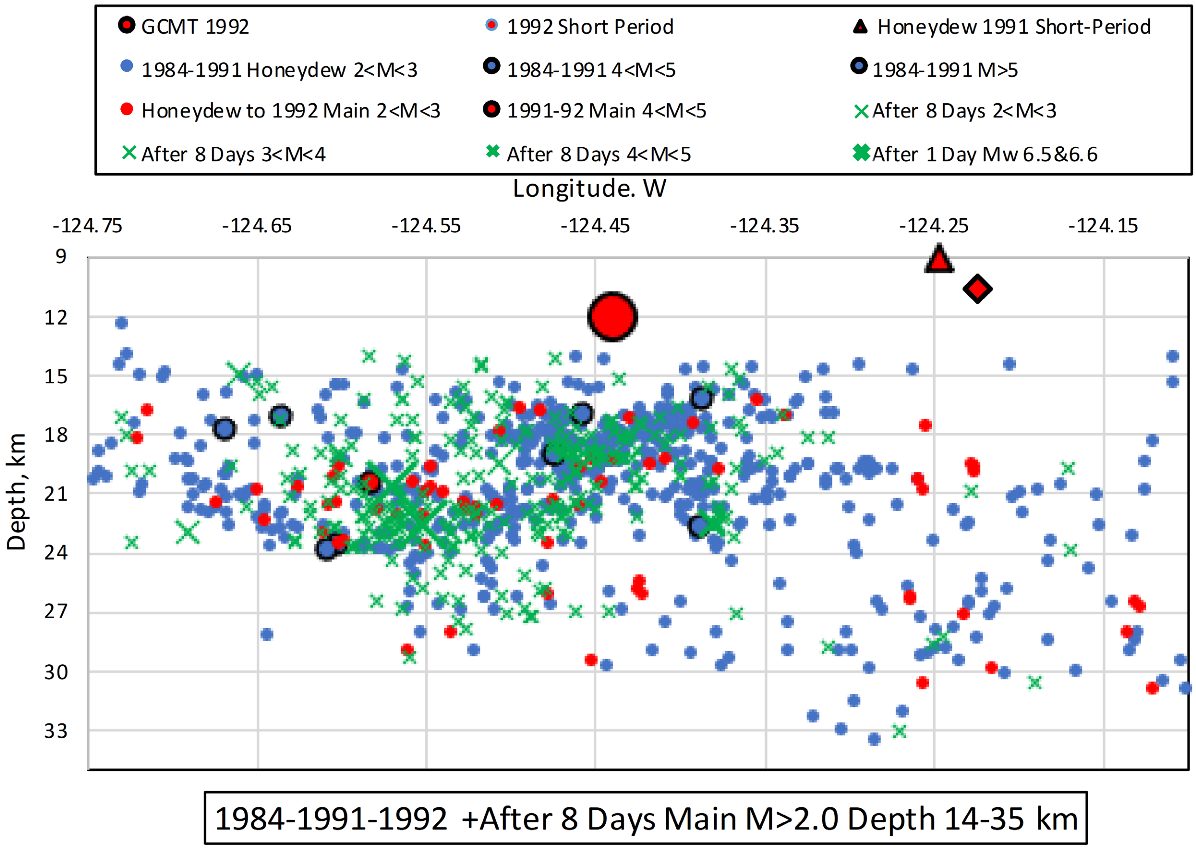

Figure 6. Earthquakes of magnitudes M > 2.0 for depths of 14 to 35 km from 1984 until 1991 Honeydew shock in blue, 1991 to 1992 mainshock in red and eight days of aftershocks in green.

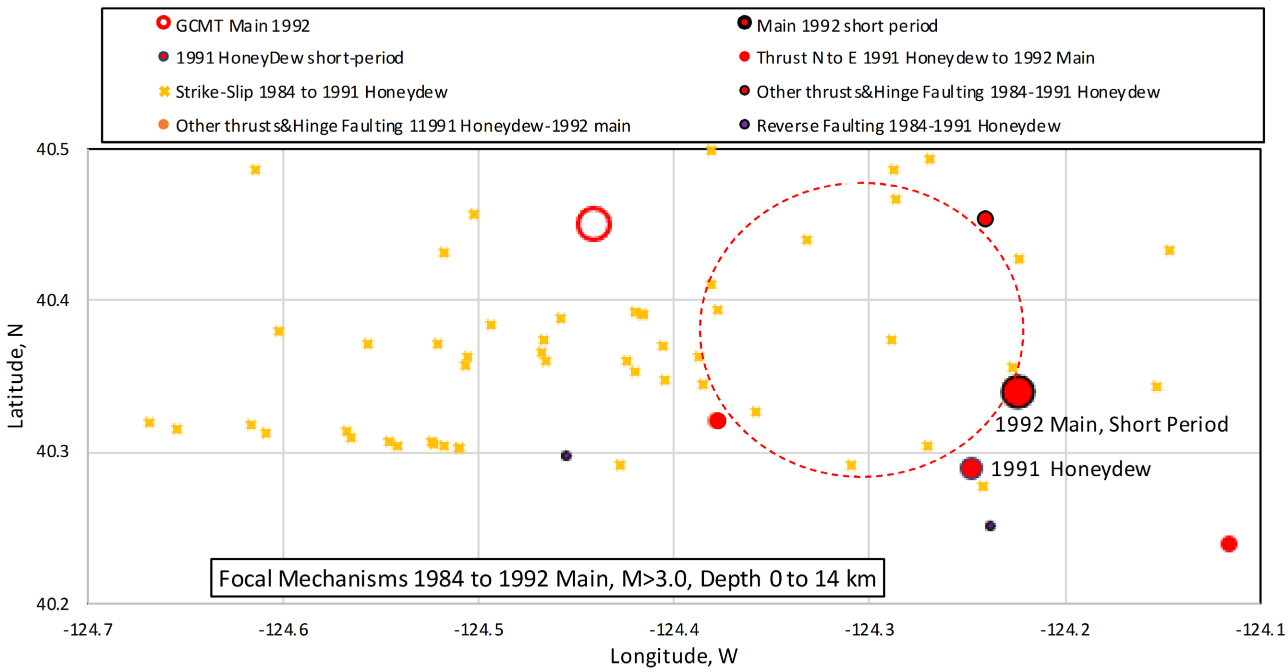

Figure 7. Forerunning activity to 1992 mainshock for which earthquake mechanism have been published for events of M > 3.0 and depths 0 to 14 km. Very approximate size of region with no forerunning thrust shocks is given by ellipsoidal region outlined in red dashes.

about 20 km in diameter. **Figure 5** and **Figure 7** indicate that care must be used in defining quiet forerunning zones to large events so as to include depth as well as latitude, longitude and magnitude.

3.4. Did the 1992 Earthquake Rupture the Plate Boundary?

The 1992 mainshock has been attributed to slip either along the Gorda-North American plate boundary or along a similar-dipping surface a several kilometers above it [9]. [18] interpreted that it occurred along a blind thrust fault above the plate boundary. [19] reached a similar conclusion based on mapping the velocity ratio v_p/v_s.

Aftershocks in **Figure 4** indicate the main rupture in 1992 took place on a shallow-dipping interface at depths between 7 to 9 km with perhaps slip on a sub-parallel fault at depths of 10 to 11 km. The 1991 Honeydew earthquake occurred at depths of 8 to 10 km (**Figure 4**). Most incoming sediments on the Gorda plate are accreted to the northern California margin [20]. [21] measured P and S velocities near the hypocenter of the 1992 shock. They also indicate the 1991 and 1992 thrust events occurred within the North American plate and not on the plate boundary. The region is unusual in that some of the youngest oceanic crust world-wide is entering the subduction zone west of the 1992 rupture zone.

Where slip occurred in 1992 has possible implications for great earthquakes to the north along the Cascadia subduction zone. [18] indicated that a portion of the old Farallon plate was accreted to the North American plate in the region of abundant seismicity between 40.3˚N and 41.2˚N in **Figure 1**. If so, the implications for great shocks farther north are questionable except for their being thrust mechanisms on shallow-dipping faults.

3.5. San Andreas Fault and 1906 Earthquake

The northwestern extent of the San Andreas fault is shown in **Figure 1**. The change in its strike shown near 40˚N, 124.1˚W [18], if correct, indicates greater structural complexity in the area of the 1992 shock. How far the 1906 great earthquake may have ruptured into that area and the triple junction is uncertain. [22] modelled geodetic and seismic data near the northwestern end of the 1906 rupture zone. They conclude that large slip in 1906 occurred as far northwest as Shelter Cove (Point Delgada) near 40˚N just to the south of the Mendocino region. The San Andreas fault comes ashore at Point Delgada before going offshore again to the northwest [23] [24].

[25] concludes that large earthquakes near the southern end of the Cascadia subduction zone may be linked with great events along the northernmost San Andreas fault. Their dates are uncertain, however, since they are from paleoseismic measurements. [25] indicates that southern Cascadia has a short repeat time of about 220 years, shorter than those of subduction segments to the north.

The Uniform California Earthquake Rupture Forecast [26] assigned the offshore Noyo segment of the northern San Andreas fault near 39.5˚N in **Figure 1** a mean repeat-time interval of 188 years (with one standard deviation of about 25 years). Since it last ruptured in a great earthquake in 1906, it is unlikely to rupture again before the year 2069. The Mendocino segment that broke in 1992 seems unlikely to rupture before then even if it broke in 1906.

3.6. Distance and Timing of Precursors with Respect to Mainshocks

Figure 8 shows the distances of forerunning earthquakes and their times before the 1992 Cape Mendocino and 1989 Loma Prieta mainshocks. The short-period hypocenters, *i.e.*, their rupture initiations, were used in determining those distances. The Lake Elsman precursors to the 1989 mainshock occurred on a separate fault zone that was very close to the 1989 rupture zone only 15 months earlier [27]. The 1991 Honeydew shock also took place very near the 1992 hypocenter 8 months beforehand.

Stress dropped in the great 1906 California mainshock along the segment of the San Andreas fault that broke in 1989. A similar drop in stress and its subsequent buildup by plate motion are taken to have occurred for the 1992 mainshock. The occurrence of shocks along the Calaveras fault zone about 30 km from the 1989 rupture zone starting a decade earlier may have been a long-term

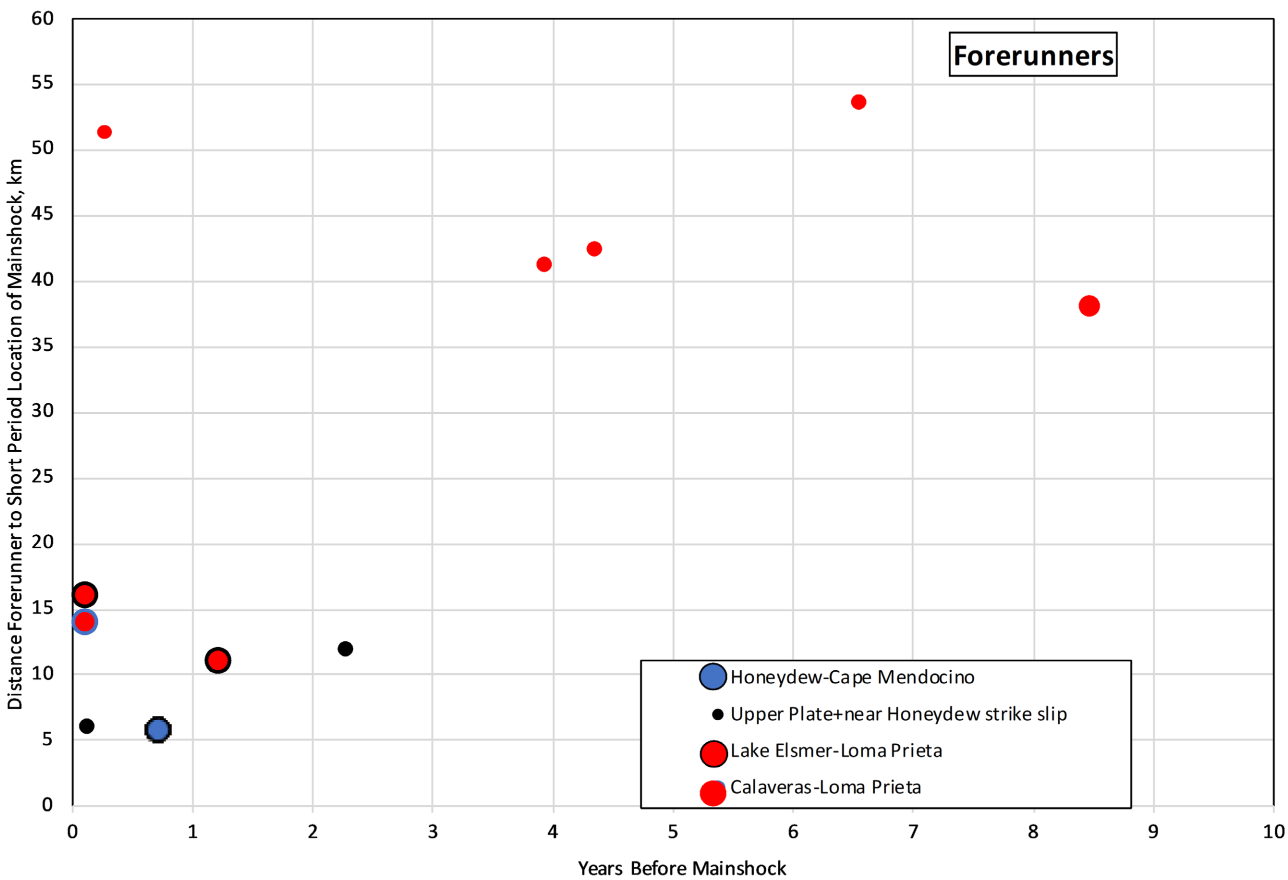

Figure 8. Forerunning activity to 1992 mainshock and 1989 Loma Prieta, California earthquakes as a function of time before and distance to mainshocks.

(decadal) precursor [27] [28]. The occurrences of those nearby precursors to the 1989 and 1992 shocks are taken to be especially important for intermediate (yearly)-term forecasting. I urge scientists to be alert for other events of significant magnitude close to active faults since they may be intermediate-term precursors of a soon-to-occur larger earthquake.

4. Conclusions

Several steps were taken to identify nearby precursors to the Cape Mendocino 1992 mainshock. First, possible precursors could be identified by their earthquake mechanisms. The 1992 mainshock and the 1991 Honeydew shock involved thrust faulting on planes of shallow dip. Most other mechanisms of moderate to large-sized events in the area involved strike-slip faulting (**Figure 1** and **Figure 7**). The 1991 event was unusual by its relatively large size, Mw 6.06. In that sense it resembled the Lake Elsman events that preceded the 1989 Loma Prieta earthquake of Mw 6.9 [27]. They were a typical for magnitudes in their areas for many preceding decades. In retrospect, the Lake Elsman forerunning shocks and the 1991 Honeydew event were precursors that preceded mainshocks by months to 1.5 years. Each occurred very close to the coming mainshock. Most of the cumulative seismic moment from 1984 to the 1992 mainshock was contributed by the 1991 Honeydew shock.

Precise locations of earthquakes in the Cape Mendocino area since 1984 were used in this study. The 1992 event occurred in a volume of space defined by aftershocks in which few forerunning earthquakes took place from 1984 to 1992. Forerunning events occurred on the periphery of that volume (**Figure 3**, **Figures 5-7**).

The quiet volume is identified as a relatively strong asperity that ruptured in the main 1992 event. Similar patterns of forerunning activity surrounded the coming rupture zones of many great earthquakes at subduction zones and transform plate boundaries [14] [15]. The same pattern occurred before the Loma Prieta earthquake of 1989 [27]. Thus, the presence of a quiet volume before the 1992 mainshock was a common phenomenon. The 1991 Honeydew shock draws attention to a possible coming larger shock like 1992 even though it was a lone large event. Its thrust mechanism and relatively large magnitude were unusual.

What might be done in the future when unusual forerunning events occur like those preceding the 1989 and 1992 mainshocks? We need to understand how common or not such events are. How many preceding events might have been false alarms that were not followed by the occurrence of larger nearby earthquakes? The Mw 7.3 Landers earthquake of 1992 occurred in southern California near to but not on the nearby part of the San Andreas fault. It is clear now that it was not a yearly to decadal precursor to a larger shock.

Paleoseismic observations in 1992 and 2022 along the nearby parts of the southern San Andreas fault are not clear about repeat times of its great events. It likely ruptured last in 1812. Much scientific monitoring and work are needed to understand possible precursors of various time durations.

I suggest the following considerations when an unusual seismic event is located along a plate boundary:

1) Determine if the fault segment has a history of large to great earthquakes. Yes, it did for Loma Prieta in 1989 and Cape Mendocino in 1992.

2) Is that fault segment advanced in time compared to its known repeat time? Yes for 1989; unknown for 1992 but it may have ruptured last in 1700.

3) Did the suspect event occur close to a quiet zone for moderate to large shocks? Yes for 1989 and 1992. Those quiet zones may have been created by previous large to great earthquakes.

4) Determine the mechanisms and coordinates in three dimensions of the events.

5) Promote extensive work on existing data.

6) If the event(s) are deemed unusual, seismologists and various agencies might consider issuing a low-level alarm of several years.

7) If unusual, install additional seismic and geodetic equipment in the area for a period of several years making sure to cover offshore regions. Offshore monitoring stations did not exist just before the 1992 mainshock. The occurrence of the Lake Elsman events in 1988 and 1989 led seismologist Karen McNally to install a seismometer nearby, which recorded the 1989 mainshock. Much more intensive monitoring and work is needed to provide assessments of an initial suspect precursor(s).

8) Periodically review the status of possible precursory events. If it seems more likely to have been precursory, consider issuing additional warnings to scientists, governmental agencies and perhaps the public. If unlikely, cancel the initial warning.

9) Realize that work on possible precursors is in its infancy in the United States and many other countries. Since monitoring and assessing possible precursors is more advanced in China, reassess and keep abreast of work there.

10) Try to deal with statements by several seismologists that earthquake prediction is either impossible or for fools and charlatans. Those views discourage others from working on prediction. Some scientists have turned down funding proposals; some journal editors and reviewers are loath to see work published that mentions the words earthquake prediction, precursors or even forerunning activity. This is not to say that all work on those topics should be supported or published.

11) Another view is that prediction must be universal, *i.e.*, applicable to all large earthquakes if it is to be considered at all. For some years or decades, we may be able only to predict some large earthquakes without issuing too many false alarms. Earthquakes off Honshu, Japan, in 2011 and Iquique, northern Chile in 2014 had significant data that could have been used to make yearly to decadal predictions beforehand. The scientific community still has much to learn about precursory changes of various time scales.

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Conflicts of Interest

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

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