Sources of North Coast Seismicity

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The interaction of three tectonic plates causes earthquakes that strongly affect northern California. This article describes historic earthquakes, summarizes evidence of older events, and discusses potential sources of damaging earthquakes. It has been updated to include three temblors that occurred during preparation of this issue...*editor*

INTRODUCTION

The vicinity of Cape Mendocino is one of California's most seismically active areas (Real and others, 1982; Toppozada and others, 1986). The Mendocino triple junction is the geologically dynamic area where the east end of the Mendocino fault meets the south end of the Cascadia subduction zone and the northern extension of the San Andreas fault. These faults define the boundaries between the Gorda, Pacific, and North American tectonic plates (Figure 1). Coastal Humboldt County has been affected by earthquakes on the San Andreas fault system, on the Mendocino fault, and in both the Gorda and North American plates. At least 60 of the earthquakes that have occurred since the mid-1800s have produced damage (Table 1). Recent studies indicate that the Cascadia subduction zone puts northern coastal California at risk also (Heaton and Hartzell, 1987). Although the subduction zone has not generated great historic earthquakes, paleoseismic evidence suggests that it is the source of large earthquakes in the recent prehistoric past (Clarke and Carver, 1992).

GEOLOGY AND TECTONIC SETTING

The present location of the Mendocino triple junction is estimated to be about 15 miles (25 km) southeast of Cape Mendocino (Clarke, 1992; McLaughlin and others, in press). South of the triple junction, the San Andreas

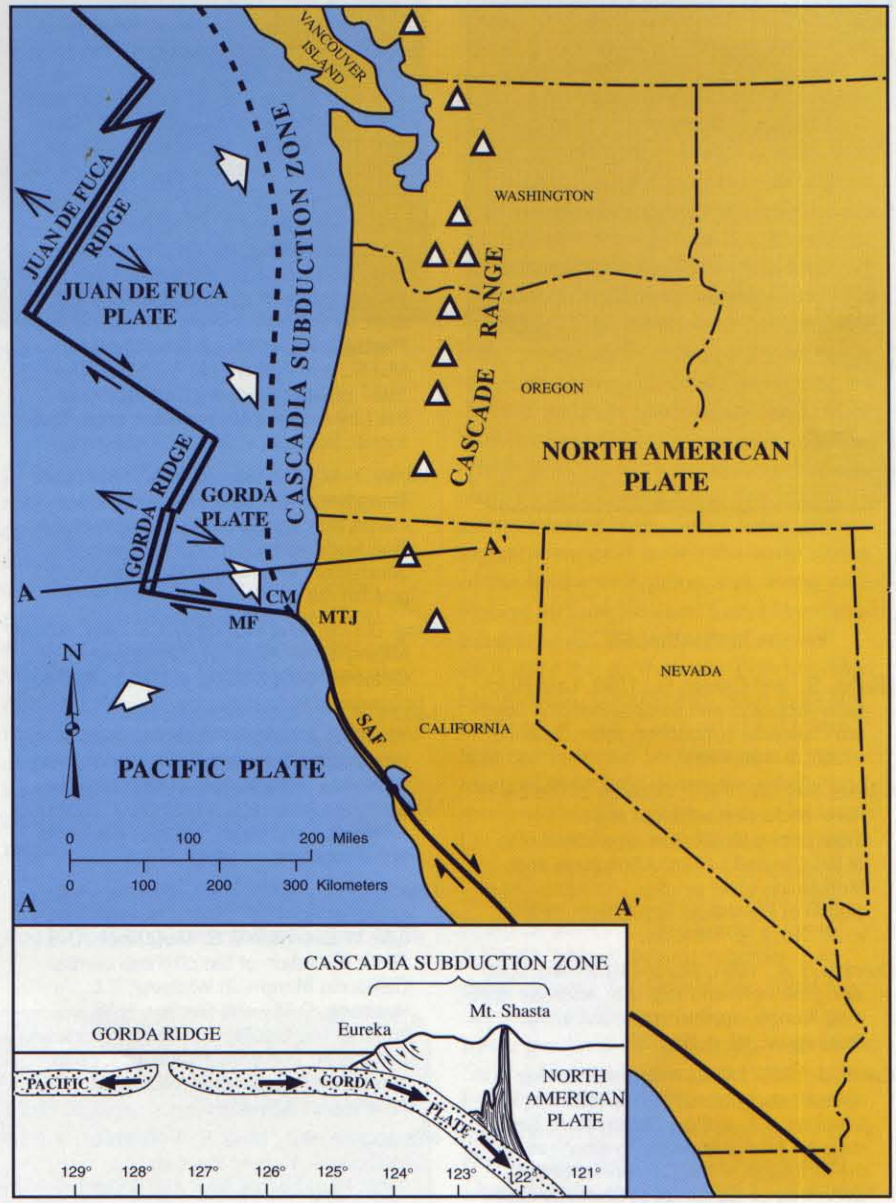

Figure 1. Simplified map of northwestern California regional tectonics. To the south of the Mendocino triple junction (MTJ), the San Andreas fault system (SAF) is the transform (strike-slip) boundary between the Pacific and North American plates. North of Cape Mendocino (CM), the Juan de Fuca and Gorda plates are converging with the North American plate along the Cascadia subduction zone. West of Cape Mendocino, the Mendocino fault (MF) is the transform boundary between the Pacific plate and the Gorda plate. White arrows denote plate motion relative to North America; black arrows denote relative plate motion at plate boundaries. The inset is a simplified cross section of the southern Gorda plate being subducted beneath the North American plate in northern California.

TABLE 1. NORTH COAST HISTORIC EARTHQUAKES OF MAGNITUDE ≥ 5.5 AND/OR INTENSITY ≥ VI.

Location	Date	M	MMI	Lat. °N	Long. °W	Reference
Eureka area (wharf sank 4 feet, or 1.2 m)	10/23/1853	(5.7)	VII	40.80	124.20	Toppazada and others, 1981
Eureka (affected flow of streams, milk thrown from pans)	3/20/1855		VI			Townley and Allen, 1939
Eureka	6/14/1857		VI			Townley and Allen, 1939
Humboldt Bay (damage to plaster and chimneys)	11/13/1860	(5.7)	VII	40.80	124.20	Toppazada and others, 1981
Eureka (damaged brick houses, fissure near Fort Humboldt)	10/1/1865	(5.4-5.7)	VII-VIII	40.80	124.20	Toppazada and others, 1981
Petrolia (chimneys damaged in Rohnerville and Petrolia)	3/2/1871	(5.9)	VIII	40.40	124.20	Toppazada and others, 1981
Crescent City (damaged most buildings in Crescent City, landslides)	11/23/1873	(6.7)	VIII	42.00	124.00	Toppazada and others, 1981
Southeast of Eureka	9/30/1875	(5.8)	VII	40.70	124.00	Toppazada and others, 1981
West of Briceland (knocked down all chimneys in Petrolia)	5/9/1878	(5.8)	VIII	40.10	124.00	Toppazada and others, 1981
North of Hoopa	1/28/1884	(5.7)	V	41.10	123.60	Toppazada and others, 1981
Petrolia (chimneys down in Ferndale and Petrolia)	7/26/1890	(6.0)	VII	40.33	124.25	Toppazada and others, 1981
Near Miranda (chimneys down in southern Humboldt County)	9/30/1894	(5.6-5.8)	VII	40.30	123.70	Toppazada and others, 1981
Offshore Arcata (damaged mill in Eureka)	4/16/1899	(6.4)	VI	41.00	124.40	Toppazada and others, 1981
Offshore Eureka	12/9/1903		V-VI	40.80	124.20	Woodward Clyde, 1980
*San Francisco (rupture began near San Francisco and extended north possibly to Shelter Cove; damage throughout Humboldt Bay region.	4/18/1906	8.3	XI; VII-IX in southern Humboldt Co. and Humboldt Bay region	37.70	122.50	Real and others, 1982
*McKinleyville (chimneys fell in Ferndale)	4/23/1906		VII	41.00	124.00	Real and others, 1982
Offshore Eureka	8/11/1907		VI	40.80	124.20	Toppazada and others, 1978
*Eureka (chimneys fell)	8/18/1908	5.0	VII	40.83	124.17	Simila, 1980
*Petrolia (damaged chimneys)	5/18/1909		VIII	40.25	124.17	Simila, 1980
*West of Scotia (much damage in Rohnerville & Upper Mattole)	10/29/1909	6.4	VIII	40.58	124.17	Simila, 1980
Offshore Petrolia	3/19/1910	6	V	40.83	124.17	Bolt and Miller, 1975
Offshore Cape Mendocino	12/31/1915	6.2-6.5	III	41.00	126.00	Bolt and Miller, 1975
*West of Ferndale	7/5/1916	4.5	VI	40.58	124.25	Bolt and Miller, 1975
Offshore Arcata	7/15/1918	6.0-6.5	VI	41.00	125.00	Bolt and Miller, 1975
Eureka (chimneys fell)	9/15/1919		VI	40.80	124.20	Simila, 1980
Offshore Cape Mendocino	1/26/1922	6.0	I	41.00	126.00	Real and others, 1982
*Offshore 37 miles (60 km) west of Arcata (felt in San Jose, California, and Oregon and Nevada)	1/31/1922	7.3-7.6	VI	40.87	125.35	Smith and Knapp, 1980
*Offshore Cape Mendocino (buildings damaged in Petrolia area)	1/22/1923	6.5-7.3	VIII	40.30	124.50	Smith and Knapp, 1980
Offshore, west of Orick	6/4/1925	6.0	I	41.50	125.00	Bolt and Miller, 1975
80 miles (130 km) west of Eureka	12/10/1926	6.0	I**	40.75	126.00	Bolt and Miller, 1975
*Offshore of Arcata (chimneys fell, landslides)	8/20/1927	5.0	VIII	41.00	124.60	Bolt and Miller, 1975
*Eureka (chimneys fell)	9/23/1930	5.0-5.5	VII	40.80	124.20	Bolt and Miller, 1975
Offshore Cape Mendocino	12/11/1930	5.0	VI	40.08	124.50	Bolt and Miller, 1975
Offshore Cape Mendocino	3/10/1931	5.6	V	40.00	125.00	Real and others, 1982
Offshore Cape Mendocino	8/23/1931	5.3	VI	40.20	125.60	Real and others, 1982
Offshore Eureka (chimneys damaged)	9/9/1931	5.8	VI	40.80	125.00	Real and others, 1982
112 miles (180 km) west of Cape Mendocino	3/2/1932	5.6	I**	40.20	127.00	Woodward Clyde, 1980
*Near Arcata (one death, much damage in Eureka)	6/6/1932	5.9-6.4	VIII	40.87	124.02	Smith and Knapp, 1980
56 miles (90 km) west of Trinidad	7/6/1934	6.5	I**	41.25	125.42	Smith and Knapp, 1980
Offshore Cape Mendocino	1/2/1935	5.8	V	40.25	125.25	Real and others, 1982
93 miles (150 km) west of Cape Mendocino	6/3/1936	5.8	V	40.16	126.45	Woodward Clyde, 1980
Offshore Cape Mendocino (slight damage)	2/6/1937	5.7-5.8	V	40.50	125.25	Coffman & von Hake, 1973
*Southeast of Cape Mendocino (slight damage in Ferndale)	9/11/1938	5.5	VI	40.00	124.00	Real and others, 1982
*Offshore Cape Mendocino (chimney damage)	11/19/1940	5.5	V-VI	40.75	124.90	Berkeley Seism. Stn.
Near Shelter Cove	12/20/1940	5.5	VI	40.00	124.00	Real and others, 1982
*Offshore northwest of Cape Mendocino	2/9/1941	6.4-6.6	VI	40.70	125.40	Real and others, 1982
Offshore Cape Mendocino	5/13/1941	6.0	V	40.30	126.40	Berkeley Seism. Stn.
*Offshore northwest of Cape Mendocino (chimneys damaged)	10/3/1941	6.4	VII	40.54	125.00	Smith and Knapp, 1980

M Richter magnitude (magnitudes in parentheses are estimated)
MMI Modified Mercalli Intensity
* Data from these earthquakes were used to make Figure 5 map
** Modified Mercalli Intensity estimated from this study

TABLE 1 (continued). NORTH COAST HISTORIC EARTHQUAKES OF MAGNITUDE ≥ 5.5 AND/OR INTENSITY ≥ VI.

Location	Date	M	MMI	Lat. °N	Long. °W	Reference
Offshore Cape Mendocino	5/19/1945	6.2	V	40.60	126.40	Coffman & von Hake, 1973
*Offshore Cape Mendocino (damage in Ferndale and Capetown)	12/18/1946	4.7	VI	40.30	124.60	Woodward Clyde, 1980
Offshore Cape Mendocino	3/30/1947	4.6	VI	40.38	124.68	Woodward Clyde, 1980
Offshore Cape Mendocino	5/27/1947	5.2	VI	40.40	124.70	Woodward Clyde, 1980
*Offshore Cape Mendocino	9/23/1947	5.6	VII	40.40	125.20	Coffman & von Hake, 1973
93 miles (150 km) west of Orick	3/24/1949	5.9	II-III	41.30	126.00	Real and others, 1982
*Offshore Cape Mendocino	1/14/1950	4.6	VI	40.22	124.42	Woodward Clyde, 1980
*Petrolia	3/10/1951	4.1	VI	40.30	124.30	Woodward Clyde, 1980
*Offshore Cape Mendocino 10 miles (16 km) west of Petrolia	10/8/1951	5.8-6.0	VII	40.35	124.60	Smith and Knapp, 1980
*Near Scotia (minor damage)	11/14/1951	4.9	VI	40.43	124.05	Woodward Clyde, 1980
12 miles (20 km) southwest of Petrolia (chimneys fell, foundation damage)	9/22/1952	5.2-5.4	VII	40.20	124.42	Real and others, 1982
Offshore Cape Mendocino	11/25/1954	6.1-6.3	V	40.48	125.46	Smith and Knapp, 1980
12 miles (20 km) northeast of Arcata ($2,100,000 damage, one death)	12/21/1954	6.5-6.6	VIII	40.85	123.96	TERA, 1977
Offshore northwest of Cape Mendocino (slight damage in Ferndale)	10/11/1956	6.0	V	40.67	125.77	Real and others., 1982
*Near Petrolia	5/24/1958	4.8-4.9	VI	40.30	124.02	Berkeley Seism. Stn.
Offshore, 56 miles (90 km) west of Trinidad	7/ 23/1959	5.8	IV	41.13	125.30	Real and others, 1982
*Offshore Arcata (plaster fell at Eureka City Hall)	6/5/1960	5.7	VI	40.87	124.50	Smith and Knapp, 1980
Offshore Cape Mendocino (felt in San Francisco and southern Oregon)	8/9/1960	6.0-6.2	V	40.32	127.07	Berkeley Seism. Stn.
Offshore 11 miles (18 km) west of Cape Mendocino (triggered landslide)	4/6/1961	5.0-5.5	VI	40.49	124.81	Smith and Knapp, 1980
*Offshore Crescent City (slight damage)	8/23/1962	5.6	VI	41.84	124.39	Nowroozi, 1973
Offshore northwest of Arcata (slight damage)	9/4/1962	4.9-5.0	VI	41.01	124.21	Nowroozi, 1973
*Offshore 12 miles (20 km) west of Petrolia (slight damage)	12/10/1967	5.6-5.8	VI	40.56	124.58	Smith and Knapp, 1980
*Offshore Cape Mendocino	6/26/1968	5.5-5.9	VII	40.29	124.67	Nowroozi, 1973
*Near Petrolia (slight damage in Petrolia)	8/9/1973	4.9-5.0	VI	40.35	124.30	Smith and Knapp, 1980
*Fortuna	6/7/1975	5.2-5.7	VII	40.51	124.27	Smith and Knapp, 1980
Offshore 93 miles (150 km) northwest of Eureka	11/26/1976	6.3	IV	41.30	125.70	Berkeley Seism. Stn.
*Offshore 16 miles (25 km) west of Arcata (pipes and windows broken in Eureka)	2/3/1979	5.2	VI-VII	40.92	124.42	Berkeley Seism. Stn.
*30 miles (48 km) west of Trinidad (bridge collapsed, six injured, $1,750,000 damage)	11/8/1980	6.9-7.4	VII	41.12	124.67	Berkeley Seism. Stn.
Offshore Cape Mendocino	8/24/1983	5.5	V	40.38	124.83	Berkeley Seism. Stn.
Offshore 155 miles (250 km) west of Eureka (felt from San Francisco to Oregon)	9/10/1984	6.6	V	40.50	126.83	NEIS
*Just offshore Cape Mendocino (two events in 1 minute, slight damage)	11/21/1986	5.1, 5.1	VI	40.37	124.44	Berkeley Seism. Stn.
*Just offshore Cape Mendocino (damage and rockslides in Petrolia)	7/31/1987	5.5	VII	40.42	124.41	NEIS
Near Honeydew (caused damage in Honeydew and Petrolia)	1/16/1990	5.3	VII**	40.23	124.14	Berkeley Seism. Stn.
Offshore 50 miles (80 km) west-northwest of Crescent City	7/13/1991	6.7-6.9	V	42.14	125.61	NEIS
Offshore 62 miles (100 km) west of Crescent City	8/16/1991	5.9-6.3	V	41.73	125.39	NEIS
Near Honeydew (chimney, foundation damage, landslides, well changes)	8/17/1991	6.0-6.2	VIII**	40.21	124.28	NEIS
Offshore 62 miles (100 km) west of Crescent City	8/17/1991	6.9-7.1	V	41.61	125.51	NEIS
South of Petrolia (foundation damage, landslides)	3/7/1992	5.3-5.6	VII**	40.23	124.29	Berkeley Seism. Stn.
3 miles (5 km) north of Petrolia (preliminary estimate – $48 million in damage, 356 injuries, tsunami, coastal uplift, liquefaction, landslides)	4/25/1992	7.0	≥VIII**	40.37	124.31	NEIS
20 miles (33 km) west-northwest of Petrolia (fire destroyed Scotia Shopping Center)	4/26/1992	6.0	VII**	40.44	124.58	NEIS
15 miles (25 km) west of Petrolia (additional damage)	4/26/1992	6.5	VII-VIII**	40.40	124.56	NEIS

M Richter magnitude (magnitudes in parentheses are estimated)
MMI Modified Mercalli Intensity

* Data from these earthquakes were used to make Figure 5 map
** Modified Mercalli Intensity estimated from this study

fault system forms the transform (strike-slip) boundary between the Pacific and North American plates. The Pacific plate is moving north relative to the North American plate, resulting in strain accumulation and episodic ruptures such as the 1906 San Francisco earthquake. Although the nature of the northern termination of the San Andreas fault is unclear, there is agreement that it does not extend beyond Cape Mendocino (Smith and Knapp, 1980; Lisowski and Prescott, 1989; McLaughlin and others, in press; Clarke, 1992).

The Cascadia subduction zone, north of the triple junction, is the convergent boundary between the Gorda and North American plates (Atwater, 1970; Engebretson and others, 1985). A schematic section across the southern portion of the Gorda plate and the subduction zone is shown in Figure 1. Subsurface earthquake locations trace the subducted portion of the Gorda plate (Smith and Knapp, 1980; McPherson 1989a; Walter, 1986). The Gorda plate dips east beneath the North American plate at an angle of 10 to 15 degrees (Smith and Knapp, 1980; McPherson, 1989a). About 60 miles (100 km) east of the coastal margin, at a depth of 25 to 30 miles (40 to 50 km), the dip steepens to 30-45 degrees (McPherson and others, 1981; Cockerham, 1984; Walter, 1986). The deepest earthquakes (50 miles or 80 km below the surface) associated with the subducted plate are east of Redding (Walter, 1986). The active volcanos of the Cascade range are about 30 miles (50 km) farther east where the subducted plate has likely reached depths of over 60 miles (100 km).

The collision between the North American and Gorda plates has deformed the leading edge of the North American plate (Carver, 1987), as seen by north-northwest trending folds and thrust faults onshore and offshore (Field and others, 1980; Clarke and Carver, 1992). At least nine major thrusts and as many folds deform the young sediments along California's north coast (Carver, 1987) (Figure 2). Offsets of the Falor Formation (Manning and Ogle, 1950) along several of these faults indicate displacement of half a mile (a kilometer) or more within the last million years (Carver, 1987).

The Mendocino fault extends due west from Cape Mendocino, forming the transform boundary between the Gorda and Pacific plates. This fault appears to be nearly vertical and motion is primarily right-lateral strike-slip (McPherson, 1989a; Eaton 1989; Wilson, 1986; Jachens and Griscom, 1983). However, reverse movement has been recorded in earthquakes in the compressional zone close to the triple junction (Nowroozi, 1973; Simila, 1980; McPherson, 1989a).

The occurrence of earthquakes within the Gorda plate indicates internal deformation. Faulted sediments on the sea floor, and aftershock sequences of recent earthquakes show a pattern of left-lateral strike-slip faulting within the offshore portion of the Gorda plate (Silver, 1971; Smith and others, 1981; McPherson, 1989a; Eaton, 1989). The faults trend northeast to east-northeast and reflect a clockwise rotation of the southern portion of the plate (McPherson, 1989a; Eaton, 1989). The pattern of deformation has been interpreted as a response to north-south compression created by the northward movement of the Pacific plate and the southeast motion of the Juan de Fuca plate (Spence, 1989; McPherson, 1989a).

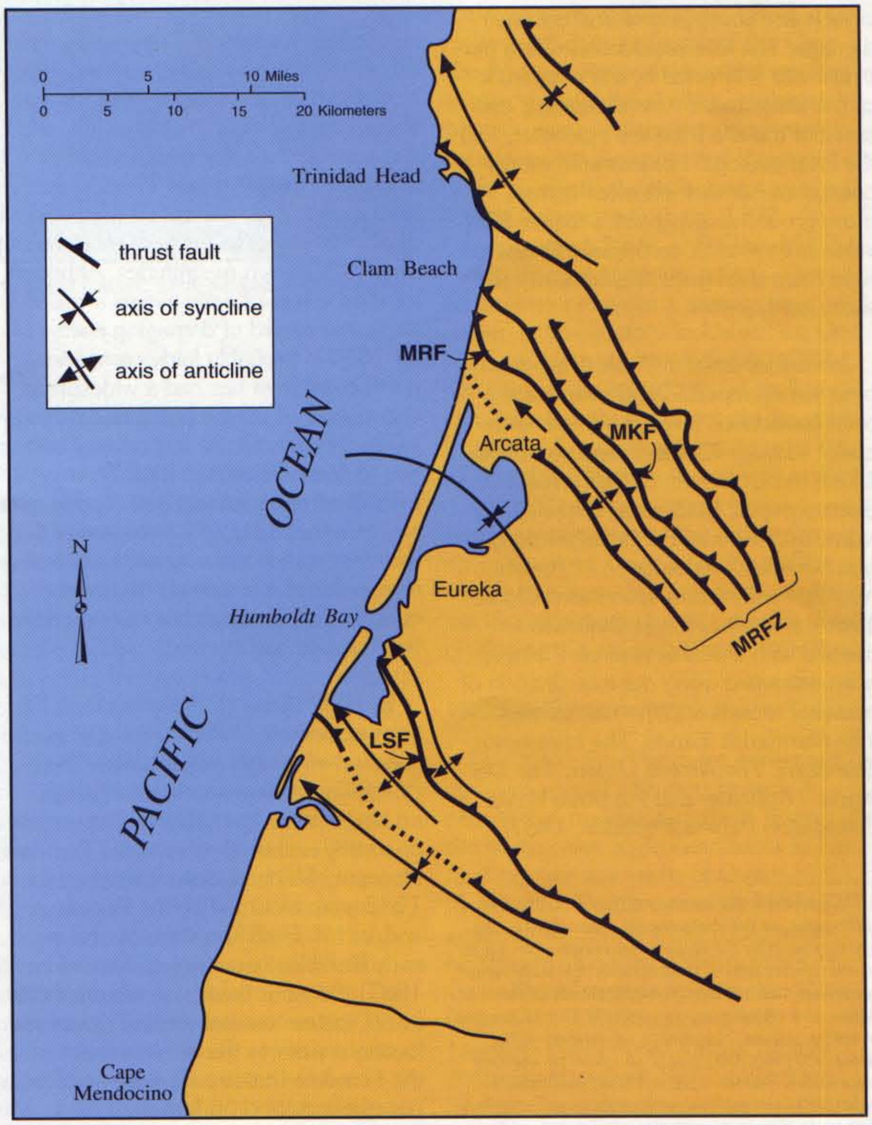

Figure 2. Sketch map of faults and folds in the vicinity of Humboldt Bay. MRFZ = Mad River fault zone; MKF = McKinleyville fault; MRF = Mad River fault; LSF = Little Salmon fault. After Clarke and Carver, 1992.

HISTORIC SEISMICITY

Pattern of Earthquakes

Table 1 summarizes regional historic earthquakes, not including aftershocks, with Richter magnitudes* of 5.5 or larger, and/or Modified Mercalli intensities (MMI) of VI or larger. MMI values are a measure of the degree of damage at a particular location and are based on personal accounts and damage reports. The Modified Mercalli Intensity Scale (Wood and Neumann, 1931; CALIFORNIA GEOLOGY, 1991) ranges from I (generally not felt) to XII (total damage with visible ground surface waves). The threshold of damage is typically VI — characterized by falling or displaced objects and some plaster and chimney damage. The intensity recorded at a particular site is affected by the magnitude of the earthquake, type of faulting, distance of the site from the epicenter, and the local geology. For example, north coast communities will often sustain more ground shaking and a higher MMI value from smaller earthquakes centered near them than from large distant offshore earthquakes.

Intensities listed in Table 1 are the peak values reported and most have been transcribed from published earthquake catalogs (Coffman and von Hake, 1973; the University of California [U.C.] Seismographic Stations at Berkeley Bulletins; the National Earthquake Information Service Determination of Preliminary Epicenters; and Woodward-Clyde, 1980). Intensities for earthquakes marked with a double asterisk (**) have been estimated using our examination of personal reports and the newspapers *The Humboldt Times, The Humboldt Standard, The Arcata Union, The Del Norte Triplicate,* and the Susie Baker Foundation Papers (Fountain, 1967).

*Magnitude is the measure of the strength of an earthquake, or the strain energy released by it, usually expressed by the Richter magnitude scale. Each whole number step of magnitude on the scale represents a ten-fold increase in the amplitude of the waves on a seismogram and about a 31-fold increase in energy release. Magnitudes determined within about 400 miles (600 km) of an epicenter are local magnitudes. Surface-wave and body-wave magnitudes are measured from seismograms recorded farther away. Energy magnitudes are determined from fault dimensions, displacement, and rigidity. These four magnitudes are usually similar for the same event.

For early events, it is likely that reports were not received from all areas and the intensity value listed is smaller than the true maximum. Also, we have found that it is not easy to differentiate among MMIs VII, VIII, and IX in sparsely settled rural areas with woodframe buildings. Because of the lack of large structures, masonry construction, buried pipe lines, and other MMI "indicators," it is possible that peak intensity estimates for some earthquakes are inaccurate by one or two intensity levels.

Epicenter locations listed in Table 1 are from the references in the last column. A range of magnitudes given for a single event reflects different reporting sources and/or different methods of measuring magnitude. Toppozada and others (1981) determined epicenter locations for pre-1900 events from the pattern of reports of earthquakes felt, and suggest there may be mislocations of 60 miles (100 km) or more. To estimate magnitudes, they compared the patterns of old felt events to those of more recent ones with known magnitudes. Although location errors of early events are likely large, the record of damaging events after 1850 is probably fairly complete. The north coast area has had a widespread distribution of small logging and fishing towns throughout the last century and two to five newspapers have been in print at all times since 1850 (Toppozada and others, 1981). Offshore events that were not widely felt may not have been reported, but it is unlikely that earthquakes causing significant damage have been missed.

In 1932 the U.C. Seismographic Stations at Berkeley installed the first north coast seismograph in Ferndale. (The Bosch-Omori seismograph, although no longer used by U.C. Berkeley, is still operating and on display at the Ferndale Museum.) Many of the events prior to 1932 were recorded by the Berkeley and/or Mt. Hamilton stations of the early Berkeley network (established in 1887). Because these stations are so far south, instrument-determined epicenter locations prior to the establishment of the Ferndale station may have uncertainties of 60 miles (100 km) or more (Urhammer, R.A., 1991, U.C. Berkeley, personal communication). Event location improved gradually throughout the middle part of the century as more instruments were installed. U.C. Berkeley established the Arcata station in 1948 and the Fickle Hill station (about 12 miles or 20 km east of Eureka) in 1968. Because of the thin distribution of stations and the complexities of local geology, it is likely that locations of even onshore or near-shore earthquakes occurring as recently as the late 1950s may be in error by as much as 30 miles (50 km) (Knapp, 1982).

In mid-1974, a 16-station array of seismographs was installed in the north coast region and operated by TERA Corporation as part of a seismic safety study for Pacific Gas and Electric Company's Humboldt Bay nuclear power plant (TERA Corporation, 1975; Woodward-Clyde, 1980; McPherson and others, 1981; McPherson, 1989a). Earthquakes recorded during the array's 12-year operation are the best located of the historic data set. After the network was disbanded, two of the stations were donated to the Berkeley network and are part of the U.C. Seismographic Stations. In response to the damaging November 1980 earthquake, the U.S. Geological Survey established a network of telemetered instruments in the region, which continue to operate (Eaton, 1989). Recent onshore and near-offshore epicenters are likely to be accurately located, but locating events far offshore continues to be a problem due to the region's lack of ocean-bottom seismographs.

Smith and Knapp (1980) published a number of relocations of the older earthquakes. They used the Joint Epicenter Determination technique, comparing the seismic traces of a well-located recent event (recorded by new and old seismic stations) to older events and simultaneously solving for a set of epicenter locations, origin times, and station corrections of the older events relative to the recent event. These relocated epicenters probably represent an improved estimate of the true location of the earthquake source.

Epicenters of the best-located historic earthquakes (those after 1960, and Smith and Knapp's relocations) are shown in Figure 3. The majority are scattered throughout the southeastern

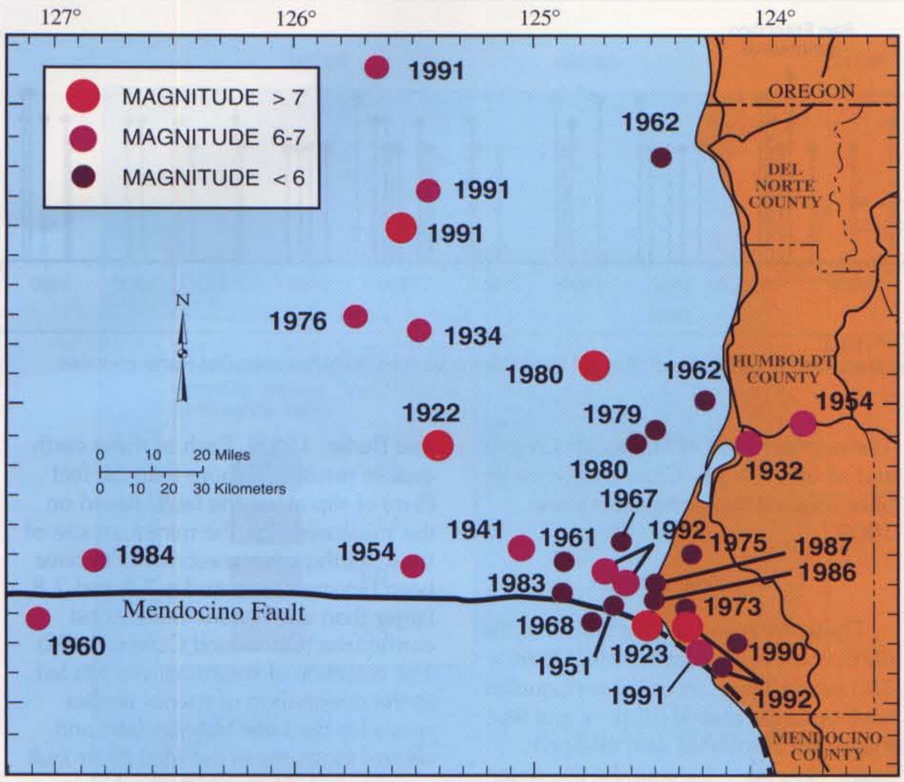

Figure 3. Epicenters and dates of best located north coast historic earthquakes of magnitude ≥5.5 and/or intensity ≥VI.

portion of the Gorda plate and along the Mendocino fault. For earthquakes in the southern portion of the Gorda plate (such as 1941, 1954, 1961, and 1984 in Figure 3), it is difficult to establish their sources as the Mendocino fault or the Gorda plate, due to the imprecision in location methods. However, most offshore earthquakes are clearly intraplate events. Aftershock data and fault plane solutions suggest that the Gorda plate earthquakes result from movement along northeast trending left-lateral strike-slip faults (TERA Corporation, 1977; Smith and others, 1981; McPherson, 1989a). Mendocino fault earthquakes show predominantly right-lateral slip parallel to the trend of the fault, but there have been a few reverse-slip events in the vicinity of Cape Mendocino (Bolt and others, 1968; Simila and others, 1975; McPherson, 1989a).

The epicenters of only eight earthquakes shown in Figure 3 fall within the onshore portion of the map. The January 1990, August 1991, and March 7, 1992 earthquakes were centered in the immediate vicinity of the triple junction (see McPherson and Dengler this issue). The April 25, 1992 $M_S = 7.0$ earthquake was located just north of the August 17th event and is discussed in more detail below. Of the onshore earthquakes north of the triple junction, only the December 1954 earthquake is thought to be shallow enough to have occurred in the overriding North American plate (Tobin and Sykes, 1968; TERA Corporation, 1977; Smith and Knapp, 1980; Knapp, 1982). Hamilton (1975) suggested that this earthquake was associated with a fault in the Mad River fault zone, although lack of documented surface rupture and uncertainty about the type of faulting involved make it impossible to confirm. The 14-mile (23-km) depth of the June 1975 earthquake (considered accurate to within 0.6 mile [1 km] [TERA Corporation, 1977; Knapp, 1982]) is clearly within the portion of the Gorda plate that has been subducted beneath the North American plate. Over 80 percent of well-located microearthquakes recorded by the Humboldt Bay seismic network between 1974 and 1984 occurred at Gorda plate depths (McPherson, 1989a), strongly suggesting that the Gorda plate is the main source for both onshore and offshore historic seismicity.

The April 25, 1992 Cape Mendocino earthquake is the only historic damaging event which may have resulted from thrusting along the Cascadia subduction zone. Prior to this earthquake, researchers had found no conclusive evidence within the historic record to suggest that such an event had occurred anywhere along the subduction zone boundary from Cape Mendocino to Vancouver Island, British Columbia during the last 150 years (Heaton and Kanamori, 1984; Heaton and Hartzell, 1987). Preliminary data suggest that the Cape Mendocino earthquake was the result of reverse slip along a shallow northeast dipping, northwest striking plane which coincides with the estimated location of the subduction zone boundary (Oppenheimer and others, 1992; Oppenheimer, 1992, U.S.G.S., Menlo Park, personal communication). This earthquake produced a tsunami recorded at tide stations in California, Oregon, and Washington (NOAA, 1992, personal communication) and preliminary investigations support coastal uplift from near Cape Mendocino to near the mouth of the Mattole River. This earthquake lends strong support to the seismogenic nature of the subduction zone; however it was a much smaller earthquake than the main portion of the locked zone is thought capable of producing (Clarke and Carver, 1992).

1906 San Francisco Earthquake

The 1906 San Francisco earthquake deserves special attention because it caused the greatest damage in history of the north coast region and because the fault rupture was south of Cape Mendocino. Rupture extended from south of the San Francisco Bay area northward along the coast perhaps as far as Point Delgada near Shelter Cove (Lawson, 1908; Prentice, 1989). Lawson (1908) noted surface rupture (interpreted as fault displacement) in Shelter Cove, duration of strong groundmotion in excess of 40 seconds throughout the Humboldt Bay region, and extensive damage to communities in the

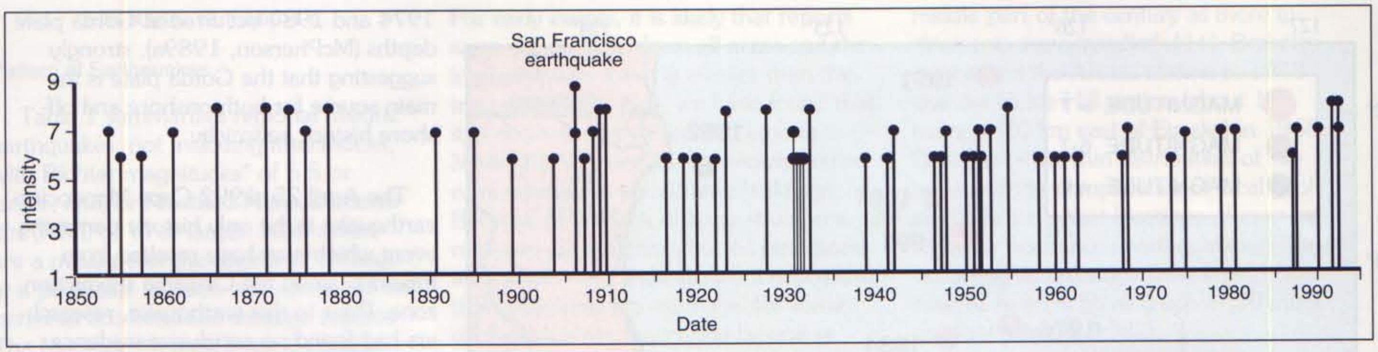

Figure 4. Frequency of historic earthquakes producing peak Modified Mercalli intensities ≥ VI in Humboldt and/or Del Norte counties.

Humboldt Bay area and in southern Humboldt County. The MMIs were at least VIII in Briceland, Eureka, and Fortuna and may have reached IX in Petrolia and Ferndale (Toppozada and Parke, 1982). In Ferndale, not a chimney remained standing and brick buildings were badly damaged. Liquefaction features were observed in the Eel River Valley and around Humboldt Bay.

Since the middle 1800s, the north coast region has experienced at least 60 earthquakes with peak MMIs of VI, 28 intensity VIIs, 11 intensity VIIIs (the epicentral area intensity of the 1989 Loma Prieta earthquake) and possibly, one IX (Figure 4). Intensity VII or greater events have recurred on the average of every 5 years, with 13 years being the longest interval between these events. The recurrence of MMI VI or greater events has averaged 2-1/2 years. Most of these events likely originated within the Gorda plate or along the Mendocino fault.

Figure 5 is a composite intensity map of the north coast area since 1900. The map was constructed from the MMI data for the 34 earthquakes marked by single asterisks in Table 1. For each of these earthquakes, communities reporting VIs or greater were marked on a map and the resulting pattern was contoured according to the number of times an area had experienced this level of intensity. Not surprisingly, communities in the coastal region near Cape Mendocino from Eureka to south of Petrolia have been damaged far more frequently than the rest of Humboldt or Del Norte County. The frequency decreases in roughly a radial pattern away from Cape Mendocino. The northern part of Humboldt County and all of Del Norte County have rarely been affected by earthquakes since 1900.

PALEOSEISMICITY

The historic earthquake record in the north coast region covers fewer than 150 years. These recorded earthquakes have occurred mainly offshore and few, if any, are associated with mapped faults. However, the youthful characteristics of the faults mapped within the North American plate and recognition of the potential of the Cascadia subduction zone require looking beyond the brief historic record and using paleoseismologic evidence to assess the seismic potential of these sources.

North American Plate Faults

Several studies have focused on a system of northwest trending thrust faults that intersect the north coast and extend offshore (Woodward-Clyde, 1980; Carver, 1987; Carver and Burke, 1988; Kelsey and Carver, 1988; Clarke and Carver, 1992; Figure 2). Studies of sediments exposed in trenches dug across fault traces suggest that these faults have generated many seismic events during the past 10,000 years (Carver and Burke, 1988; Clarke and Carver, 1992). The three most studied faults are the Little Salmon in the southern Humboldt Bay area, and the McKinleyville and Mad River of the Mad River fault zone north of Arcata (Figure 2).

The Little Salmon fault has been the most active fault in the region during the Holocene, with a minimum of three events in the last 2,000 years, about 300, 800, and 1,700 years ago (Carver and Burke, 1988). Each of these earthquakes resulted in more than 16 feet (5 m) of slip along the fault. Based on the measured slip, the minimum size of these earthquakes is estimated to have been between magnitudes 7.6 and 7.8, larger than any historic north coast earthquake (Clarke and Carver, 1992). The evidence of recent activity has led to the designation of special studies zones for the Little Salmon fault and several segments in the Mad River fault zone, in accordance with the Alquist-Priolo Geologic Hazard Zones Act of 1972 (Hart, 1988).

Cascadia Subduction Zone

Heaton and Kanamori (1984) drew national attention to the seismic potential of the Cascadia subduction zone by noting similarities with other seismically active subduction zones. Since then a number of paleoseismicity studies (Atwater, 1987; Grant and others, 1989; Peterson and Darienzo, 1989; Adams, 1990; Clarke and Carver, 1992) and recent geodetic data (Lisowski and Prescott, 1989; Savage and Lisowski, 1991) have strengthened arguments that very large earthquakes have occurred along this zone, and are likely to recur. The onshore system of folds and thrust faults in the Humboldt Bay region clearly joins similar structures offshore (Clarke and Carver, 1992) and is likely the southernmost manifestation of the subduction zone. In similar convergent boundary settings there is little evidence that thrust faults like these move independently of their associated subduction zones (Heaton and Hartzell, 1987). The emerging chronology of slip events on the Little Salmon fault is similar to the timing of

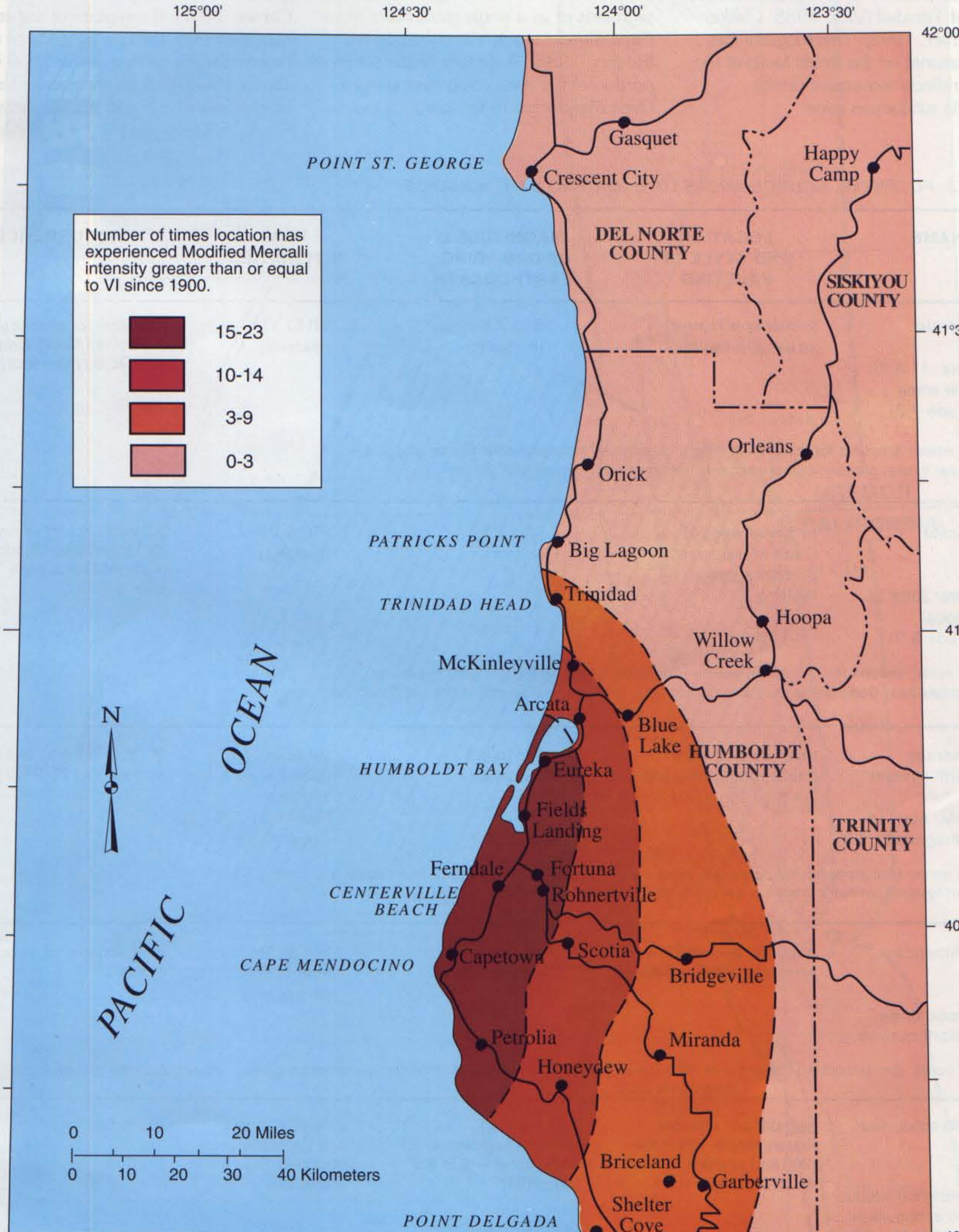

Figure 5. Cumulative frequency of ground shaking in north coast communities. Communities within the darkest area have experienced at least 15 earthquakes with ground shaking equivalent to or larger than VI on the Modified Mercalli Scale. Data used to compile this map are from 34 earthquakes since 1900, denoted by single asterisks (*) in Table 1.

sudden submergence events in Humboldt Bay and uplift events along Clam Beach south of Trinidad (Vick, 1988; Clarke and Carver, 1992). This suggests that slip measured on the thrust faults in the region reflects movement on the Cascadia subduction zone.

There is no consensus as to whether the Cascadia subduction zone ruptures in segments or as a single giant event from Cape Mendocino to Vancouver Island (Rogers, 1988). A rupture of the southern portion of the zone could extend from Cape Mendocino to just north of the Oregon border, corresponding to an earthquake of about magnitude 8.5 (Clarke and Carver, 1992). If a rupture of the entire zone occurred, the energy released could be comparable to that of the 1960 Chilean or 1964 Alaskan earthquake (energy magnitudes of 9.6 and 9.2 respectively),

TABLE 2. POTENTIAL SOURCE AREAS OF DAMAGING EARTHQUAKES.

NAME	LOCATION AND STYLE OF FAULTING	MAGNITUDES OF DAMAGING EARTHQUAKES	PEAK INTENSITIES	RECURRENCE
Gorda plate *Example:* 11/8/80 (surface wave magnitude 7.2)	primarily offshore; strike-slip faulting	5 to 7.5 (historic)	VII to VIII (historic)	5.5 years for intensities ≥VII (combined Mendocino fault and Gorda plate sources)
Special notes: accounts for majority of historic seismicity, most probable source of damage in the near future; primary impact to coastal communities of Humboldt County				
Mendocino fault *Example:* June 25, 1968 (local magnitude 5.9)	offshore west of Cape Mendocino; primarily strike-slip faulting	5 to 7.5? (historic)	VII to VIII (historic)	5.5 years. for intensities ≥VII (combined Mendocino fault and Gorda plate sources)
Special notes: second most common source of historic earthquakes, primarily impacting communities near Cape Mendocino and those in the Eel River Valley and Humboldt Bay areas				
San Andreas transform system *Example:* April 18, 1906 (magnitude 8.3)	onshore and near-shore, south of triple junction; primarily strike-slip	5.0 to 8.3 (historic)	VII to IX (historic) in southern Humboldt County	of 1906 San Andreas-type earthquakes 200-400 years
Special notes: less probable but potentially more damaging than Gorda plate or Mendocino fault earthquakes; primary impact in southern Humboldt County and Humboldt Bay areas.				
North American plate no historic large thrust earthquakes	onshore and shallow; primarily thrust-faulting	6.5 to 8+ (expected)	≥IX for thrust events (expected)	for thrust events, hundreds of years
Special notes: less probable in near future than Gorda plate or Mendocino fault earthquakes; much greater impact; possible tsunami				
Cascadia subduction zone no historic great subduction zone earthquakes. April 25, 1992 M = 7.0 may have involved slip at the southern end of the zone.	onshore and offshore; rupture length 125 miles (200 km) or more; thrust-faulting	7.0? (historic) southern segment — 8.5 whole zone — 9 to 9.5 (expected)	in Humboldt and and Del Norte counties: ≥X (expected)	300 to 500 years
Special notes: less probable in near future than Gorda plate or Mendocino fault earthquakes; most damaging of all potential sources; likely to generate a tsunami				

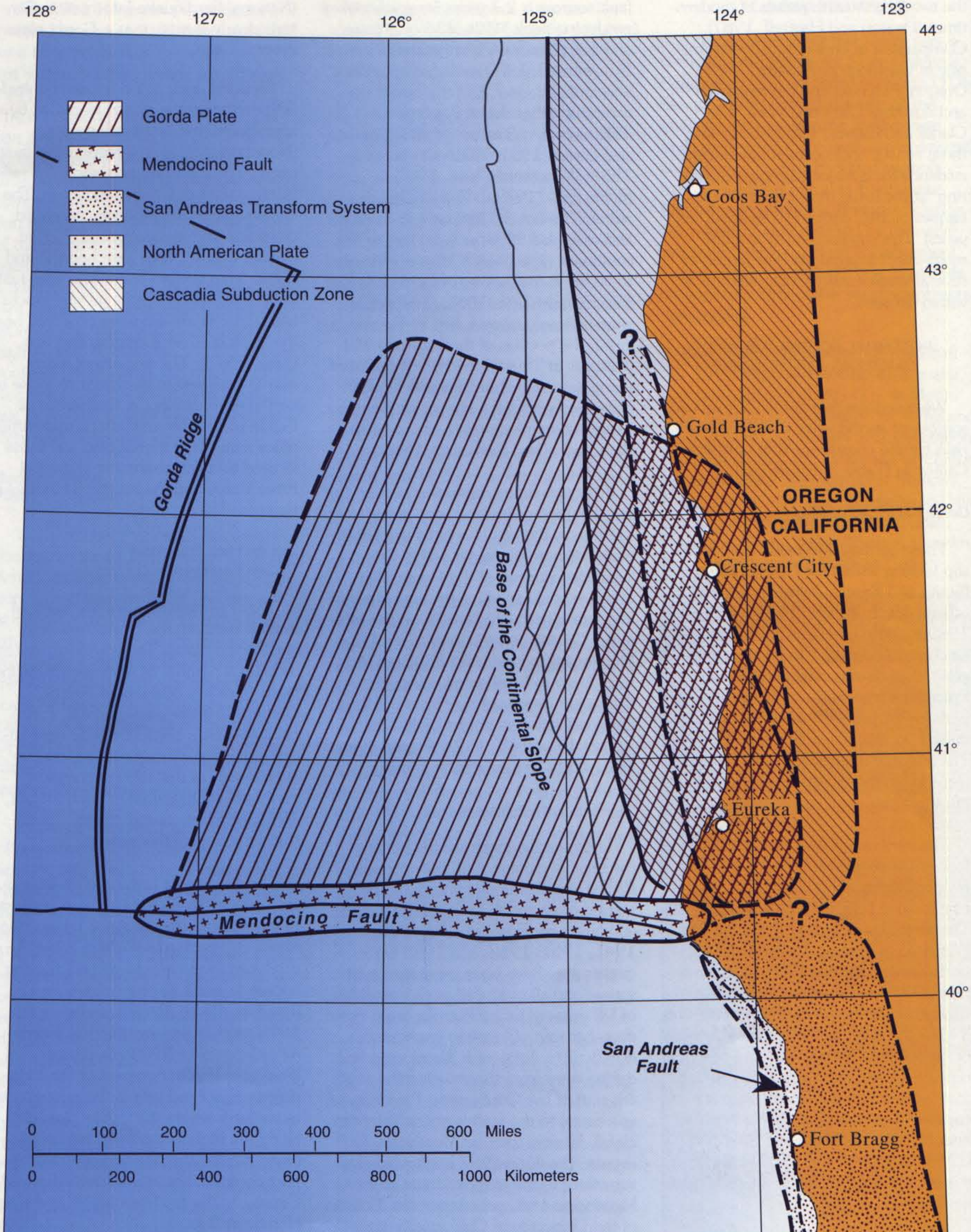

Figure 6. Summary of regional earthquake source zones.

the two largest earthquakes of modern times (Heaton and Hartzell, 1987). Comparison of buried marsh stratigraphy in Washington (Atwater, 1987), Oregon (Peterson and Darienzo, 1989), and northern California (Vick, 1988; Clarke and Carver, 1992) shows that these coastal areas exhibit paleoseismic evidence for a major earthquake occurring at the same time within the uncertainties of 14C dating (10 to about 100 years). This suggests either a single mega-event (magnitude 9 or larger) or several smaller events (magnitude 8.5) within decades.

POTENTIAL SOURCE AREAS OF DAMAGING EARTHQUAKES

We recognize five distinct but related sources of earthquakes that pose seismic risks for the coastal areas of northern California (Table 2; Figure 6).

Gorda Plate Earthquakes

These earthquakes result from strike-slip faulting within the Gorda plate (Smith and Knapp, 1980; Smith and others, 1981; Wilson, 1989; McPherson 1989b). Although these faults may extend inland beneath the North American plate, they do not reach its surface. Epicenters are usually offshore, although perhaps 10 percent are within the subducted portion of the Gorda plate. The majority of damaging earthquakes recorded in the Humboldt Bay region are this type.

The earthquake of January 1922 (surface wave magnitude 7.6) is the largest historic earthquake in California's north coast region (TERA Corporation, 1977). The MMI-III region extended from San Francisco to Eugene, Oregon and into northwestern Nevada. TERA Corporation (1977) staff assumed the earthquake was along the Mendocino fault, believing it to be the only fault in the area capable of producing a 50-mile (80-km) or longer rupture. However, it is now recognized that faults within the Gorda plate are capable of producing large earthquakes and, considering Smith and Knapp's (1980) location of the 1922 earthquake, it is more likely that it was a Gorda plate earthquake.

The average recurrence from the combined Gorda plate and Mendocino fault sources is 2.7 years for earthquakes producing peak MMIs of VI or greater, and 5.5 years for VII or greater. The November 8, 1980 earthquake (surface wave magnitude 7.2) is the best-documented earthquake of this type (Kilbourne and Saucedo, 1981; Smith and others, 1981; TERA Corporation, 1982; Woodward-Clyde, 1982; McPherson, 1989a). Rupture began about 30 miles (50 km) west of Trinidad and extended 90 miles (150 km) to the southwest. The peak MMI was estimated to be VII in the vicinity of Fields Landing (Woodward-Clyde, 1981). Six people were seriously injured, five by the collapse of a portion of the Highway 101 overpass at Thompkins Hill. There were many damaged chimneys and foundations throughout the Humboldt Bay area. Liquefaction effects were observed near Big Lagoon and Centerville Beach.

Although future damaging events are likely to be similar in size and effects to those in the past, we believe an earthquake with an epicenter within the subducted portion of the Gorda plate onshore could produce stronger shaking and intensities as high as IX on the MMI scale. Coastal communities in the Cape Mendocino to Humboldt Bay area are most likely to be affected, although the recent large events offshore of the Oregon-California border (July 13, August 16 and 17, 1991) suggest risk as far north as the Oregon border.

Mendocino Fault Earthquakes

These earthquakes are the result of the relative plate motion between the Pacific and Gorda plates and are the second most common source of historic damaging earthquakes. The 1923, 1941, 1951, 1952, and 1968 earthquakes may have been generated by this source and all produced peak intensities of VII or more in the Petrolia area. However, because of location uncertainties, it is difficult to distinguish Mendocino fault earthquakes from those within the southern part of the Gorda plate. Proximity of epicenters to the fault is not sufficient to clearly identify them as Mendocino fault events. The June 1987 earthquake lies very close to the mapped trace of the Mendocino fault, yet aftershocks (Bulletin of the University of California Seismographic Stations) and the focal mechanism, or fault orientation determination (National Earthquake Information Center), clearly identify it as a Gorda plate event.

Only the June 1968 (local magnitude 5.9) earthquake is clearly identified by aftershocks and first-motion data (Nowroozi, 1973) as a Mendocino fault event. The epicenter was about 25 miles (40 km) west of Cape Mendocino. The earthquake broke windows, damaged chimneys and foundations, dislodged plaster, and knocked merchandise and dishes from shelves in communities near Cape Mendocino. Large ground cracks and minor landslides were observed near the Mattole River (Coffman and von Hake, 1973). The impacts of future events are likely to be similar to those of earthquakes within the southernmost Gorda plate, primarily affecting communities near Cape Mendocino and those located on thick sediments in the Eel River Valley and the southern Humboldt Bay area.

San Andreas Transform System Earthquakes

These earthquakes are the result of motion between the North American and Pacific plates. The transform system includes a number of northwest trending faults from just offshore to east of Garberville (Kelsey and Carver, 1988). Fault motion is predominantly right-lateral strike-slip although thrust/reverse events such as the 1991 Honeydew earthquake (Oppenheimer and Magee, 1991; McPherson and others, 1992) may be a part of this system.

The only major historic plate-boundary earthquake on the northern segment of this system was the April 1906, magnitude-8.3 earthquake which probably produced the strongest ground shaking known to occur in Humboldt County (Lawson, 1908). Recent studies of the 1906 rupture segment suggest a recurrence interval of 200 to 400 years (Prentice, 1989). A repeat of the 1906 rupture is not as likely in the near future as ruptures within the Gorda plate or along the Mendocino fault, but could cause greater damage and severely impact communities in southern Humboldt County, in the Eel River basin, and near Humboldt Bay.

The 1991 Honeydew earthquake involved reverse motion along a northwest trending fault at the north end of this system (Oppenheimer and Magee, 1991; McPherson and others, 1991). The relationship among this fault, the San Andreas fault, and other strike-slip faults in the transform system is not clear. We believe this earthquake reflects compression near the termination of the San Andreas system and may be a part of this system. The Honeydew earthquake produced peak intensities of VIII, a 3.6-mile-long (6-km-long) zone of surface cracking, widespread changes in groundwater flow, and accelerations high enough to dislodge and flip stream boulders (McPherson and others, 1992). Recurrence of this event, and the seismic potential of other faults in the transform system are not known.

North American Plate Earthquakes

The potential sources of these earthquakes are thrust faults within the North American plate north of the triple junction. Epicenters would be onshore and at depths of fewer than 12 miles (20 km). Primary evidence for this source area is the zone of Holocene northwest-trending thrust faults extending from south of Bridgeville to north of Big Lagoon and offshore to north of the Oregon border. There are no verified historic examples of large thrust earthquakes along any of these faults.

Evidence does not indicate whether offsets observed on these faults represent intraplate events restricted to the North American plate or ruptures of the Cascadia subduction zone. Only one damaging event, the December 21, 1954, magnitude-6.5 earthquake, appears to have been located within the overriding North American plate. However, the absence of documented surface rupture and the lack of information about the earthquake source make it difficult to associate the 1954 event with any of the mapped faults in the epicentral region. This earthquake caused one death, much structural damage, and numerous landslides and rockfalls, and it temporarily reversed water flow in the Mad River (TERA Corporation, 1977). Recurrence of events like the 1954 earthquake cannot be estimated with the present data.

Paleoseismic evidence suggests that several large thrust earthquakes occurred in the Holocene (Carver and Burke, 1988) with recurrence intervals on the order of hundreds of years. If the observed offsets are the result of slip within the North American plate independent of the subduction zone, magnitudes of 7.5 to 8 or greater are suggested (Clarke and Carver, 1992). This size earthquake onshore could cause surface ground rupture and would produce stronger ground shaking than any events in the 150-year historic record. Movement along an offshore portion of one of these faults might trigger a local tsunami.

Cascadia Subduction Zone "Great" Earthquakes

These earthquakes would be caused by movement along all or part of the Cascadia subduction zone between the Gorda and/or Juan de Fuca plates and the North American plate. Rupture of the southern portion of the zone might extend from Cape Mendocino to north of the Oregon border; rupture of the whole zone could extend to Vancouver Island. These earthquakes would have magnitudes of at least 8.5, and could produce strong ground-motion lasting a minute or more, cause coastal uplift and subsidence of several feet, and generate large local tsunamis affecting coastal areas of northern California, Oregon, and Washington. Distant tsunamis might also be generated, with the potential to affect other coastal regions of California and large areas of the Pacific basin. Events of this magnitude are rich in long-period ground motion (Heaton and Hartzell, 1987) and have the potential to damage large structures hundreds of miles away, particularly when local soil and geologic conditions amplify the ground motion.

Paleoseismic evidence suggests the last such earthquake occurred about 300 years ago and the recurrence interval of Cascadia subduction zone earthquakes is 300 to 500 years (Clarke and Carver, 1992). There is less probability of such an earthquake within the near future than of ruptures within either the Gorda plate or on the Mendocino fault. However, the increasing weight of scientific evidence supporting the recurrence of such earthquakes, and the enormity of their effects make emergency planning and mitigation efforts essential at county, state, and national levels.

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Robert McPherson was the chief seismologist for the Humboldt Bay Seismic Network, a 16-station array operated by TERA Corporation as part of a seismic safety study for the Humboldt Nuclear Power Plant. He currently lectures at Humboldt State University, Arcata and works as an independent consultant.

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