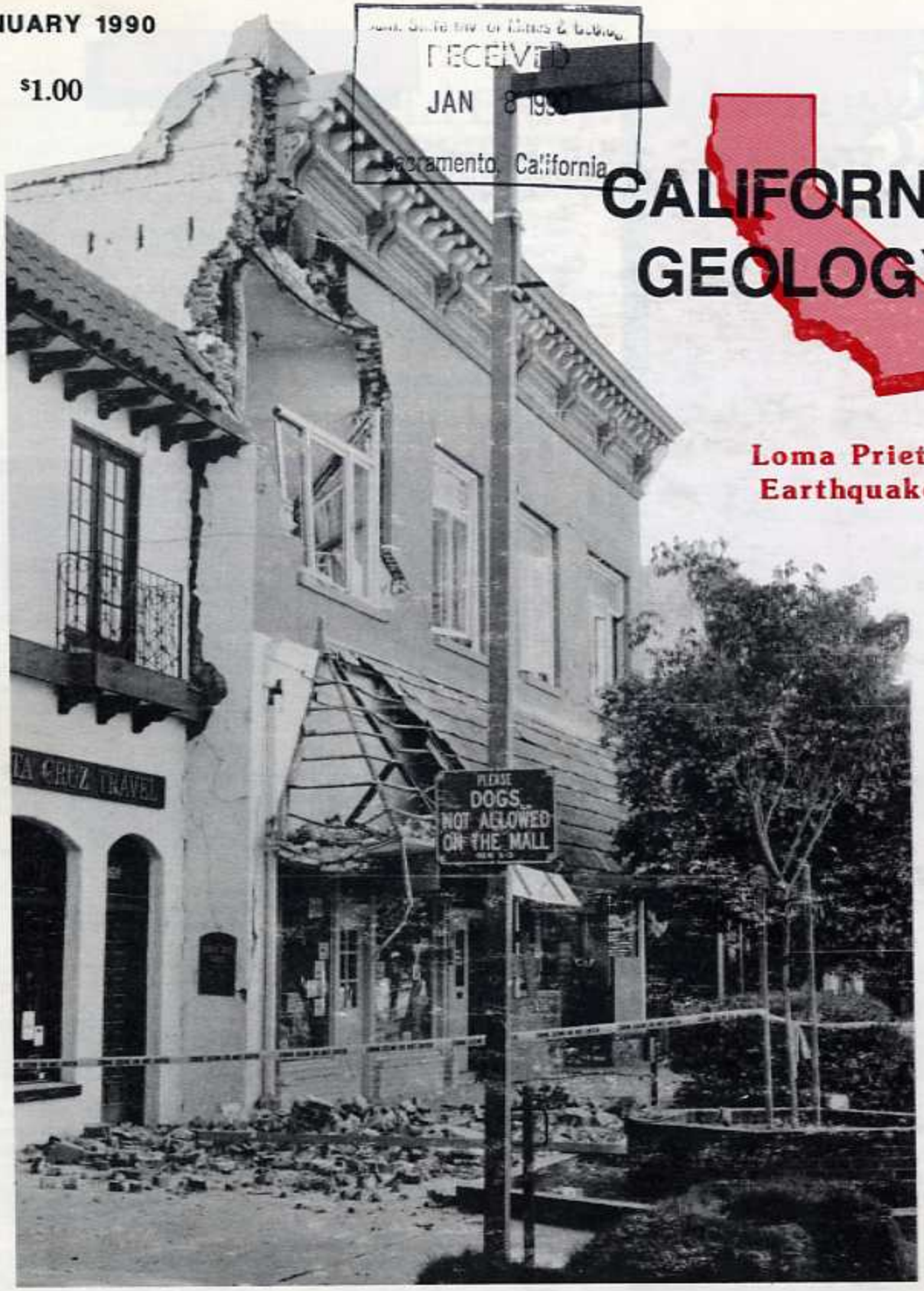
JANUARY 1990

$1.00

CALIFORNIA GEOLOGY



Loma Prieta Earthquake

Understanding California's Geology

Our Resources – Our Hazards

CALIFORNIA
DEPARTMENT
OF CONSERVATION
Division of Mines and Geology

GEORGE DEUKMEJIAN, Governor
STATE OF CALIFORNIA

GORDON K. VAN VLECK, Secretary
THE RESOURCES AGENCY

RANDALL M. WARD, Director
DEPARTMENT OF CONSERVATION

LOMA PRIETA EARTHQUAKE
OCTOBER 17, 1989
Santa Cruz County, California

By

STEVE McNUTT, Seismologist
Division of Mines and Geology

INTRODUCTION

On Tuesday, October 17, 1989 at 5:04 p.m. Pacific Daylight Time, a magnitude 7.1 earthquake occurred on the San Andreas fault 10 miles northeast of Santa Cruz. This earthquake was the largest earthquake to occur in the San Francisco Bay area since 1906, and the largest anywhere in California since 1952. The earthquake was responsible for 67 deaths and about 7 billion dollars worth of damage, making it the biggest dollar loss natural disaster in United States history. This article describes the seismological features of the earthquake, and briefly outlines a number of other geologic observations made during study of the earthquake, its aftershocks, and its effects. Much of the information in this article was provided by the U.S. Geological Survey (USGS).

Previous Activity

Earthquakes of magnitude 7 or larger occur, on average, about once every 18 years in California. All earthquakes that have occurred in California over the last 100 years with magnitudes greater than, or equal to, 6.5 are listed in Table 1. The events do not occur very regularly; for example, the period from 1895 to 1915 was very active in northern California, whereas the next 50 years were very quiet.

The section of the San Andreas fault that ruptured on October 17 probably also ruptured in 1865 and 1906. Since 1906, this section has been very quiet. Over the last one and one half years, however, two separate events of magnitude 5.1 and 5.2 occurred in the area on June 27, 1988 and August 8, 1989, respectively. Although these events were widely felt and caused minor damage, it should be kept in mind that earthquakes of this magnitude occur about 8 times per year in California. The average numbers of earthquakes per year in California for different magnitudes are shown in Table 2. Small earthquakes are much more common than large ones.

TABLE 1. CALIFORNIA EARTHQUAKES M ≥ 6.5, 1889-1989.*

Date (Greenwich)	Lat. °N	Long. °W	Location	Magnitude
1892/02/24	32.7	116.3	SE San Diego County	6.7
1899/07/22	34.3	117.5	Cajon Pass	6.5
1899/12/25	33.8	117.0	San Jacinto	6.6
1906/04/18	37.7	122.5	San Francisco	8.3
1908/11/04	36?	117?	Death Valley	6.5
1918/04/21	33.8	117.0	San Diego	6.8
1922/03/10	35.75	120.25	Kettleman Hills	6.5
1923/01/22	40.5	124.5	Humboldt County	7.2
1927/11/04	34.7	120.8	Santa Barbara Channel	7.0
1940/05/19	32.73	115.5	Imperial Valley	6.7
1942/10/21	32.97	116.0	Imperial Valley	6.5
1948/12/04	33.93	116.38	Palm Springs	6.5
1952/07/21	35.0	119.0	Arvin-Edison	7.2
1954/12/21	40.8	123.9	Humboldt County	6.5
1979/10/15	32.63	115.32	Imperial Valley	6.6
1980/11/08	41.0	124.64	Gorda Basin	6.9
1983/05/02	36.2	120.3	Coalinga	6.5
1986/07/21	37.54	118.44	Chalfant	6.5
1987/11/24	33.02	115.85	Superstition Hills	6.6
1989/10/17	37.03	120.88	Loma Prieta	7.1

*Adapted from: Toppozada, T.R., and others, 1985, Earthquake history of California: CALIFORNIA GEOLOGY, v. 39, no. 2, p. 29.

MAGNITUDE 7.1 EARTHQUAKE

The October 17 earthquake occurred in the Santa Cruz Mountains at latitude 37 degrees, 02 minutes north, longitude 120 degrees, 53 minutes west, at a depth of 11.5 miles. The location of the event is shown in Figure 1 as the star; other symbols show the locations of aftershocks. The magnitude (M_S)* of the earthquake is 7.1, as determined from readings at 18 stations throughout the world (National Earthquake Information Center). The individual station values ranged from M_S 6.6 to M_S 7.4. Several preliminary magnitude estimates, ranging from 6.7 to 7.0 were widely quoted in the media. These preliminary magnitudes were determined from only a handful of stations. It is quite normal for individual readings to vary somewhat, whereas averaged values tend to be more stable and are used in standard catalogs.

*M_S = Surface wave magnitude

TABLE 2. CALIFORNIA SEISMICITY, JANUARY 1980 THROUGH DECEMBER 1986.

Magnitude Range	Total Number Events	Average Number Events per Year
>3.0	3484	498
>3.5	1106	158
>4.0	395	56
>5.0	54	7.7
>6.0	10	1.4

Characteristics

The aftershock zone for the October 17 earthquake is about 31 miles long (Figure 1). This is about average for earthquakes of this size. For example, the aftershock zone of the magnitude 6.9 Armenian earthquake of December 7, 1988 was approximately 37 miles long, and the aftershock zone of the October 15, 1979 magnitude 6.6 Imperial Valley earthquake was also approximately 37 miles long. In general, the aftershock zones outline the rupture areas of the mainshocks — the larger the events, the larger the aftershock zones.

Cross sectional views of the aftershock zone are shown in Figure 2. The aftershocks define a plane dipping about 70

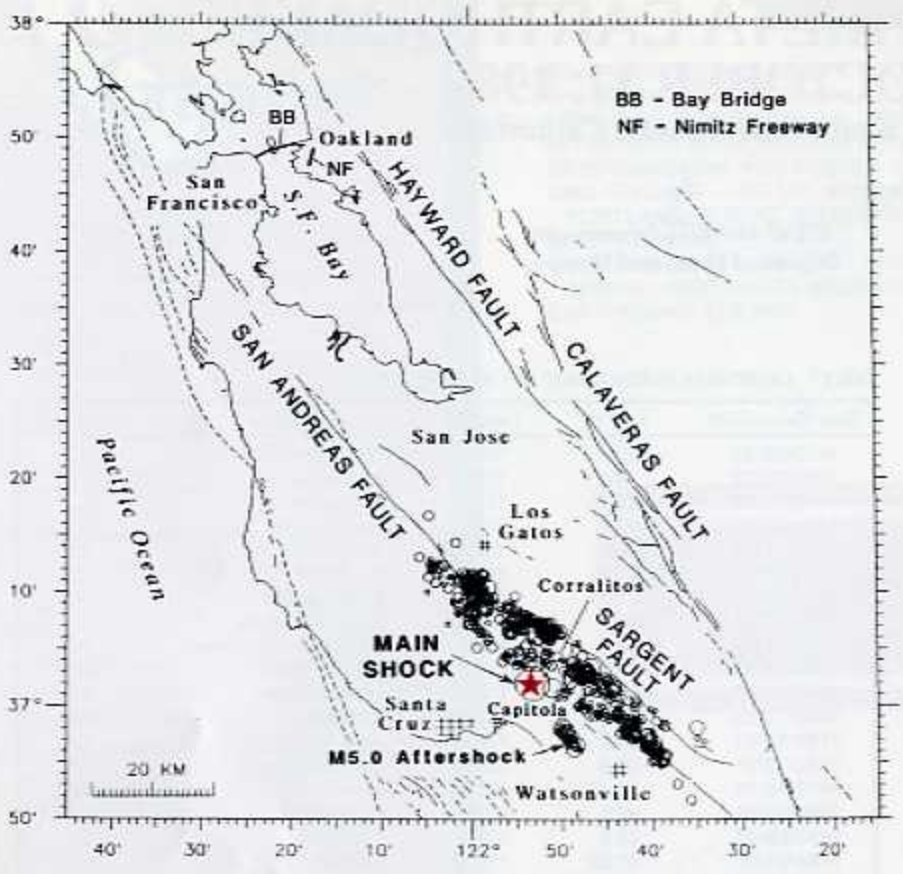


Figure 1. Epicenter map of the Loma Prieta earthquake and the first four days of aftershocks. The mainshock is shown as the star. *Figure courtesy of the U.S. Geological Survey.*

degrees to the southwest. That means the San Andreas fault plane in this region is not vertical, but dips at a steep angle. For this reason the epicenter does not plot on the fault; it occurred at a depth of 11.5 miles, and is thus located to the southwest of the surface expression of the fault. Note also that there is a cluster of events off of the main fault to the southwest; one of the magnitude 5 aftershocks occurred in this off-fault cluster. Such clusters are common in aftershock zones, although clearly most of the aftershocks occur on the main fault.

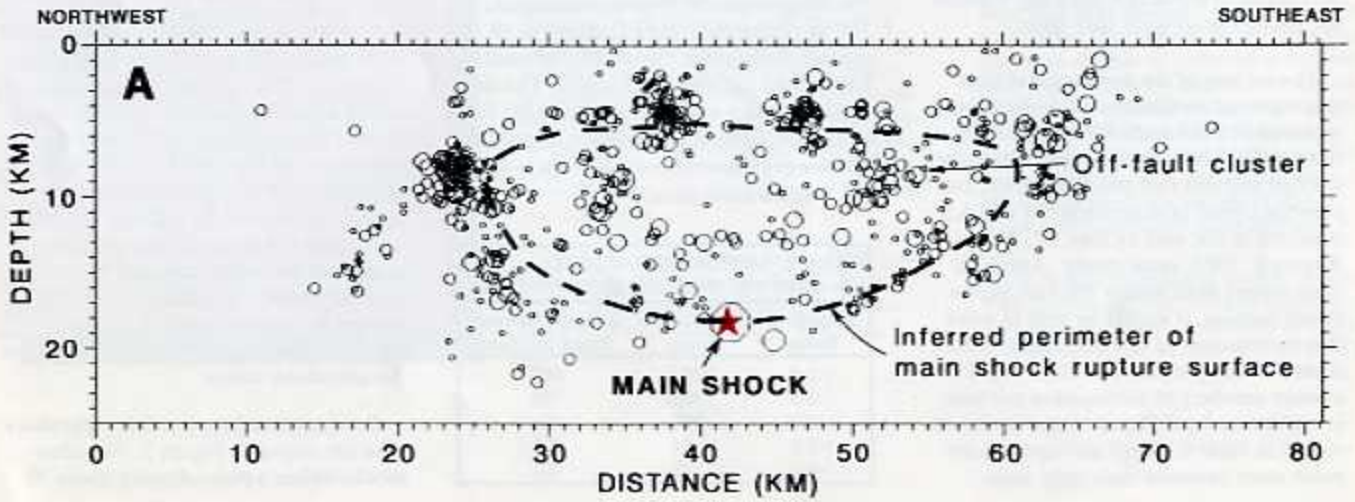
A block diagram of the motions of the earthquake is shown in Figure 3. These motions were calculated from geodetic observations made in the region after the earthquake occurred. The slip during the event was about 6.5 feet of right lateral strike slip, and 4.6 feet of vertical slip (high angle reverse slip). This slip occurred at depth and was not observed at the surface.

The earthquake is called the Loma Prieta earthquake. Standard practice for naming significant earthquakes is to name the event after the nearest prominent geographic feature. In this case Loma Prieta peak, the highest peak in the Santa Cruz Mountains, is several miles from the earthquake epicenter.

Aftershocks

Numerous smaller earthquakes — called aftershocks — occur after every moderate or large earthquake. In general, the largest of these events is about one magnitude unit smaller than the mainshock, although there are exceptions. For example, the Whittier Narrows earthquake of October 1, 1987 was magnitude 5.9, but a magnitude 5.5 aftershock occurred three days later. There are two other rules of thumb about aftershocks. First, as the events get smaller, they become more numerous. Within ten days after the Loma Prieta mainshock, there were two aftershocks of magnitude 5.0 and larger, 20 of magnitude 4.0 and larger, and 79 of magnitude 3.0 and larger as of October 27, 1989. The second rule of thumb is that as time goes by after the mainshock, the frequency of aftershocks tends to decrease proportional to one divided by time (1/time). For example, if there are 100 after-

Figure 2. Cross sections of the Loma Prieta earthquake and aftershocks of the first four days. The cross sections are oriented (A) parallel to and (B) perpendicular to the fault. The mainshock is shown as the star. *Figure courtesy of the U.S. Geological Survey.*



shocks the first day, there will be about 50 the second day (1/2), 10 the tenth day (1/10), and so on. The number of aftershocks and their magnitudes after the Loma Prieta earthquake are roughly typical for earthquakes in California. Based on statistical studies of average California aftershock sequences, the USGS estimated that there was a 12 percent chance of an aftershock of magnitude 6 or greater in the two months following October 21, 1989. Significant aftershocks of the Loma Prieta earthquake are listed in Table 3.

EARTHQUAKE EFFECTS

Transportation Routes

Damage from the Loma Prieta earthquake was fairly widespread. Several lifelines were damaged, notably the Nimitz Freeway and the Bay Bridge (Figure 1). Numerous other roads were damaged, and it will be some time before a comprehensive damage survey is completed. Some of the damaged areas were identified prior to the quake as areas of potential damage in scenarios published by the Division of Mines and Geology (Special Publication 61, Earthquake planning scenario for a magnitude 8.3 earthquake on the San Andreas fault in the San Francisco Bay area, and Special Publication 78, Earthquake planning scenario for a magnitude 7.5 earthquake on the Hayward fault in the San Francisco Bay area).

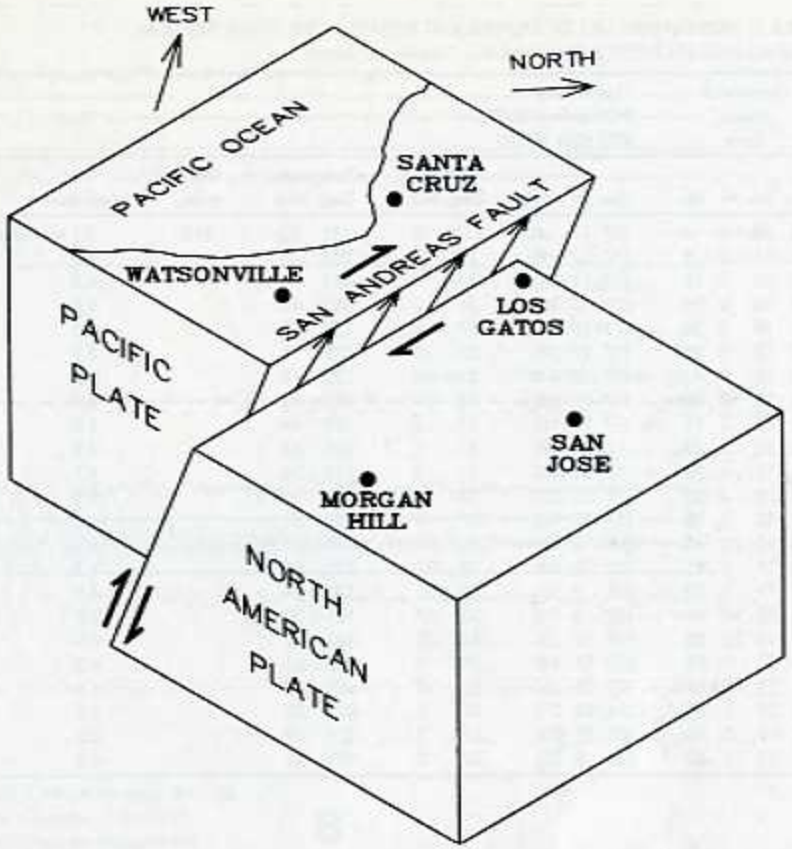
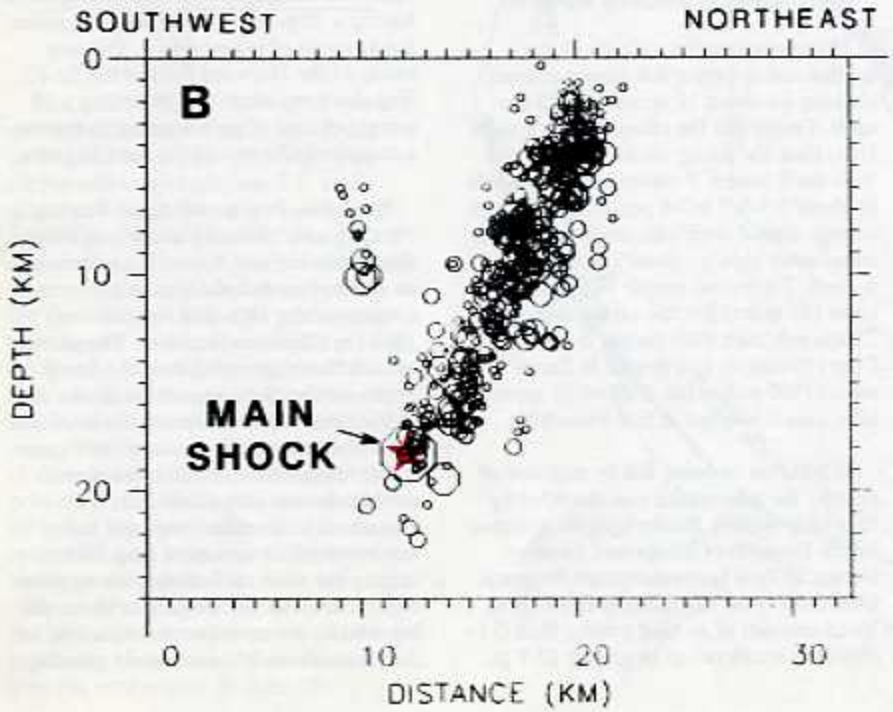


Figure 3. Schematic or block diagram of the earthquake mechanism. The portion of the Pacific plate including Santa Cruz and Watsonville moved 6.5 feet north and 4.6 feet up relative to the portion of the North American plate. Slip was confined to depth and did not reach the surface. *Figure courtesy of the U.S. Geological Survey.*



These published scenarios are planning documents which describe the effects of specific earthquakes. Even though no scenario had been prepared for the Loma Prieta earthquake in particular, the conclusions of the scenarios about the overall expected level of damage proved to be fairly accurate in outlining the actual damage pattern. The specific lessons learned during this earthquake will be used in future scenarios.

Building Damage

Although damage to the two highways and to structures in the Marina district of San Francisco was widely reported, most of San Francisco fared well during this earthquake with an epicenter about 56 miles away. Most damage was located in isolated pockets, and was severe only where it affected older buildings constructed on fill material or on unconsolidated strata. In Santa Cruz, Watsonville, and Los Gatos, by comparison, a much

TABLE 3. PRELIMINARY LIST OF SIGNIFICANT EVENTS IN THE LOMA PRIETA M_S = 7.1 EARTHQUAKE SEQUENCE. Data from U.S. Geological Survey.

Greenwich Mean Time				Local Time (PDT before 10/29) (PST after 10/29)							
Mo	Da	Hr	Mn	(Da	Hr	Mn)	Latitude Deg	Min	Longitude Deg	Min	Depth (miles)	Magnitude
10	18	0	4	(17	17	4)	37	2	121	53	11.5	7.1 Mainshock
10	18	0	9	(17	17	9)	37	1	121	51		4.3
10	18	0	12	(17	17	12)	37	7	122	1		4.5
10	18	0	25	(17	17	25)	37	2	121	48		4.8
10	18	0	30	(17	17	30)	37	5	122	0		4.2
10	18	0	38	(17	17	38)	37	10	122	1		4.3
10	18	0	41	(17	17	41)	37	10	122	3		5.2
10	18	0	45	(17	17	45)	36	55	121	43		4.0
10	18	2	15	(17	19	15)	37	4	121	44		4.5
10	18	2	26	(17	19	26)	37	1	121	46		4.2
10	18	4	16	(17	21	16)	37	3	121	54		4.1
10	18	4	50	(17	21	50)	37	8	122	3		4.3
10	18	5	18	(17	22	18)	37	1	121	51		4.2
10	18	10	22	(18	3	22)	36	59	121	51		4.5
10	19	8	45	(19	1	45)	36	57	121	51		4.3
10	19	9	53	(19	2	53)	36	55	121	41		4.5
10	19	10	14	(19	3	14)	36	57	121	50		5.0
10	19	12	25	(19	5	25)	36	55	121	41		4.0
10	21	0	49	(20	17	49)	37	1	121	53		4.3
10	21	22	15	(21	15	15)	37	3	121	53		4.6
10	25	1	27	(24	18	27)	37	5	121	50		4.5
11	02	5	50	(01	21	50)	37	3	121	49		4.4
11	05	13	37	(05	5	37)	37	3	121	53		4.0

higher percentage of structures was affected; these cities were located only about 10 to 20 miles from the epicenter. In total, in all areas, 22,000 homes were damaged and 1,500 homes were destroyed or rendered uninhabitable.*

Ground Failures

One unusual feature of this earthquake was the lack of primary surface fault rupture. The impressive cracks shown in the media were superficial features caused by the strong shaking. The largest such crack was located near the intersection of Summit Road and Highway 17 in Santa Cruz County, and was 650 yards long, 2.5 feet wide, and showed 2.5 feet of left-lateral offset at one point. Numerous ground failures occurred over an area 60 miles long by 25 miles wide, stretching from San Gregorio to Hollister, with additional ground failure occurring in a narrow strip along the coast from Santa Cruz all the way up to San Francisco. Ground failure included landslides, debris slides, rockfalls, and bedrock slides. The largest landslide identified as of November 1989 measured 220 yards by 330 yards. Liquefaction phenomena were widespread, occurring from Oakland to Salinas, and produced numerous sand boils and mud volcanoes.

*Red Cross estimate

FELT AREA OF STRONG SHAKING

Most people in the vicinity of the earthquake epicenter felt strong ground shaking for about 10 seconds to 15 seconds. People felt the effects of the P wave first, then the strong shaking associated with the S waves. P waves travel at speeds of about 3.1-3.7 miles per second through average crustal materials, whereas S waves travel more slowly, about 2.0 miles per second. Therefore, people in San Francisco (56 miles) felt the earthquake about 23 seconds later than people in Santa Cruz (10 miles), and people in Sacramento (100 miles) felt it about 22 seconds later than it was felt in San Francisco.

In addition to being felt by millions of people, the earthquake was recorded by 93 strong-motion accelerographs operated by the Division of Mines and Geology Strong Motion Instrumentation Program. Data from these instruments show about 10-15 seconds of motion greater than 0.1 times the acceleration of gravity (0.1 g). This is the same motion that was felt by most people. The strongest shaking recorded at a free-field site, that is, a site not located in or near a structure such as a building or bridge, was about 0.64 g. Examples of strong motion records are shown in Figure 4.

The felt area for the earthquake was about 54,000 square miles. Note, however, that the earthquake occurred near the coast, so half of the potential felt area is westward in the Pacific Ocean. The felt area is similar in size to the felt area of other earthquakes of similar magnitude.

PROBABILITY ESTIMATES AND FUTURE STUDY

The Loma Prieta earthquake occurred in an area that had been identified in several studies as having a relatively high probability for an earthquake of magnitude 6.5 or greater. In the most recent such study, the probability had been estimated at 30 percent over the 30 year period from 1988 to 2018. The occurrence of the Loma Prieta earthquake in the forecast area and with the size within a half magnitude unit of the forecast size has essentially served to validate the approach used to develop the probability estimates. Now that the event has occurred, it can be used to help calibrate the measurements and procedures used to make such probability estimates elsewhere. The section of the San Andreas fault immediately to the north of the Loma Prieta segment was identified in the same studies as having a 20 percent probability of producing an event of magnitude 7. Two segments of the Hayward fault in the East Bay also were identified as having a 20 percent chance of each segment producing a magnitude 7 event in the next 30 years.

The Loma Prieta earthquake was not "the big one." Usually when people talk about "the big one," they are referring to an event of magnitude 8 or larger, such as a repeat of the 1906 San Francisco or 1857 Fort Tejon earthquakes. The section of fault that ruptured during the Loma Prieta earthquake compared with the area of fault that ruptured during the 1906 San Francisco earthquake is shown on Figure 5. For comparison, the San Francisco earthquake was magnitude 8.3, the rupture was 280 miles long, and the maximum offset was more than 20 feet. During the 1906 earthquake, strong shaking occurred for one minute or more, during which time most people in the city of San Francisco could not remain standing.

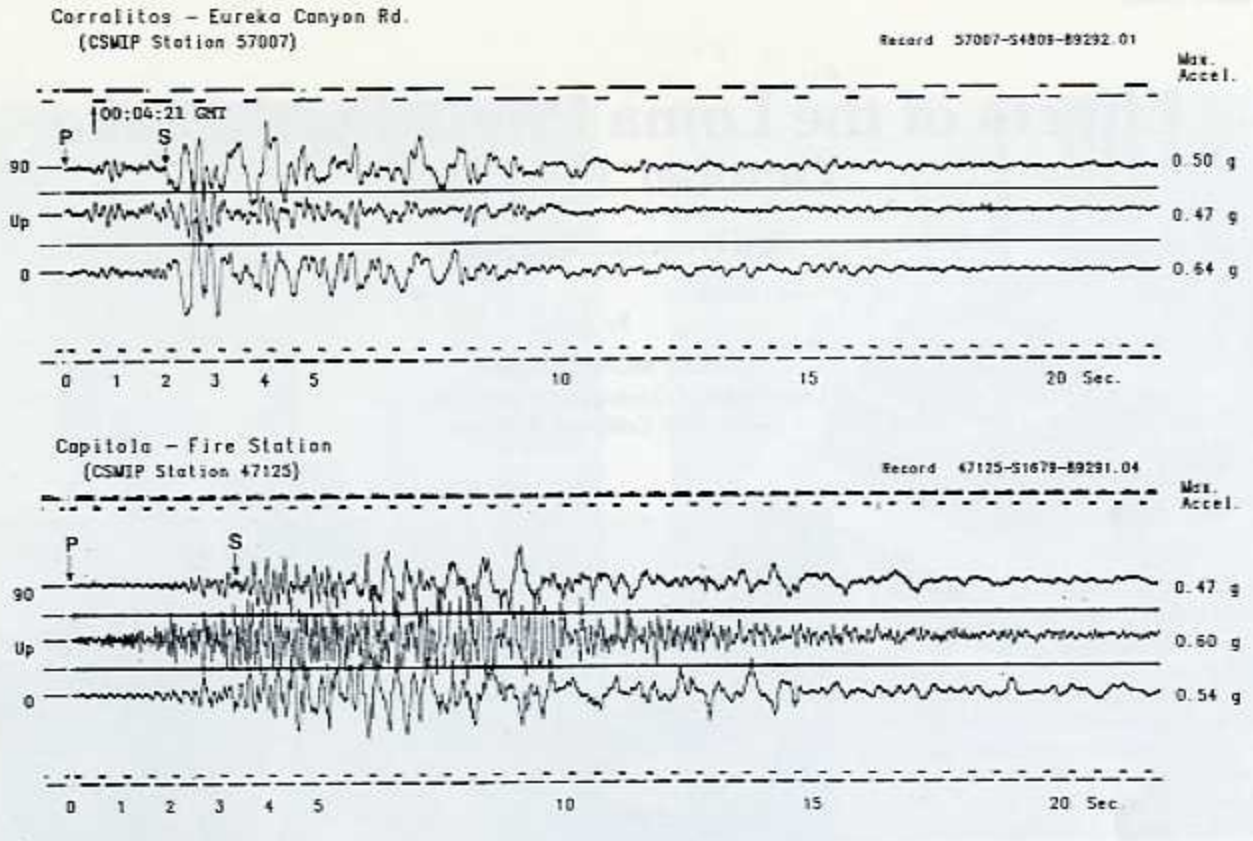


Figure 4. Examples of accelerogram records from two strong motion instruments at Corralitos and Capitola. P wave and S wave arrivals are indicated. For each station, three components of ground acceleration are shown: east-west (90), vertical (up), and north-south (0). Each record shows 20 seconds of motion. The peak acceleration on each record is shown at the right. *Figure provided by the DMG Strong Motion Instrumentation Program.*

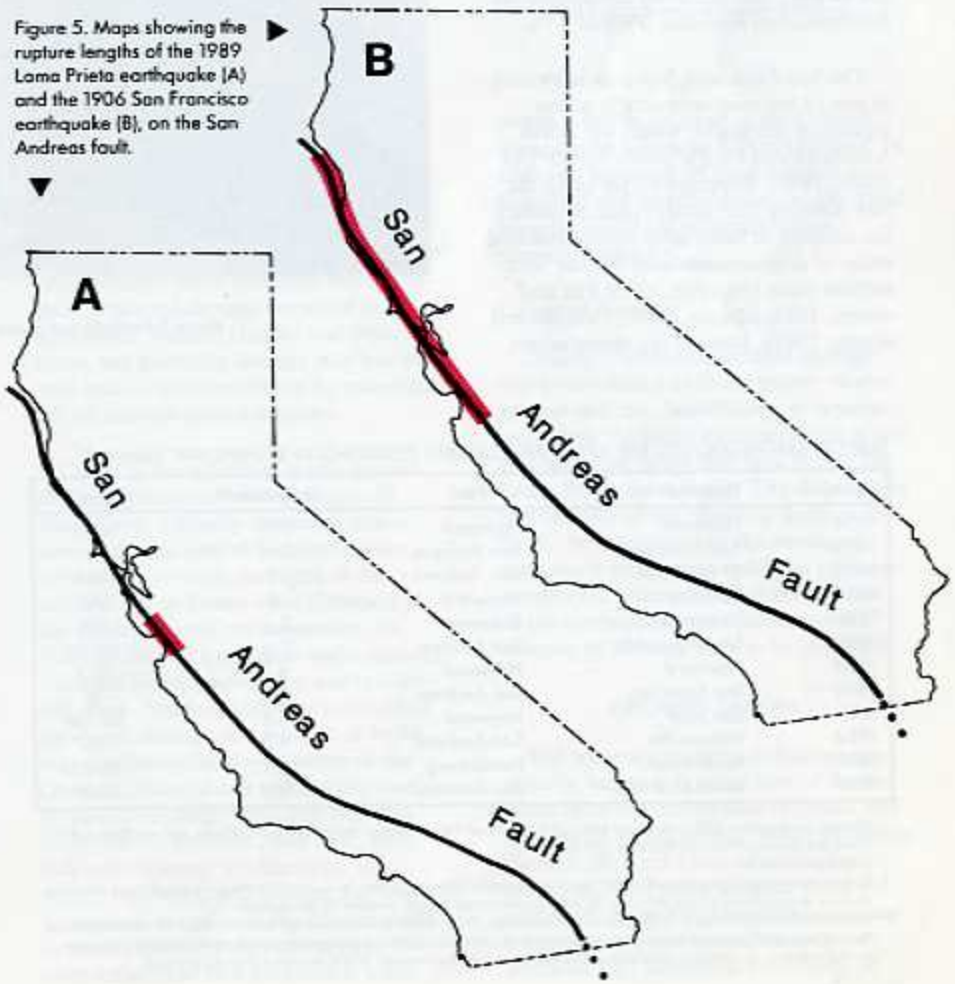


Figure 5. Maps showing the rupture lengths of the 1989 Loma Prieta earthquake (A) and the 1906 San Francisco earthquake (B), on the San Andreas fault.

SUMMARY

This article highlights some of the seismological features of the Loma Prieta earthquake of October 17, 1989. The earthquake magnitude was 7.1, and it originated at a depth of 11.5 miles in the Santa Cruz Mountains. The aftershock zone is about 31 miles long, and included 79 events of magnitude 3.0 and greater in the first 10 days. While no primary surface rupture occurred, numerous ground cracks and other forms of ground failure were observed. Strong shaking from the earthquake occurred for 10-15 seconds over a wide area, resulting in high levels of damage near the epicenter and isolated pockets of damage at distances of up to 60 miles. For most residents of the Bay area, the Loma Prieta earthquake was the strongest earthquake they have ever experienced. Several other segments of faults in California have similar probabilities for producing earthquakes of similar size over the next several decades.