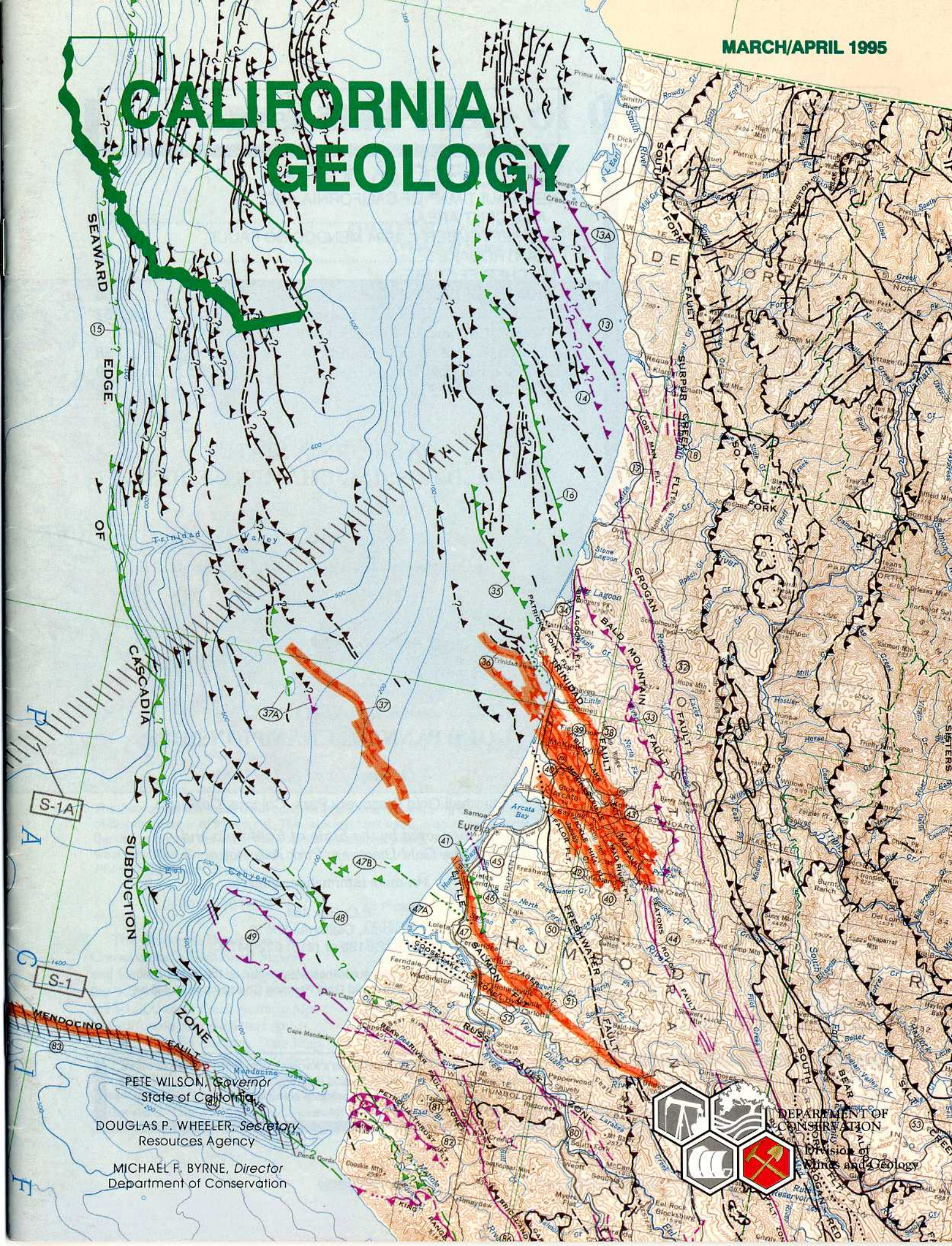
MARCH/APRIL 1995

CALIFORNIA GEOLOGY



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DEPARTMENT OF CONSERVATION
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THE SEPTEMBER 1, 1994 MENDOCINO FAULT EARTHQUAKE

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INTRODUCTION

On September 1, 1994, a large region of northern California and southern Oregon was shaken by a moment **magnitude*** M_W6.9 earthquake. This earthquake was felt over an area of approximately 50,000 square miles from the San Francisco Bay Area to southwestern Oregon and was the largest magnitude earthquake to occur in 1994 within the territorial limits of the United States. Although the earthquake was large in magnitude and widely felt, it produced virtually no damage because its epicenter was about 85 miles (140 km) west of Cape Mendocino and the nearest coastal communities (Figure 1). This earthquake is important for several reasons: 1) It is the largest historical earthquake clearly associated with the Mendocino Fault; 2) A detailed post-shock intensity study allows understanding of the felt effects of far-offshore earthquakes and better location of pre-instrumental historical events; 3) A Global Positioning System (GPS) survey in the Cape Mendocino region allowed direct observation of the coseismic displacements; 4) This was the eighth magnitude 6 or larger earthquake in the last 3 years, illustrating the extremely high seismic activity of the north coast region; 5) The earthquake produced a 5.5-inch (14-cm) tsunami which, although not damaging, underscores the problem of tsunami warning in a region that has the potential to produce large tsunamis.

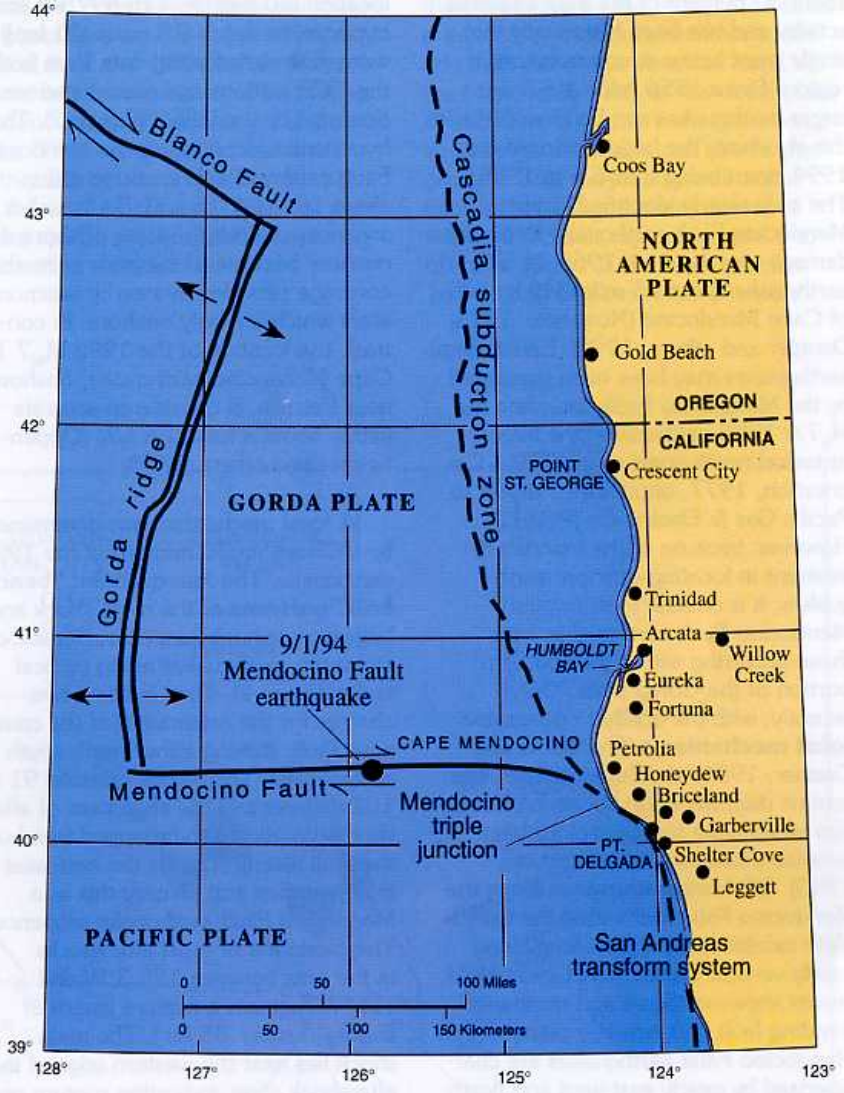


Figure 1. Simplified map of north coast California regional tectonics and the location of the September 1, 1994 Mendocino Fault earthquake. Arrows show the relative plate motion across plate boundaries.

GEOLOGIC SETTING AND HISTORICAL SEISMICITY

The Mendocino Fault is a 165-mile-(260-km-) long east-west structure that forms the transform plate boundary between the older and thicker Pacific plate to the south and the younger and thinner Gorda plate to the north (Front Cover). The Gorda ridge terminates the fault to the west. To the east, the Mendocino Fault joins the Mendocino triple junction, a complex region in the vicinity of Cape Mendocino where the Gorda, North American, and Pacific plates meet. See Dengler and others (1992) for an overview of the tectonics of this region. The Mendocino Fault is nearly vertical and motion is primarily right-lateral strike-slip with the Gorda plate moving east relative to the Pacific plate (Jachens and Griscom, 1983; Eaton, 1989; McPherson, 1989; Wilson, 1989; De Mets and others, 1990). The fault zone deepens and reverse slip has been recorded in earthquakes near the eastern end of the Mendocino Fault close to the triple junction (Nowroozi, 1973; McPherson, 1989).

* Terms in **boldface** type are in the glossary on page 52.

The north coast region is one of the most seismically active areas in the contiguous United States, accounting for about 25 percent of California's seismic energy released in the past 50 years (Gee and others, 1991). The Mendocino Fault is responsible for about 30 percent of the area's seismic activity and has been historically the single most active structure in the region. Since 1950, nine M5.5 or larger earthquakes can be identified with this structure, the largest prior to the 1994 event being a M_L6.6 in 1984. The only clearly identified historical Mendocino Fault earthquake to produce damage was the June 1968 (M_L5.9) earthquake about 25 miles (40 km) west of Cape Mendocino (Nowroozi, 1973; Dengler and others, 1992). Earlier large earthquakes may have been generated by the Mendocino Fault, including the M_S7.6 1922 earthquake, the largest historical north coast event (TERA Corporation, 1977, unpublished report to Pacific Gas & Electric Co [PG&E]). However, because of the inaccuracy inherent in locating offshore earthquakes, it is difficult to distinguish Mendocino Fault earthquakes from those occurring within the southern portion of the Gorda plate. Only recently, with the ability to determine **focal mechanisms** (Sherburne and Cramer, 1984) of offshore events, has routine discrimination between these two earthquake source regions been possible (Romanowicz and others, 1993). Offshore earthquakes along the Mendocino Fault and within the Gorda plate exhibit strike-slip faulting along nearly vertical planes. The Gorda plate events show northeast and northwest trending fault and auxiliary planes, while Mendocino Fault earthquakes are characterized by nearly east-west and north-south planes (McPherson, 1989).

THE MENDOCINO FAULT EARTHQUAKE

Main Shock and Aftershocks

The Mendocino Fault earthquake occurred at 8:15 a.m. Pacific Daylight Time (PDT) (15:15 UTC [Universal or Greenwich mean time]) on September 1, 1994. Magnitude determinations range from 6.7 to 7.2, depending on the type of magnitude and the agency making the calculation (U.S Geological Survey [USGS], 1994). The moment magnitude, considered to most directly reflect the dimensions of the earthquake source (Spence and others, 1989), was estimated to be 6.9 using broadband instruments of the Berkeley Seismographic Station (UCB) network. The location (40.445°N; 125.897°W) and hypocentral depth (13 miles [21 km]) were determined using data from both the UCB stations and Calnet stations operated by the USGS (Figure 2). This hypocenter location (for the Mendocino Fault earthquake) is accurate within about 10 miles (16 km). Earthquakes are more difficult to locate offshore than onshore because of the poor azimuthal coverage provided by nearby seismometers which are only onshore. In contrast, the location of the 1992 M_W7.1 Cape Mendocino earthquake, onshore near Petrolia, is considered accurate within about a mile (1.6 km) (Oppenheimer and others, 1993).

A focal mechanism was determined by UCB within 30 minutes of the 1994 earthquake. The four-quadrant **"beachball" patterns** of the main shock and largest aftershocks are characteristic of strike-slip earthquakes along vertical faults (Figure 2). They indicate two choices for the orientation of the causative fault, striking either north-south or east-west. The planes oriented 91 to 102 degrees and the alignment of aftershocks parallel to the mapped trend of the fault clearly support the east-west interpretation and identify this as a Mendocino Fault earthquake sequence. The clustering of most aftershocks in the area between 125.3°W and 126°W suggests a rupture length of about 40 miles (65 km). The main shock lies near the western edge of the aftershock zone, indicating rupture proceeded eastward.

The number of aftershocks recorded during the 10 weeks following the Mendocino Fault earthquake seems anomalously low. The paucity of M2 to 3 aftershocks may be due largely to the difficulty of recording small earthquakes located so far offshore. However, there has also been a lack of aftershocks of greater magnitude, with only four events in the M4 range and none at the M5 or 6 level. In contrast, the January 17, 1994 Northridge earthquake (M_W6.7) had five aftershocks greater than M5 and 43 events greater than M4 in the 4-week period after the earthquake. The November 8, 1980 Trinidad earthquake (M_S7.1) had one M5.2 and 20 shocks greater than M4 within 20 days following the main shock. The largest Mendocino Fault aftershock to date was a M_W4.6 event on September 19, 1994.

Global Positioning System Study

The earth's surface near Cape Mendocino is being constantly deformed in response to the complex set of tectonic forces associated with the triple junction. Some of the deformation is caused by the relatively steady accumulation of strain on the Mendocino and San Andreas fault systems and Cascadia subduction zone. Other deformation is caused by the sudden release of strain during earthquakes such as the Mendocino Fault earthquake which, although rupturing offshore, nevertheless subtly deformed a large area onshore.

The USGS has been studying the ground deformation near Cape Mendocino since 1981 by annually measuring distances between survey benchmarks. Since 1989, these measurements have been made with GPS, a navigation aid recently developed by the Department of Defense to provide immediate locations anywhere on earth. GPS uses radio signals transmitted by 24 satellites orbiting at an altitude of 12,420 miles (20,000 km), to precisely locate the positions of receivers with antennas on the ground. Using special processing techniques, GPS can determine the distance between stations separated by thousands of miles to an accuracy of less than 0.4 inch (1 cm). GPS gives geophysicists a powerful and fairly inexpensive tool to study the deformation of the earth's surface. Following the 1992 M_W7.1 Cape Mendocino earthquake, the USGS found that 12 benchmarks within 60 miles (100 km) of the epicenter had moved measurably, some by as much as 16 inches (40 cm) horizontally and 6 inches (15 cm) vertically. USGS was able to use these and other measurements of displacement to locate the buried thrust fault and determine how much it had slipped at depth (Oppenheimer and others, 1992; Murray and others, 1993).

Fortunately, the USGS redetermined the benchmark locations near Cape Mendocino just 1 week before the Mendocino Fault earthquake. They were able, therefore, to return 3 weeks after the earthquake to see how much the benchmarks had been moved by this latest event. Both pre- and post-earthquake surveys monitored stations in eastern California not significantly affected by the earthquake as well as stations near the coast. The stations near Cape Mendocino, on average, moved 0.4 to 0.8 inches (1 to 2 cm) closer to eastern California (Figure 2), with most stations near the coast moving more than those inland. None of the stations exhibited measurable vertical displacements.

Unfortunately, the fault ruptured too far offshore and the station displacements are too small compared with their errors (represented by 95 percent confidence level ellipses in Figure 2) to permit a very detailed study of the fault. Assuming the rupture initiated at the hypocenter and continued unilaterally toward the coast on a 6-mile- (10-km-) wide vertical fault, the GPS displacements can be used to estimate the best-fitting geodetic model of fault length and strike. The best model estimates the earthquake had a moment magnitude M_W7.1 with 17.5 feet (5.35 m) of right-lateral slip on a 19-mile- (30-km-) long fault with a strike of N65W.

The moment magnitude of the best-fitting geodetic fault model is greater than the seismic estimate, and other aspects of the geodetic model differ from the seismic evidence. For example, the aftershocks (Figure 2) suggest the earthquake had a longer rupture zone than predicted by the model. The strike predicted by the model is more southerly than either the observed trend of the Mendocino Fault or the nodal plane of the seismic mechanism. However, a large range of models can also fit the geodetic data reasonably well within their errors. Magnitude moments of 6.8 to 7.2, fault rupture lengths 6 to 60 miles (10 to 100 km), and strikes 100 to 130 degrees relative to north

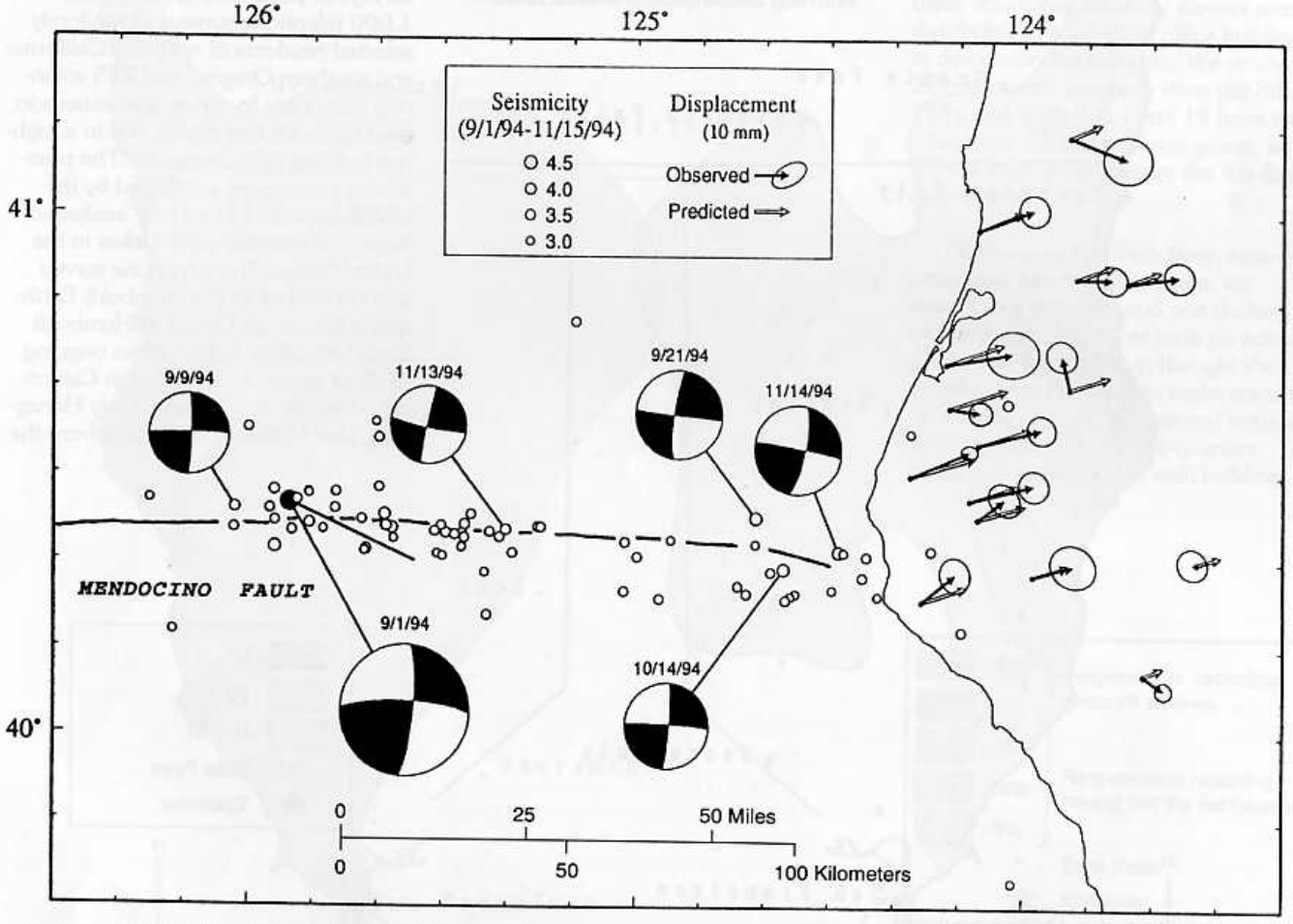


Figure 2. Seismicity from September 1, 1994 through November 15, 1994, and movements of the earth's crust produced by the Mendocino Fault earthquake. Focal mechanisms for the main shock and five of the largest aftershocks indicate fault strikes from 91 to 102 degrees, consistent with the strike of the Mendocino Fault. Solid arrows show the change in station position between the pre- and post-earthquake surveys. The ellipses represent the 95 percent confidence interval. The open arrows are the predicted displacements produced by the best-fitting geodetic fault model.

fit the data within the 95 percent confidence limits.

The Tsunami

Tsunamis are produced by vertical motion of the sea floor during an earthquake, volcanic eruption, or submarine landslide. The most common cause of tsunamis are subduction zone earthquakes that produce permanent vertical deformation of the sea floor. The 1992 Cape Mendocino earthquake produced a tsunami that reached Eureka about 20 minutes after the earthquake, with wave heights of about 1 foot (0.3 m) (Oppenheimer and others, 1993). Oceanic strike-slip earthquakes produce predominantly horizontal deformation of the sea floor and are much less commonly followed by tsunami. However, the ground shaking produced by strike-slip earthquakes may induce submarine landslides, which can generate a tsunami.

Following the September 1 earthquake, the National Warning System (NAWAS) issued a tsunami watch for Hawaii, but no watch was issued on the north coast. The Alaska Tsunami Warning Center issued its first tsunami information bulletin 13 minutes after the earthquake advising that an "investigation of a possible tsunami" was underway. This bulletin was never received by the Humboldt County Office of Emergency Services. The Tsunami Warning Center issued a second tsunami bulletin about an hour after the earthquake, which was received by the Humboldt County Office of Emergency Services at 9:22 a.m. PDT. This bulletin reported that no destructive tsunami threat existed but that some areas could experience small changes in sea level. The evaluation was based on tide gauge data from the Eureka and Crescent City areas. The tsunami watch was canceled at this time. Detailed processing of the Crescent City tide gauge data several days after the earthquake revealed a 5.5-inch (14-cm) tsunami had arrived at 9:01 PDT, approximately 45 minutes after the earthquake.

Intensity Survey

A Modified Mercalli intensity (MMI) map (Figure 3) of the Mendocino Fault earthquake was constructed from 336 surveys of postmasters, more than 1,000 telephone surveys of randomly selected residents of northern California and southern Oregon, and 725 voluntary responses to survey solicitations in the Humboldt Bay region and in a high-rise building in Sacramento. The postmaster survey was conducted by the USGS as part of its routine analysis of large or damaging earthquakes in the United States. The telephone survey was conducted by the Humboldt Earthquake Education Center at Humboldt State University as part of an ongoing study of recent earthquakes in California, Oregon, and Nevada. Only Honeydew, about 90 miles (144 km) from the

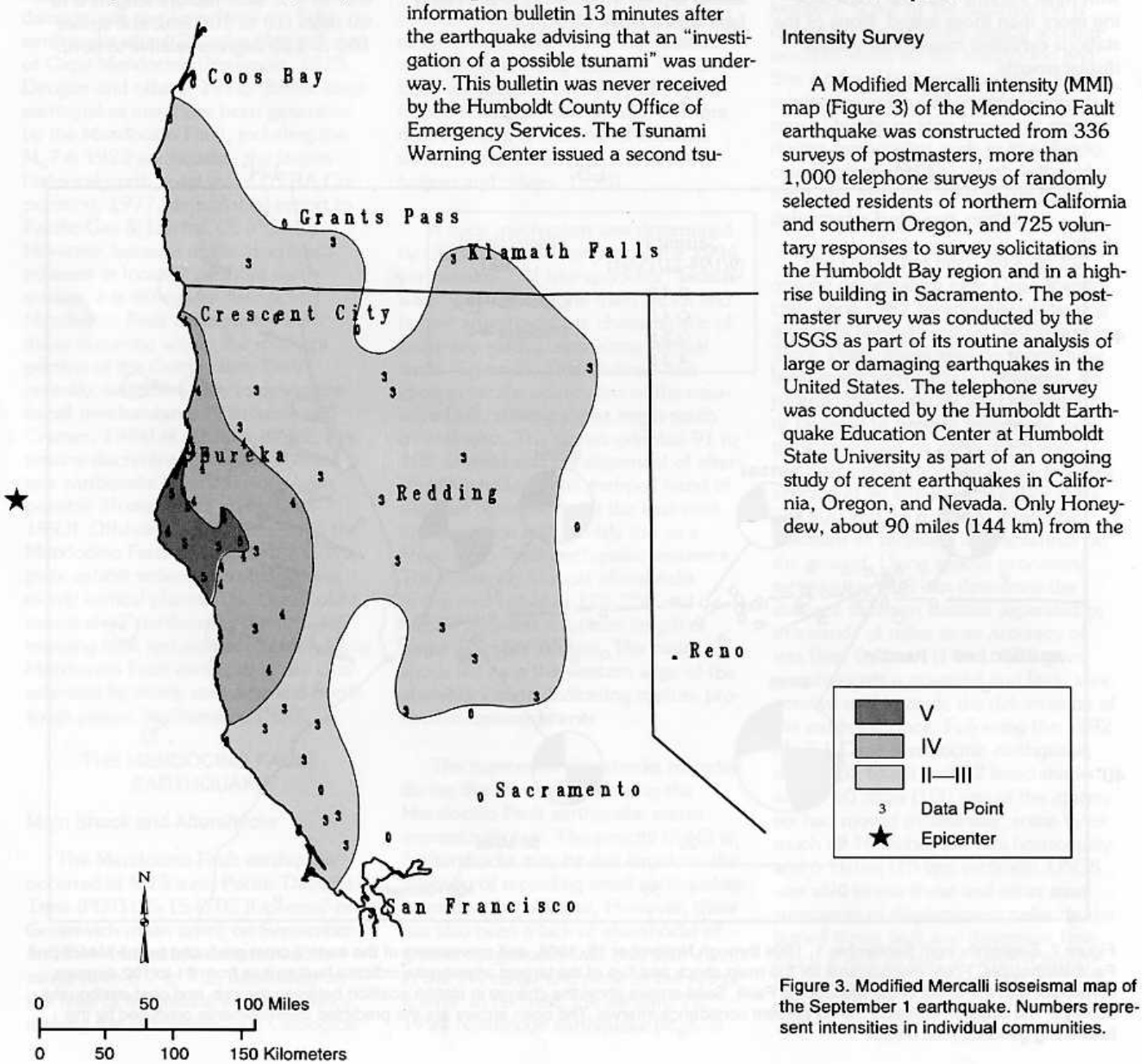


Figure 3. Modified Mercalli isoseismal map of the September 1 earthquake. Numbers represent intensities in individual communities.

epicenter, justified an intensity VI level of shaking where residents reported plaster cracks, a broken pipe, and separation of porch and house. No damage was reported in Petrolia, the community closest to the epicenter, where most residents described ground shaking as "mild." The map is dominated by a broad, somewhat elongated pattern of intensity III, IV, and V isoseismals. The irregularity of the V isoseismal due to the inclusion of the communities of Miranda, Myers Flat, and Phillipsville (towns just north of Garberville) may reflect the alluvial deposits in the Eel River Valley which tend to amplify ground shaking. The earthquake was reported felt in most communities within the outermost isoseismal. A few reports of shaking were, however, received from some communities outside the outer isoseismal, such as San Francisco and Sacramento. We will discuss a number of felt reports received from occupants of tall buildings in Sacramento.

The telephone survey allows for contouring individual categories such as percentage of persons reporting damage, items fallen off shelves, and so forth. Figure 4 contours the telephone data felt percentages. The data shown here are based only on reports of persons who were indoors at the time of the earthquake and on the first or second floor. The felt map closely resembles the intensity map; the simpler contour shapes mainly reflect the smaller number of communities sampled in the telephone survey. Figure 4 also shows the percentage of persons reporting items toppled over or fallen off shelves. The highest percentage was in Ferndale where 42 percent of the telephone respondents reported "a few" items knocked off shelves.

High-Rise Effects

Sacramento was classified as an area where the earthquake was "not felt" according to telephone and postmaster surveys. The 19 Sacramento residents surveyed at random by telephone were on the first or second floors of buildings during the earthquake but felt no motion. However, we heard several reports of persons in high-rise office buildings feeling the earthquake. To get a sense of perceived ground shaking in these structures, intensity surveys were distributed in a 27 story office building in downtown Sacramento. We received 22 responses, one each from the 8th, 12th, and 19th floors and 19 from the 24th floor. Of the high-rise group, all felt the earthquake except the 8th floor respondent.

Of those on the 24th floor, nine reportedly ran from the room, six moved to a doorway and one ducked and covered; only three took no action. About half of this group thought the motion strong enough to make standing or walking difficult, 63 percent noticed swaying, and nearly three-quarters heard noises associated with building

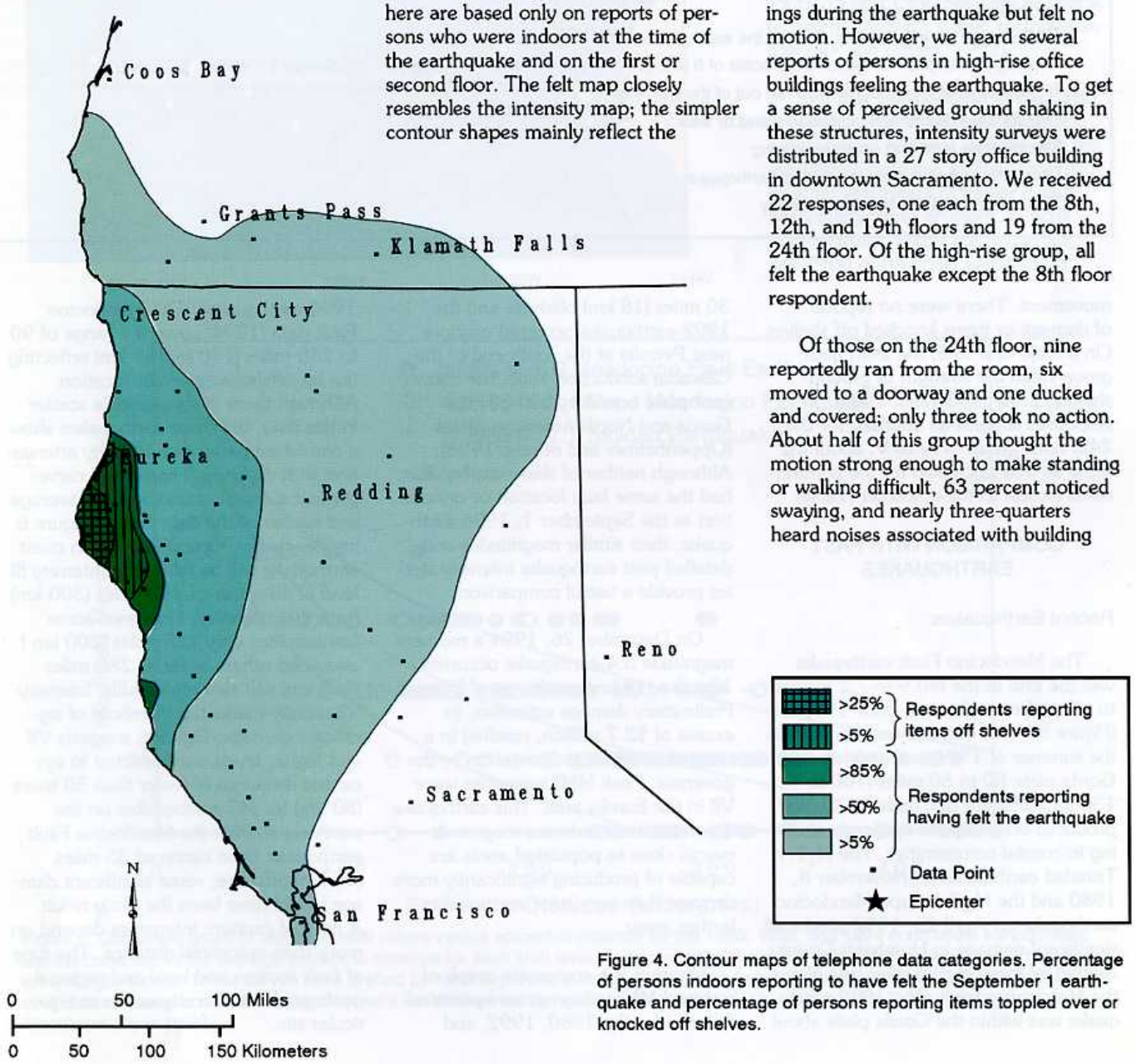


Figure 4. Contour maps of telephone data categories. Percentage of persons indoors reporting to have felt the September 1 earthquake and percentage of persons reporting items toppled over or knocked off shelves.

High-Rise Effects of the September 1, 1994 Mendocino Fault Earthquake.

COMMUNITY	NUMBER[1]	% FELT[2]	MOTION[3]	% RAN[4]	% STAND[5]	% SWAY[6]	% NOISE[7]	INTENSITY[8]
Petrolia	17	94	2.4	24	59	31	35	V
Ferndale	19	100	2.8	32	20	60	50	V
Sacramento (1st/2nd floors)	19	0	0.0	0	0	0	0	not felt
Sacramento (24th floor)	19	100	3.0	47	47	63	74	IV-V

COLUMN HEADINGS:

[1]Number of survey responses

[2]Percentage of respondents who felt the earthquake

[3]Average perception of motion on a scale of 0 to 5 (0 – not felt; 1 – weak; 2 – mild; 3 – moderate; 4 – strong; 5 – violent)

[4]Percentage of respondents who ran out of the building

[5]Percentage reporting it difficult to stand or walk

[6]Percentage reporting objects swaying

[7]Percentage hearing noises during earthquake

[8]Estimated Modified Mercalli Intensity

movement. There were no reports of damage or items knocked off shelves. On a scale of 0 to 5, the 24th floor group rated the strength of ground shaking 2.95 (moderate). These responses suggest an intensity for the 24th floor group of IV to V, about the same as that calculated for the communities closest to the epicenter (Table).

COMPARISON WITH PAST EARTHQUAKES

Recent Earthquakes

The Mendocino Fault earthquake was the fifth in the M6.9-to-7.2 range to affect the north coast since 1980 (Figure 5). Two of these earthquakes, in the summer of 1991, were within the Gorda plate 60 to 80 miles (100 to 130 km) offshore of Crescent City and produced only weak to moderate shaking in coastal communities. The M_S7.1 Trinidad earthquake on November 8, 1980 and the M_W7.1 Cape Mendocino earthquake on April 25, 1992 produced significant damage in Humboldt County. Neither of these earthquakes was along the Mendocino Fault. The 1980 earthquake was within the Gorda plate about 30 miles (18 km) offshore and the 1992 earthquake occurred onshore near Petrolia at the south end of the Cascadia subduction zone, the convergent plate boundary between the Gorda and North American plates (Oppenheimer and others, 1993). Although neither of these earthquakes had the same fault location or orientation as the September 1, 1994 earthquake, their similar magnitudes and detailed post earthquake intensity studies provide a useful comparison.

On December 26, 1994 a moment magnitude 5.4 earthquake occurred 12 miles (19 km) southwest of Eureka. Preliminary damage estimates, in excess of $2.7 million, resulted in a state of emergency declaration by the governor. Peak MMI intensities were VII in the Eureka area. This earthquake illustrates that moderate magnitude events close to populated areas are capable of producing significantly more damage than very large earthquakes farther away.

Figure 6 is a composite graph of assigned MMI values versus epicentral distance for the 1980, 1992, and 1994 earthquakes. The Mendocino Fault data (1994) cover the range of 90 to 280 miles (140 to 450 km) reflecting the far offshore epicenter location. Although there is considerable scatter in this data, the three earthquakes show a consistent pattern of intensity attenuation with distance. The plotted curves present a rough estimate of the average and scatter of the data points. Figure 6 implies that a "typical" M7 north coast earthquake will be felt at the intensity III level at distances of 190 miles (300 km) from the epicenter. However, some communities only 125 miles (200 km) away and others as far as 280 miles (450 km) will also register IIIs. Intensity VII usually marks the threshold of significant damage. Figure 6 suggests VII and higher levels are restricted to epicentral distances of fewer than 50 miles (80 km) for M7 earthquakes on the north coast. Had the Mendocino Fault earthquake been centered 35 miles (56 km) offshore, some significant damage would have been the likely result. A note of caution: intensities depend on more than epicentral distance. The type of fault motion and local and regional geology affect intensity values at a particular site.

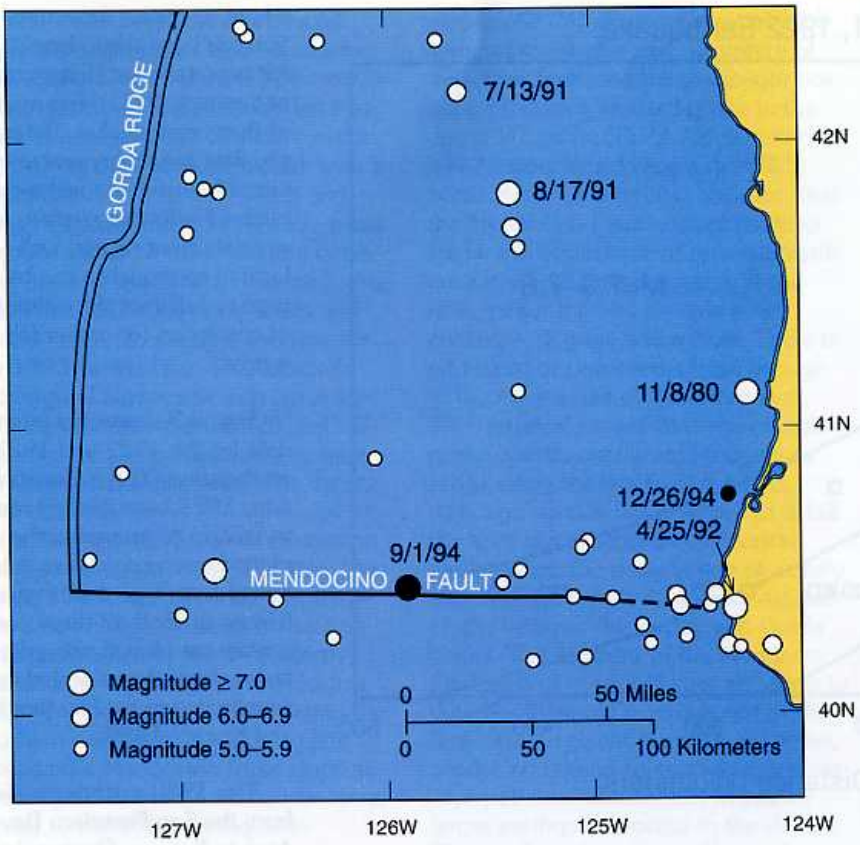


Figure 5. Magnitude 5.0 or larger earthquakes in the north coast region since 1/1/1980. Large black dot is the epicenter of the 9/1/1994 earthquake. Small black dot marks the much more damagng 12/26/1994 earthquake. The 12/26/1994 and 9/1/1994 locations are from the Berkeley Seismograph Stations. Other epicenter locations are from USGS, Golden, Colorado.

Historical Earthquakes

The recent high level of seismic activity in the north coast region is not unusual. Historical records show that the periods 1906-10, 1916-23, 1931-33 and 1950-54 were all characterized by frequent strong earthquakes (Dengler and others, 1992).

The first seismograph in the north coast area was installed in 1932 and a network of regional stations was not established until the 1970s. This made locating epicenters of earlier events, particularly those offshore, difficult until recently. There are numerous pre-1900 north coast earthquakes

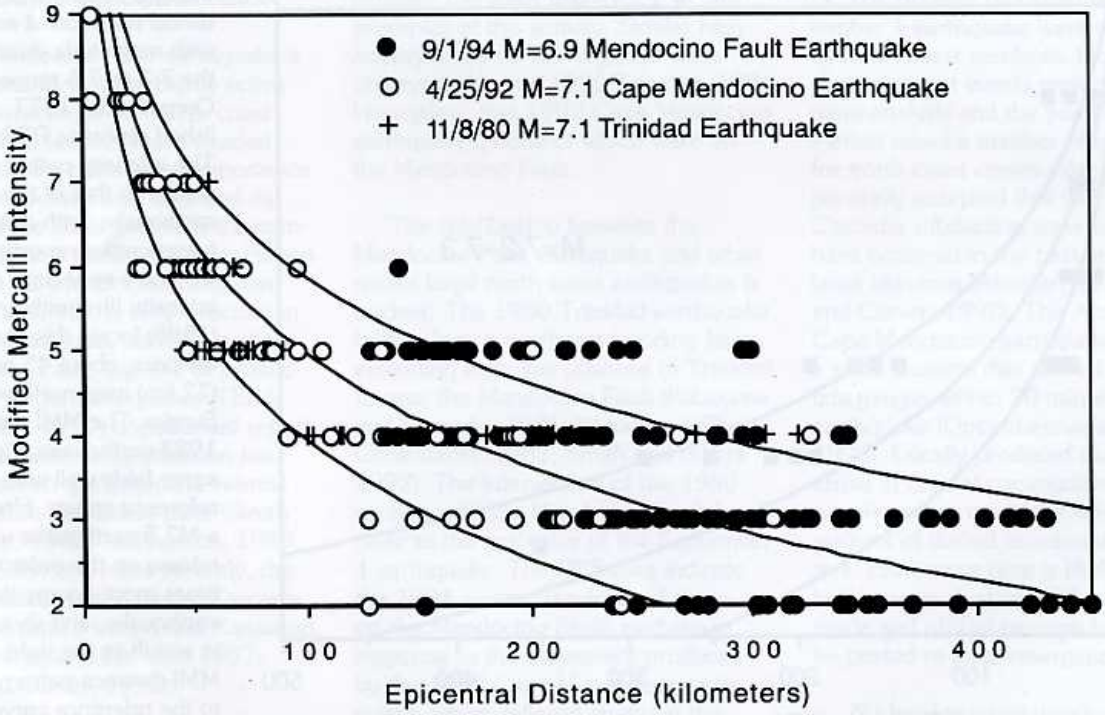
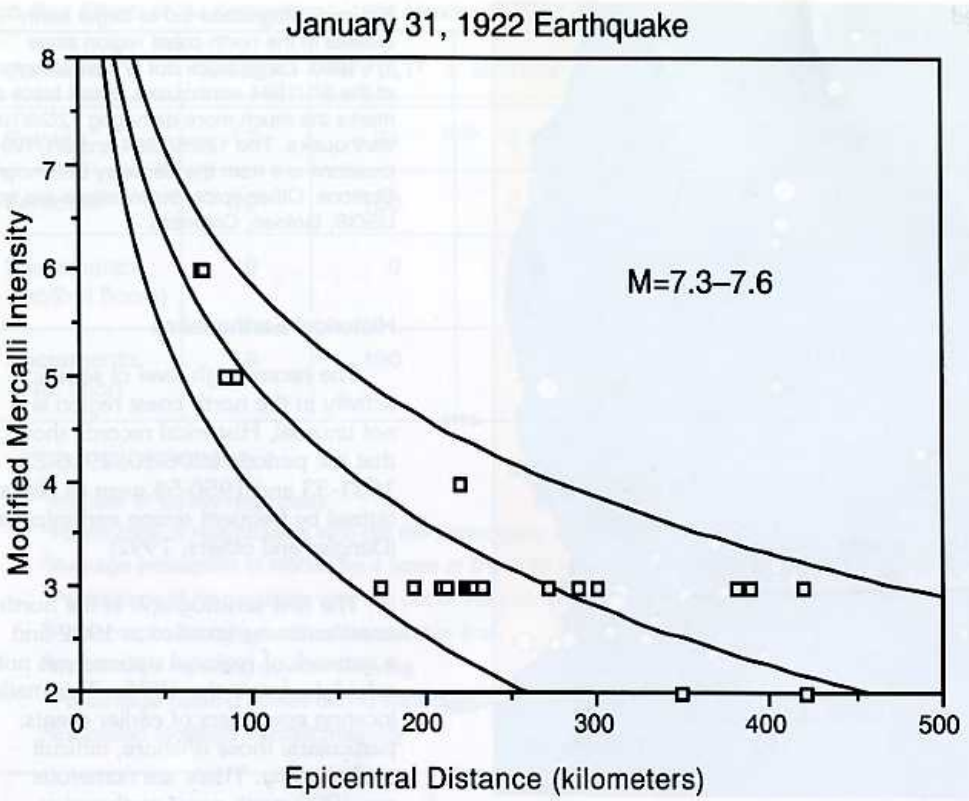


Figure 6. Composite graph of assigned MMI values versus epicentral distance for the 1980, 1992, and 1994 north coast earthquakes. Central curve marks the average epicentral distance for each MMI level. Approximately 75 percent of the MMI data points fall between the left and right curves. These curves were drafted by hand to provide a visual reference so intensity observations from earlier earthquakes could be compared to recent events; they were not determined by rigorous statistical analysis. MMI data for Trinidad earthquake from Woodward-Clyde (1981).



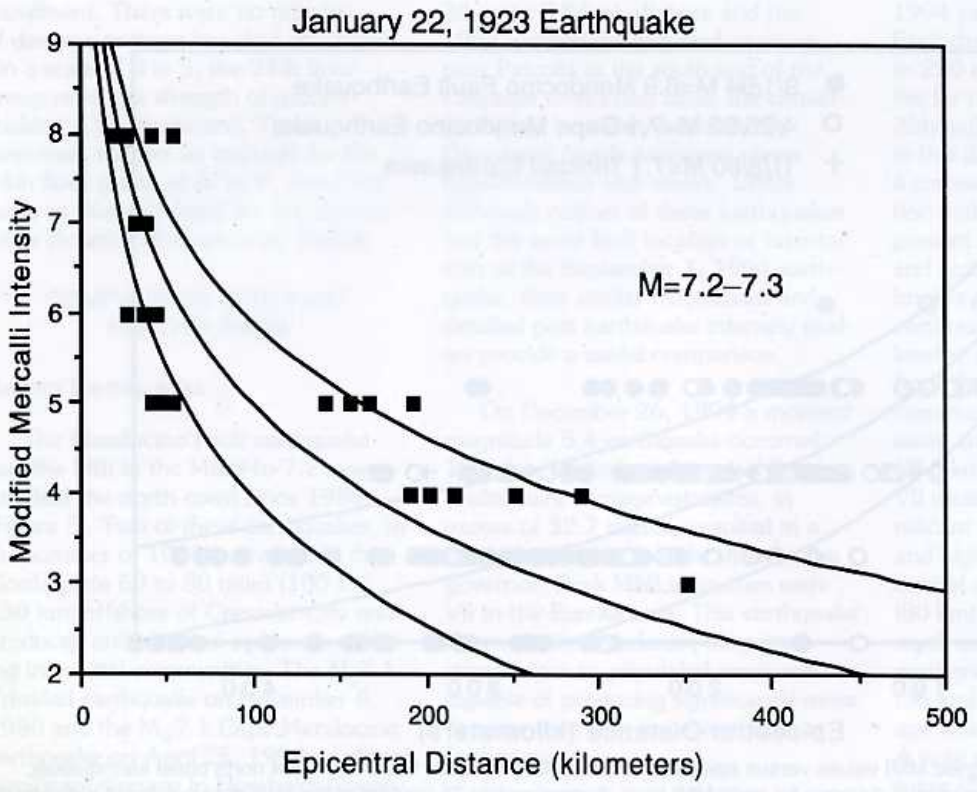


Figure 7. MMI values versus epicentral distance for the 1922 and 1923 earthquakes compared to the curves from Figure 5. *MMI data from TERA Corporation (1977, unpublished report to PG&E).*

where epicenter determination has been made from felt reports alone (Toppozada and others, 1981). For many of these earthquakes, the intensity data are scanty and uncertain. However, the technique outlined below suggests intensity data from recent, well located earthquakes can be used to calibrate the estimation of epicenters for earlier felt events.

Figure 7 shows the intensity data for the 1922 and 1923 earthquakes (TERA Corporation, 1977, unpublished report to PG&E) compared to the plotted reference curves determined from recent earthquakes (Figure 6). Both of these earthquakes are plotted using distances from the relocated epicenters determined by Smith and Knapp (1980).

The 1922 earthquake, felt from the San Francisco Bay Area to Eugene, Oregon, is thought to be the largest historical north coast earthquake, with magnitude estimates in the 7.3-to-7.6 range (TERA Corporation, 1977, unpublished report to PG&E). The intensity pattern is quite similar to that of the 1994 earthquake, with only a few communities reporting intensity VI, and a very large area of intensity III. Smith and Knapp (1980) locate this earthquake offshore, about 45 miles (72 km) west-northwest of Eureka. The MMI data for the 1922 earthquake (Figure 7) agree fairly well with the M7 reference curves. However, a M7.5 earthquake would release on the order of five times more energy than a M7 earthquake, and should result in a shift to the right in the MMI-distance pattern relative to the reference curves. This suggests that the 1922 earthquake may have been farther offshore than determined by Smith and Knapp (1980).

The 1923 earthquake produced major damage in the Cape Mendocino area. TERA Corporation (1977, unpublished report to PG&E) concluded that this was a major plate boundary event likely along the Mendocino Fault with a magnitude of 7.2 to 7.3. Smith and Knapp's (1980) location puts this event offshore about 13 miles (20 km) northwest of Cape Mendocino. Figure 7 also shows the MMI data using Smith and Knapp's (1980) epicenter location for the 1923 earthquake. This location shows good agreement with the reference curves. The intensity VII and VIII values constrain the epicenter to near the Cape Mendocino area. The distant MMI estimates lie on the right edge of the calibration curves, consistent with a somewhat larger magnitude than the 1980, 1992, and 1994 earthquakes. The data however, cannot be used to distinguish whether the 1923 earthquake occurred along the Mendocino Fault very close to the coast, within the southern portion of the Gorda plate close to the Mendocino triple junction, or along the Cascadia subduction zone, similar to the 1992 earthquake.

DISCUSSION & CONCLUSION

The Mendocino Fault earthquake is another reminder of the highly active seismic character of the north coast region. It also focuses much needed attention on the nature and importance of the Mendocino Fault itself and its relation to the other pieces of the complex north coast tectonic puzzle. Fifteen years ago, the Mendocino Fault was widely considered the only structure in the north coast area, aside from the San Andreas Fault, capable of producing M7 or larger earthquakes (TERA Corporation, 1977, unpublished report to PG&E). Since then, attention has focused first on the intraplate seismic activity within the Gorda plate (Smith and Knapp, 1980; McPherson, 1989; Wilson, 1989) and more recently, the seismic hazards posed by the Cascadia subduction zone (Heaton and Kanamori, 1984; Heaton and Hartzell, 1987; Clarke and Carver, 1992).

The September 1 earthquake clearly shows the Mendocino Fault is capable of producing large earthquakes. It is still unclear, however, just how large an earthquake this structure is capable of generating. At one time, a rupture of the whole fault length was thought possible, producing an earthquake in the upper M7 range (TERA Corporation, 1977, unpublished report to PG&E). Some evidence suggests, however, that the Mendocino Fault is more likely to fail by the occurrence of separate earthquakes on different segments of the fault, rather than by a single event encompassing the entire fault. There is no record of past events large enough to involve rupture of the entire fault. The historical record does show earthquake activity over a wide magnitude range along the length of the fault. Although no one has analyzed in detail the total slip produced by historical earthquakes, the present rate of activity may well account for the observed rate of slip between the Pacific and Gorda plates. The segment of the Mendocino Fault east of the 1994 rupture seems to behave differently from the rest of the fault. This segment is extremely active, producing numerous small to moderate "sympathetic" aftershocks whenever larger earthquakes occur in the vicinity. The small earthquakes in Figure 2, between the coast and 125.1°W, are examples of this activity. Similar high activity levels on this segment were observed after the 1980 Trinidad, 1991 Honeydew, and 1992 Cape Mendocino earthquakes, none of which were on the Mendocino Fault.

The relationship between the Mendocino Fault earthquake and other recent large north coast earthquakes is unclear. The 1980 Trinidad earthquake broke along a northeast trending fault extending from just offshore of Trinidad to near the Mendocino Fault (Kilbourne and Saucedo, 1981; Woodward-Clyde Consultants, 1982; Smith and others 1992). The intersection of the 1980 rupture with the Mendocino Fault lies close to the epicenter of the September 1 earthquake. The GPS data indicate the 1994 earthquake relieved strain on the Mendocino Fault, perhaps in response to the movement produced by the 1992 Cape Mendocino earthquake, which relieved strain on the Cascadia subduction zone. However, the observed displacements of the 1994 event are in the opposite direction and an order of magnitude smaller than those caused by the 1992 event. This suggests the Mendocino Fault earthquake may have once again slightly increased the strain on the locked portion of the subduction zone, hastening the arrival of the next megathrust earthquake. Clearly, adjacent plates and structures are affected by the complex interplay of fault movement in the vicinity of the Mendocino triple junction and Mendocino Fault.

Although extremely active, the Mendocino Fault probably does not pose as great a seismic hazard to north coast residents as earthquakes either within the Gorda plate close to the coast or along the Cascadia subduction zone (Dengler and others, 1992). The fault extends west from the coast and even the near-shore segment is relatively far from the more populated areas of the north coast. Future earthquakes along the Mendocino Fault are likely to be similar to those in the past, with events far offshore producing very wide felt areas but little damage, or near-shore events causing some damage to communities in the Cape Mendocino area.

The tsunami produced by the September 1 earthquake went unnoticed by north coast residents. However, the chronology of events regarding the tsunami analysis and the posting of information raises a number of concerns for north coast communities. It is now generally accepted that very large Cascadia subduction zone earthquakes have occurred in the past and produced large tsunamis (Atwater, 1987; Clarke and Carver, 1992). The April, 1992 Cape Mendocino earthquake produced a small tsunami that arrived at coastal tide gauges within 20 minutes of the earthquake (Oppenheimer and others, 1993). Locally produced tsunamis would arrive at coastal communities before the seismic waves reach the seismographic stations of distant tsunami warning centers. Even more time is likely to elapse before an evaluation of the hazard is made and official tsunami bulletins can be posted to local emergency officials.

No local tsunami watch was initiated after the lightly felt September 1 earthquake even though some earthquakes of this size have produced devastating tsunamis, such as the

September 2, 1992 Nicaragua earthquake (Satake and others, 1993). Not until coastal tide data were available was it clear that no tsunami threat existed. Yet this information was not available until after the 5.5-inch (14-cm) wave reached the coast. Responding to the local tsunami threat on the north coast is a serious issue requiring the combined efforts of local communities, affected states, and the federal government in developing consistent policy and regional public education programs.

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Glossary

Focal mechanisms and "Beachballs": Focal mechanisms describe the orientation of the earthquake fault surface and the direction of slip along the fault. Focal mechanisms can be determined by analyzing seismograms. In the 1930s, seismologists realized that by plotting the sense of motion of the first P-wave arrival at various seismographic stations surrounding the epicenter, the pattern of "ups" (compressions) and "downs" (dilatations) revealed the type of earthquake fault and gave two possible orientations for the fault surface. These "first motion studies" or "fault plane solutions" were usually displayed by constructing an imaginary sphere around the earthquake focus and projecting the point where the ray path to each seismographic station pierced the sphere onto an equal-area stereographic plot. Regions of compressions and dilatations were grouped into quadrants, and the compressional regions darkened, to make a light and dark "beachball" pattern. In recent years, the focal mechanism is more likely to be constructed by detailed analysis of the wave train than by the first motions. The process of "waveform inversion" allows seismologists using one or more seismic stations that can record a broad range of frequencies (broadband instrument) to determine the best approximation of the fault orientation. The focal mechanisms based on this technique are called moment tensors. Like the first motion studies, the moment tensor solutions can also be displayed by stereographic "beachball" projections.

Magnitude: The measure of the size of an earthquake, or the strain energy released by it, traditionally expressed by the Richter magnitude scale. Energy, or moment magnitudes, M_w, are usually determined by analyzing the waveforms recorded on broadband seismographs. Moment magnitudes are increasingly used to describe the size of moderate to very large earthquakes because they most directly reflect the dimensions of the earthquake source. M_L is the local magnitude and corresponds most closely to Richter's original magnitude. It traditionally was determined by measuring the peak wave height (amplitude) on a standardized seismograph. Local magnitudes are restricted to earthquakes located within about 400 miles (600 km) of seismic stations. Surface-wave and body-wave magnitudes, M_s and m_b, are measured from the surface waves or P waves, respectively, recorded on stations often far from the earthquake source. These four magnitudes are usually similar but not exactly the same for a particular event. Each whole number step in magnitude represents about a 30-fold increase in energy released. For example, a magnitude 8 earthquake releases about 30 times the energy of a 7 and more than 900 times that of a magnitude 6.

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