The Loma Prieta, California, Earthquake: An Anticipated Event

U.S. GEOLOGICAL SURVEY STAFF

The first major earthquake on the San Andreas fault since 1906 fulfilled a long-term forecast for its rupture in the southern Santa Cruz Mountains. Severe damage occurred at distances of up to 100 kilometers from the epicenter in areas underlain by ground known to be hazardous in strong earthquakes. Stronger earthquakes will someday strike closer to urban centers in the United States, most of which also contain hazardous ground. The Loma Prieta earthquake demonstrated that meaningful predictions can be made of potential damage patterns and that, at least in well-studied areas, long-term forecasts can be made of future earthquake locations and magnitudes. Such forecasts can serve as a basis for action to reduce the threat major earthquakes pose to the United States.

IN THE LATE AFTERNOON OF 17 OCTOBER 1989, AS THE EYES of America turned toward Game 3 of the World Series at Candlestick Park, the largest earthquake in northern California since the great earthquake of 1906 struck the San Francisco Bay Area. Game anticipation quickly turned to surprise, incredulity, and horror as the crew of the Goodyear Blimp transmitted pictures of the collapsed section of the Bay Bridge, the I-880 disaster in Oakland, and the Marina District fire in San Francisco. Within less than an hour, it became clear, however, that this earthquake was not the "big one." The evident scenes of destruction were due to a smaller event with an epicenter well removed from San Francisco (Fig. 1).

In this article, we summarize the causes and effects of the Loma Prieta (*1*) earthquake, on the basis of 1 month of post-earthquake investigations, and place them in the context of two decades of research that allowed an accurate long-term forecast of both the occurrence and consequences of this earthquake. The occurrence of the earthquake where it was anticipated underscores the earthquake hazard in other areas of California where long-term forecasts point to an elevated risk. Even though San Francisco and Oakland suffered considerably in October 1989, events of comparable or greater strength will someday rupture the Hayward and San Andreas faults beneath the most heavily urbanized parts of the San Francisco Bay Area. These earthquakes will be far less kind to the Bay Area if we do not proceed vigorously to meaningfully reduce the risks from earthquakes.

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Overview of the Earthquake and its Effects

The M_S 7.1 (M_S, surface wave magnitude) Loma Prieta earthquake was felt as far away as Los Angeles to the south and Reno, Nevada, to the east. It left in its wake 62 confirmed fatalities, 3,757 injuries, more than 12,000 homeless, and property losses and recovery costs estimated at $6 billion (*2*). Although larger earthquakes have affected the United States in recent decades, most notably the Kern County, California, earthquake (21 July 1952; M 7.5) and the great Alaskan earthquake (28 March 1964; M 9.2), not since 1906 has an earthquake had such dramatic effects on the nation. Indeed, the losses in lives and in public and private property place it among the nation's most costly natural disasters.

The Loma Prieta earthquake ruptured a segment of the San Andreas fault in the Santa Cruz Mountains that had been recognized as early as 1983 as having a high probability for rupture in the following few decades (*3, 4*). In a study in 1988, this segment was assigned the highest probability for producing a M 6.5 to 7 earthquake of any California fault segment north of the Los Angeles metropolitan area (*5*).

Just as the occurrence of this earthquake was anticipated, so were its principal effects. The extent of damage that this earthquake caused in San Francisco and Oakland at great distances (~100 km) from the epicenter has many parallels with the tragedy in Mexico City as a result of the Michoacan earthquake (19 September 1985; M 8.1) some 350 km away. In both cases, the principal culprit was the young, poorly consolidated, water-saturated, fine-grained sediments that underlie Mexico City and line most of the natural margin of the San Francisco Bay. The Bay margin, moreover, has been modified extensively with man-made fill as a means of increasing the available subaerial real estate; the fill in most cases has been placed atop the naturally occurring Bay mud. We know from the clear lessons of history as well as from elementary physics that the performance of such materials, even at modest levels of seismic shaking, is poor. Accounts of the effects of the 1865, 1868, and 1906 earthquakes in the South of Market and Mission districts of San Francisco differ little from what has been written about these areas in October 1989.

In the epicentral region (Fig. 1), far to the south, damage in the hard-hit communities of Watsonville, Santa Cruz, and Los Gatos was most severe in unreinforced masonry buildings, which were constructed long before the modernization of California's building codes. Local ground conditions seem also to have played a significant role in the damage patterns. Observed building damage revealed the usual problems with unreinforced brick masonry and with structures having the soft, open-ground-floors that possess insufficient resistance to shear deformation induced by strong earthquake shaking. There, and in nearby San Jose, modern structures generally fared well in the earthquake.

In the central San Francisco Bay Area, all of the sites of principal damage were in areas known to be at enhanced risk in earthquakes. The Marina District tragedy is one of special irony. Placed in a picture-book setting overlooking San Francisco Bay 3 km east of the Golden Gate Bridge, the Marina District is a community of single-family homes and several-story apartment houses. Built mostly of wood-frame construction, such structures ordinarily fare well even in very strong earthquake shaking, given solid ground beneath them. As are many other waterfront areas around San Francisco Bay, however, the Marina District is built on fill, originally placed for the site of the Panama-Pacific International Exposition. The Exposition celebrated two principal themes: the opening of the Panama Canal in 1915 and the recovery of San Francisco from the 1906 earthquake in less than a decade. This artificial fill failed massively and pervasively during the Loma Prieta earthquake. The Marina District fire resulted from a broken gas main, as happened in many areas with artificial fill in 1906, and the efforts to control it were hampered by broken water mains, as happened in many areas with artificial fill in 1906.

Geologic Setting of the Earthquake

The San Andreas fault first drew general attention when it broke in 1906. The surface rupture in the 1906 earthquake extended 300 km from San Juan Bautista to Point Arena and offered dramatic evidence for the previously unrecognized continuity of this major fault in its oblique traverse of the California Coast Ranges. Now recognized as the principal fault along the North American–Pacific plate boundary, the 1200-km-long San Andreas fault accommodates the steady northwestward movement of the Pacific plate relative to the North American plate. Over the 30-million-year history of the fault, this movement has offset correlative rocks in California some 450 to 600 km in a right-lateral sense. Movement occurs in a cycle of elastic strain accumulation and release. When the accumulated stress overcomes the frictional resistance, the fault ruptures and produces an earthquake, and a new earthquake cycle begins.

In the Loma Prieta earthquake, fault rupture occurred in the southern Santa Cruz Mountains along the southernmost 45 km of the 1906 break. Here, the fault makes a distinct left bend to connect straighter subparallel fault segments to the north and south (Fig. 1). Surface faulting in this segment was exceptionally complex in 1906, and the right-lateral displacement was only about half the average of that along the rest of the rupture trace (*6*).

The slight component of compressional shortening across the San Andreas that has raised mountains and depressed broad valleys in the Coast Ranges is exaggerated in the southern Santa Cruz Mountains by this bend. The bulging eastern flank of these mountains lies above a series of prominent eastward-directed thrusts that have accommodated shortening both within the past 20,000 years and over the longer history of the San Andreas system. The range contains uplifted and deformed rocks as young as 400,000 years old and is flanked by uplifted marine and stream terraces.

Composition of the upper crustal blocks adjacent to the 1989 rupture surface must be inferred from surface geology and geophysical studies. On the east, the exposed metasedimentary rocks of the Franciscan Complex are probably underlain at a depth of about 5 km by associated mafic volcanic rocks. To the west, beyond the Zayante fault (Fig. 1), granitic rocks are exposed in the mountains north of Santa Cruz. Between the Zayante fault and the San Andreas fault, folded Tertiary sedimentary rocks overlie possible mafic crystalline rocks at a depth of 5 to 10 km.

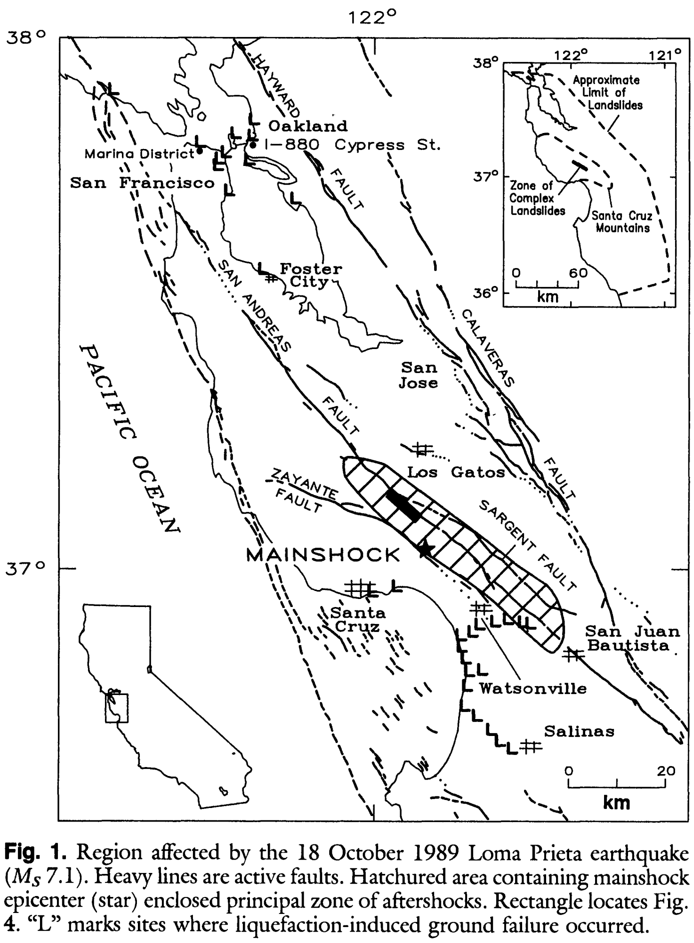


Fig. 1. Region affected by the 18 October 1989 Loma Prieta earthquake (M_S 7.1). Heavy lines are active faults. Hatchured area containing mainshock epicenter (star) enclosed principal zone of aftershocks. Rectangle locates Fig. 4. "L" marks sites where liquefaction-induced ground failure occurred.

Forecasting the Earthquake

A number of studies had forecast a significant long-term seismic potential for segments of the San Andreas fault, including the 1989 rupture zone. Along the 1906 rupture, the time-predictable model (*7*) has been used to estimate the time required to reaccumulate slip on the fault equal to that released in the earthquake of 1906. In these calculations, the ratio of 1906 fault slip on each segment to long-term slip rate determines the estimated occurrence time of the next large event. Casting these estimates into a statistical framework then permits calculation of conditional probability for the occurrence of a specified earthquake within a specified time interval (*3, 4*).

On the basis of these conditional probability estimates, the southernmost portion of the 1906 earthquake rupture was identified in several studies (*3–5, 8, 9*) as an area of high probability of failure. A major earthquake was considered to be possible both along a 75-km-long segment (*4*) and a 30- to 45-km-long segment (*3, 5*) (southern Santa Cruz Mountains segment, Fig. 2). In all of these studies, a slip rate of 15 to 20 mm per year was used for this portion of the San Andreas, and differences among probability estimates depend primarily on the use of different estimates of the amount of slip that occurred at seismogenic depths in the great earthquake of 1906. The 30-year probabilities for rupture of the entire San Francisco Peninsula segment (75 to 90 km) were low to moderate (10 to 20%) when the geodetically estimated 1906 slip values (2.5 m) were used (*4, 5, 8*) and high (19 to 95% over 20 years) when surface fault offsets (0.4 to 1.5 m) were used (*4, 9*). Lindh (*3*) explicitly considered the earthquake hazard of the south- of the 1906 rupture and estimated that there was a 47 to 83% probability of a M 6.5 event on this segment within 30 years.

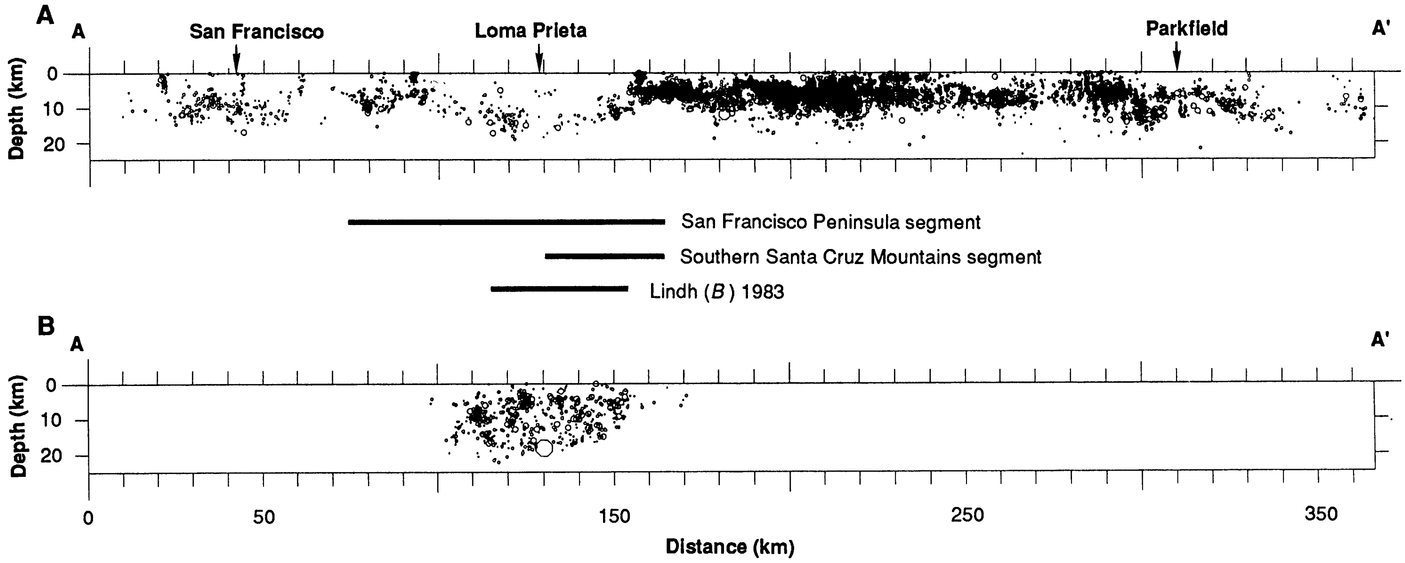


Fig. 2. (**A**) Cross section of seismicity of the San Andreas fault 1969 to 1989 (no vertical exaggeration). The dense concentration of seismicity between Loma Prieta and Parkfield corresponds to the central creeping segment of the fault where the fault moves aseismically and produces many small earthquakes ($M \leq 5$). Lines denote the approximate boundaries of fault segments considered in several forecasts of future earthquakes (see text). (**B**) Loma Prieta mainshock and aftershocks (through 30 October 1989) fill the seismic gap identified by Lindh (*3*).

In 1988 all earlier estimates for the San Andreas fault system were reassessed by the Working Group on California Earthquake Probabilities (*5*). Geodetic estimates of the 1906 earthquake slip distribution were relied on to define segments of the fault where smaller earthquakes might occur and to constrain 1906 slip values used in time-predictable recurrence calculations. A 30-year probability of a 90-km-long rupture on the San Francisco Peninsula segment was estimated at 20% and a 30-km-long rupture on the southern Santa Cruz Mountains segment was estimated at 30%. Because the amount of 1906 slip was not well-constrained on this latter segment, a low level of reliability was attached to this probability estimate. The 1989 earthquake corresponded most closely to the event

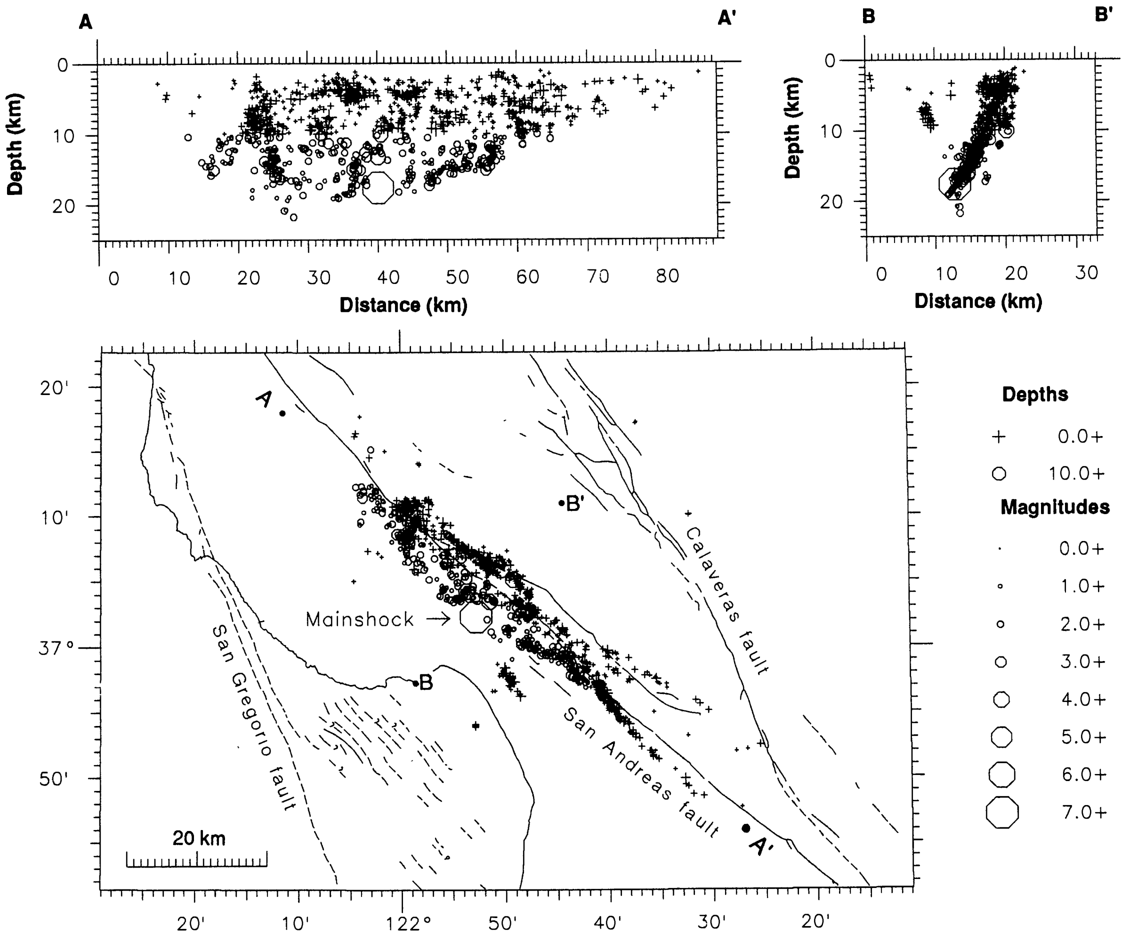


Fig. 3. Mainshock and aftershock locations for the Loma Prieta earthquake through 30 October 1989. Symbols assigned according to focal depth and scaled by magnitude.

forecast for the southern Santa Cruz Mountains segment (*3, 5*) (Fig. 2). At M_S 7.1, it was larger than expected for such a short segment and equalled the magnitude forecast by Sykes and Nishenko (*4*) for the longer segment.

The Earthquake Source

The Loma Prieta earthquake began suddenly and without foreshock activity at 00:04:15.25 UTC on 18 October 1989 (17:04 PDT on 17 October) at a point 17.6 km beneath the earth's surface (*10*) (Fig. 3). The rupture, as defined by the spatial extent of its aftershocks, spread unilaterally upward and bilaterally along strike. By the time rupture was complete, some 7 to 10 s later, it had attained a surface-wave magnitude of 7.1 (*10*).

The earthquake resulted from slip on an inclined fault plane, dipping 70° to the southwest, in contrast to the commonly vertical faults of the San Andreas system (*11*). Both *P*-waves, which are indicative of the initial fault movement, radiated at the start of the earthquake, and long-period body waves and surface waves, which are more representative of the average fault movement, indicate nearly equal components of right-lateral strike slip and reverse slip. At even longer periods, geodetic displacements measured the day after the earthquake are best-fit by 1.9 ± 0.2 m of right-lateral strike slip (±SE) and 1.3 ± 0.4 m of reverse slip on the same fault plane (*11*). The geodetic model constrains the top of the principal slip surface to lie 4 to 6 km beneath the surface, or slightly below the shallowest concentrations of aftershocks at 3 to 5 km depth (Fig. 2).

The sense of horizontal fault movement in the Loma Prieta earthquake conforms with expectations for an event on the San Andreas fault. The modeled right-lateral displacement of 1.9 m agrees reasonably well with the amount believed to have accumulated since the 1906 earthquake (*12*). The large component of reverse slip, however, was unexpected but in hindsight agrees well with simple kinematic models for slip on a dipping plane in a compressional bend (*13*). The net movement in the earthquake thus advanced a small part of the Pacific plate to the northwest, while locally uplifting the southern Santa Cruz mountains and elevating the adjacent marine terraces.

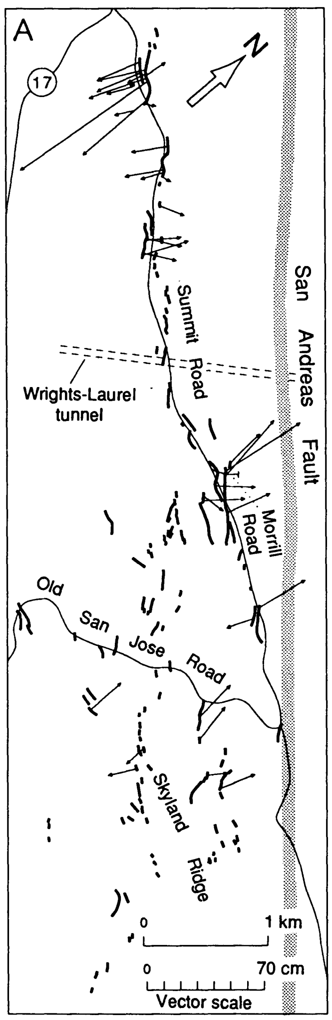
Aftershocks of the earthquake clearly define the dipping plane of the mainshock at depths below 10 km as well as several other subparallel faults at shallower depths (Fig. 3). In traverse cross section, the deeper aftershocks define a plane with a 70° dip over most of the zone, but the distribution of aftershocks appears to broaden toward the surface. The plane defined by the deeper activity projects to the surface closer to the trace of the Sargent fault than to the San Andreas fault. At depths less than 9 km, however, most of the hypocenters lie directly beneath the trace of either the San Andreas fault or the trace of the Sargent fault (Fig. 3). Thus, the mainshock could be on a plane that either truncates a vertical San Andreas fault at about 9 km depth or steepens and merges with a vertical San Andreas fault.

A comparison between the aftershock locations and background seismicity for 1969 to 1989 (Fig. 2) illustrates that this event filled a seismic gap. The background activity outlines an aseismic zone which was hypothesized by Lindh (*14*) to represent the locked portion of the fault plane (asperity) storing energy for release in a major event. What little seismicity that did occur during this background period forms a "u-shaped" pattern that outlines the base of the Loma Prieta rupture. A similar aseismic zone can be recognized currently at Parkfield (Fig. 2) that defines the asperity where four *M* 6 earthquakes have occurred in this century, the last in 1966. The next *M* 6 earthquake at Parkfield is anticipated by 1993 (*15*).

Events Leading to the Mainshock

The Loma Prieta earthquake, while anticipated, carried no obvious short-term seismic or strain precursors. Its clearest harbinger, a marked increase in seismicity in the 16 months before the event, although recognized and widely discussed before the event (*16*), ended without any imminent foreshock activity. Both geodetic and borehole measurements of crustal strain show slight, only marginally significant, changes in strain rate beginning at roughly the same time as the rise in seismic activity.

Borehole strainmeters, although neither ideally situated nor particularly close to the hypocenter, place constraints on possible strain precursors. The nearest instruments, about 45 km from the epicenter of the mainshock and 10 km from the southern end of the eventual rupture, recorded no strain events above the background noise level (10 nanostrain) during the month to seconds before the earthquake. These data limit the preseismic deformation to about 1/1000th of the coseismic strain signal (13 microstrain), or to roughly the strain change that would be generated by a *M* 5 earthquake (17). There are also monthly geodetic measurements of distance between Loma Prieta, a station located almost directly over the hypocenter, and three other sites, determined to a precision of about 3×10^{-7} (*18*). Available data indicate that no significant short-term changes took place to within at least 2 weeks before the earthquake.



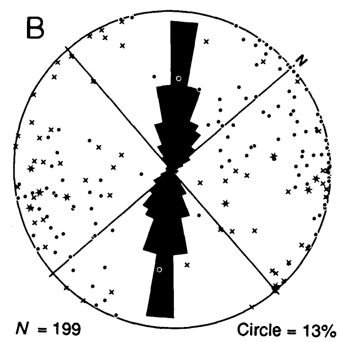


Fig. 4. (**A**) Map showing zones of prominent surface cracks (heavy lines) and net displacement vectors near Summit Road and Skyland Ridge, Santa Cruz Mountains. Vectors greater than 14 cm are shown. Vectors point in plunge direction; true lengths are shown, not their horizontal projections. Open cracks obviously related to local ground failure or landslides are not shown. Patterned zone shows approximate location of main trace of the San Andreas fault as shown by 1906 offset in Wrights-Laurel tunnel and by topography in and beyond the northwest and southeast ends of this map. (**B**) Fracture trends and slip vectors for surface cracks in the Summit Road–Skyland Ridge area. Rose diagram shows strike of cracks, most of which are subparallel to the San Andreas fault. Largest radius represents 12% of all cracks. Also shown are lower hemisphere equal-area projection of slip vectors that have left (dots), right (crosses), or no (stars) lateral component of displacement. Extension is the dominant component of displacement of most vectors. Derived from figure prepared by Z. Reches.

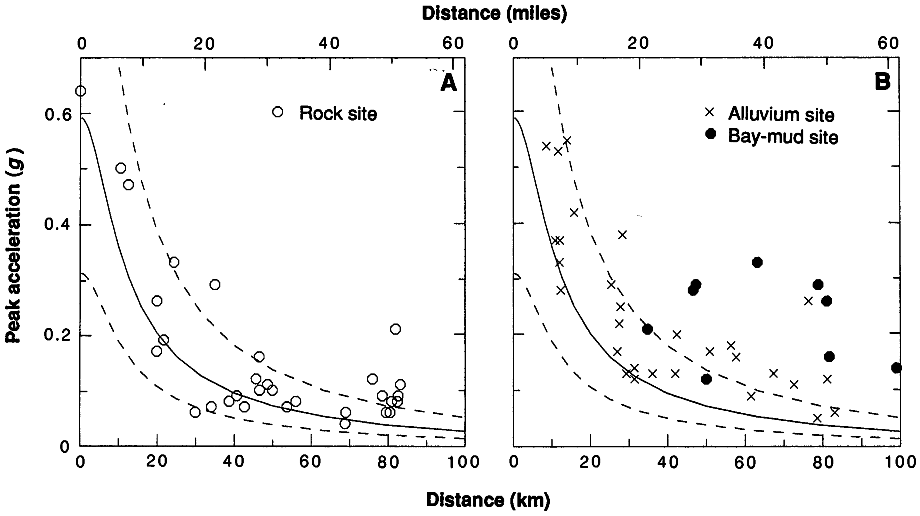


Fig. 5. Peak horizontal acceleration as a function of the minimum distance to the surface projection of the fault for (**A**) rock sites and (**B**) sites on alluvium and Bay mud. A convenient yardstick against which to compare the ground shaking from the Loma Prieta earthquake is the equation given by Joyner and Boore (*28*). The solid line is the prediction. Dashed lines are ±1 SD of a single observation.

Surface Displacements Created by the Earthquake

After the earthquake, no throughgoing right-lateral surface faulting was found along the San Andreas fault above the rupture defined by the mainshock and aftershocks. The nearby Sargent and Zayante faults also lacked clear evidence of tectonic rupture. Magnitude 7 earthquakes along the San Andreas fault and other strike-slip faults worldwide commonly produce throughgoing surface faulting with a displacement of 1 to 2 m.

The most prominent evidence of primary surface deformation was a discrete and unusual zone of extensional and left-lateral fractures located just southwest of the main trace of the fault about 12 km northwest of the epicenter (Fig. 4) (*19*). Individual cracks in this zone of unusual fractures generally follow topography and occur at the base of breaks in slope and linear ridges; some bound linear depressions. The present topography in the Summit Road ridge area appears to have formed as a result of repeated movements along these ruptures. Some of the ruptures closely follow linear topographic trends that have been mapped as a complex fault pattern associated with this section of the San Andreas fault (*20*). The 1906 surface rupture and associated ground failure were also poorly developed along this part of the San Andreas fault. Two of the 1989 fractures along Summit Road, however, occur exactly where left-lateral offsets were mapped following the 1906 earthquake. The larger of the two fractures showed left slip of about 1.1 m in 1906 and 0.4 m in the Loma Prieta earthquake. These cross Morrell Road southeast of the now abandoned and sealed Wrights-Laurel railroad tunnel, which passes 215 m beneath the crest of Summit ridge. After the 1906 earthquake the best measurement of offset along this reach of the fault, 1.5 m of right-slip, was made in the tunnel about 950 m north-northeast of these left-slip fractures.

The origin of the Summit Road fractures is uncertain, but they could be tectonic features resulting from dextral shear at depth that is expressed across a broad zone at the surface (*21*). Surface fractures are best developed in the hanging-wall block of the fault zone, and this geometry suggests that extension of the hanging wall block as it was broadly uplifted during the earthquake formed the fractures. The fractures commonly follow the strike of shale beds in the underlying Tertiary strata, and the sense of the displacements suggests that failure has occurred along bedding planes. Ridge-top spreading resulting from topographic focusing and amplification of seismic waves could also have enhanced these surface displacements.

The earthquake triggered surface slip along the San Andreas and Calaveras faults well outside the epicentral region of the earthquake, as well as possibly along some of the thrust faults at the northeastern base of the Santa Cruz Mountains (*22*). Triggered slip on the San Andreas fault was observed as much as 225 km to the southeast near Parkfield.

The absence of right-lateral surface faulting suggests that other *M* 7 earthquakes in this area may not have left direct evidence in the geologic record. This issue is important because geological slip-rate and recurrence estimates form an important part of the basis for long-term forecasting and seismic hazard assessment. Although slip

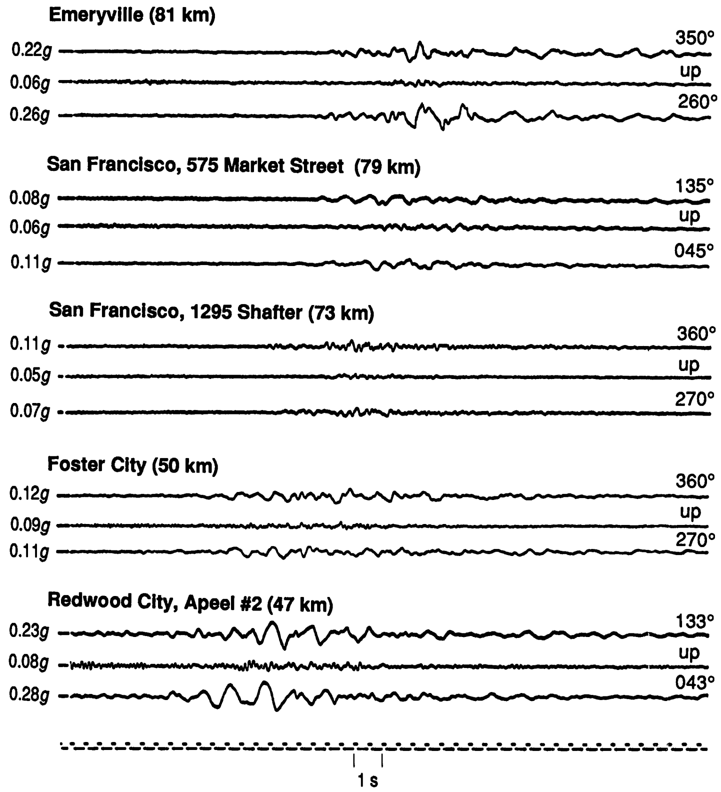


Fig. 6. Photocopies of selected accelerograms for the mainshock, arranged in order of increasing epicentral distance (in parentheses). The directions of ground accelerations are given above each trace, and the peak accelerations appear to the left. The timing trace (bottom) marks 0.5-s intervals. The accelerograms from 1295 Shafter were recorded on rock. The Emeryville record is from a free-field site on Bay mud, whereas the 575 Market Street record comes from a site underlain by dune sands. The Foster City and Redwood City records both come from areas of artificial fill overlying Bay mud, fill that performed well during the Loma Prieta earthquake.

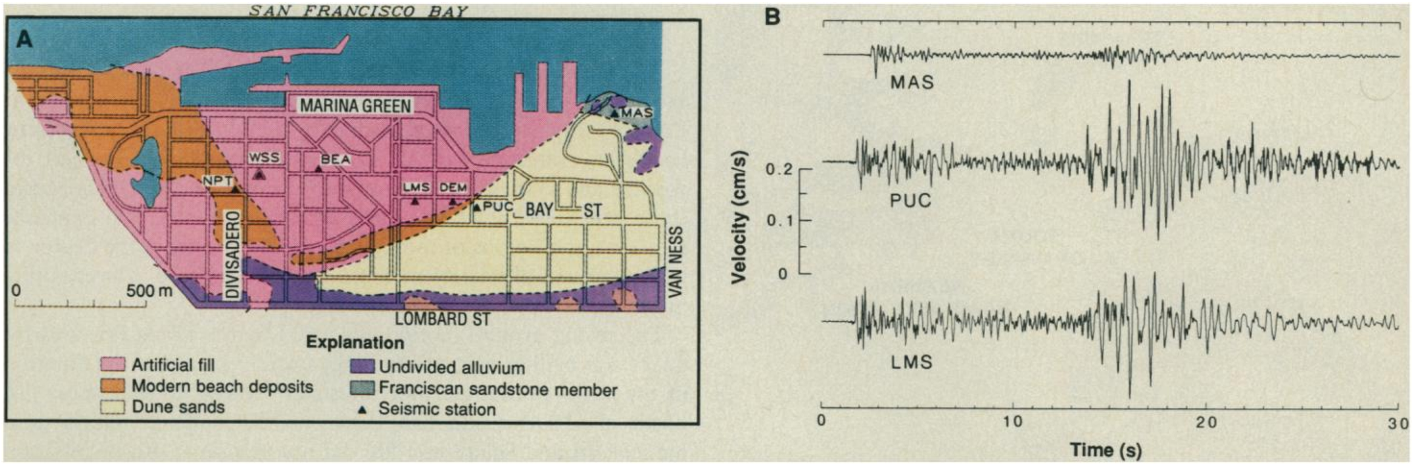


Fig. 7. (**A**) Geologic map of foundation materials in the Marina District, San Francisco. (**B**) Seismograms of vertical ground velocity for a *M* 4.6 aftershock. The top trace (MAS) is from a site underlain by a competent sandstone member of the Franciscan assemblage. The second trace (PUC) is from a site underlain by clean dune sands just onshore of the pre-fill shoreline. At this site, a two-story brick building with a massive turret on its northwest corner, constructed in 1893, rode through the recent earthquake and the great 1906 earthquake without a crack. The third trace (LMS) is from a site one and one half blocks away in the area containing artificial fill. Here, houses were badly deformed by foundation failure, and the north side of the street (North Point) dropped 0.5 m below the south side. All three components of ground motion at PUC and LMS are amplified by comparable amounts relative to MAS, but the local damage patterns are significantly different. These data suggest that the problems in the Marina District were fundamentally a result of permanent deformation of the man-made fill rather than local amplification differences.

did not reach the surface, the event did leave its signature in the form of the surface fractures discussed above and liquefaction, lateral spread-failures, and warped ground surfaces in sag ponds along the fault trace (*23*). Thus, the occurrence but not the amount of fault offset of pre-historic earthquakes may be all that is preserved in the geologic record.

Strong Ground Motion

The Loma Prieta earthquake provides a direct test of seismic zonation methods based on detailed classification of geologic units according to their performance in weak ground motion (*24*). The influence of the local geologic deposits on the amplitudes of ground shaking and extent of damage has been known since the time of the 1906 earthquake. In discussing the 1906 damage, Wood (*25*) concluded: ". . . the amount of damage produced by the earthquake . . . depends chiefly on the geological character of the ground. Where the surface was of solid rock, the shock produced little damage; whereas upon made land great violence was manifested . . . ."

It has also been known for two decades (*26*) that weak ground motion on firm alluvium can be amplified by factors of 2 to 4 in the frequency band of a few tenths to several hertz, the band that has the greatest effect on man-made structures. Similarly, amplification factors for the Bay mud and artificial fill can be 5 to 10 or more.

More than 170 records of ground shaking obtained within 200 km of the epicenter (*27*) form the basis for direct comparisons with expectations. For all practical purposes the records are directly proportional to acceleration; and thus peak accelerations can be obtained and analyzed easily.

Observed accelerations and the predicted values (*28*) are compared in Fig. 5 for recording sites on various underlying geologic materials. Accelerations from rock sites were in reasonable agreement with the predictions. Accelerations at soil sites were systematically greater than the predictions, and the accelerations at Bay mud sites are much larger than those from most of the alluvium sites. Relative to rock sites, ground motion on young, poorly consolidated, water-saturated alluvium and mud tended to be deficient in high-frequency motion and enriched in longer-period motion; in detail, frequency-dependent amplification is a function of rigidity contrasts and basin geometry. These effects are illustrated by the mainshock accelerograms from five sites in the San Francisco region (Fig. 6).

There is ample evidence, then, in both the historical and instrumental records that the observed patterns of damage and strong ground motion for the Loma Prieta earthquake were both predictable and predicted (*24*). Whereas the Marina District disaster was fundamentally the result of pervasive failure of the artificial fill, the district also experienced significant local amplification relative to rock sites, as shown by recordings of aftershocks (Fig. 7). Whereas the portion of the Cypress Street section of I-880 that collapsed long had been recognized as a structure in need of retrofitting for seismic safety, this section was also founded on Bay mud and thus probably sustained higher levels of ground motion than undamaged parts on firmer ground. Both of these areas, as well as many others that sustained significant but less severe damage, had been identified on maps as areas of high potential for damage (Fig. 8).

Landslides

The Loma Prieta earthquake generated landslides throughout a region of approximately 14,000 km^2 (Fig. 1). The epicentral region of the earthquake in the steep, rugged, and heavily vegetated Santa Cruz Mountains has historically produced abundant landslides, both during earthquakes and during the region's rainy winters. Even though only about 7 cm of rain had fallen in the preceding 6 months (*29*), the earthquake generated thousands of landslides throughout the mountains.

The zone of largest and most complex landslides is within and adjacent to the zone of surface fractures (Fig. 1). In this zone, where fissures due to landslide movement are intermixed with other fractures, large, deep-seated blocks of ground moved downslope along a part of the ridge crest. The largest individual landslide block yet identified is more than 0.75 km^2 and damaged dozens of residences riding on it.

Away from the zone of surface fractures, the most numerous earthquake-generated landslides in the Santa Cruz Mountains are rock falls, rock slides, and debris slides. Also abundant are deeper

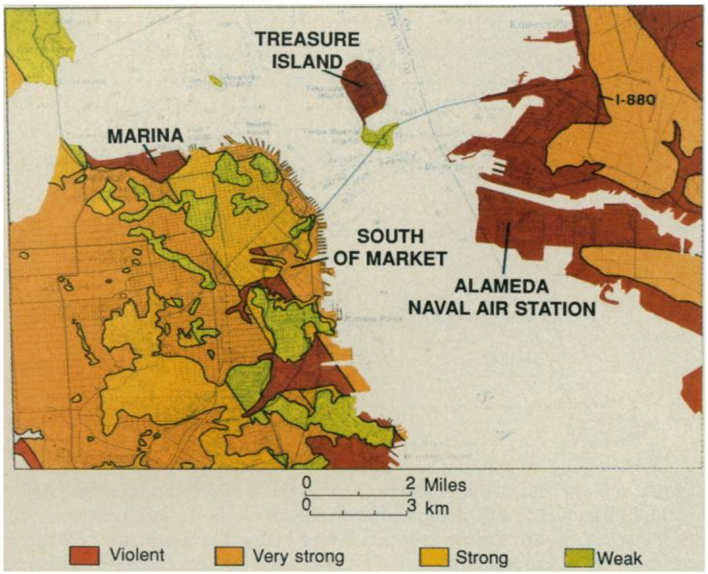


Fig. 8. Predicted intensity of shaking in strong earthquakes along either the San Andreas or Hayward faults (*35*). Intensity values correspond to scale developed for 1906 earthquake.

seated, more coherent block slides and slumps, which involve man-made fill as well as natural soil and bedrock. Beyond the Santa Cruz Mountains, the earthquake generated widely scattered landslides, as far as about 130 km from the epicenter on coastal cliffs.

Liquefaction

Some of the most devastating damage during the earthquake was caused by liquefaction of loose, saturated sand. Liquefaction (*30*) occurred in man-made fill around the margins of the San Francisco Bay and in floodplain deposits in the Salinas–Santa Cruz area. Within the latter area, most of the catalogued 1906 failures (*31*) at epicentral distances of up to 40 km were reactivated.

In the San Francisco Bay Area, liquefaction-induced ground failure occurred mainly along the northern shores of the bay in artificial fill. It was most extensive in the hydraulically emplaced sand fills beneath the Oakland International Airport; the Alameda Naval Air Station; the eastern approach and toll plaza of the San Francisco Bay Bridge; the Marina, South of Market, and Mission districts of San Francisco. At these sites, the fill principally consists of hydraulically emplaced sand underlain by water-saturated mud or sand and overlain by broad pavements such as airport runways, streets, and slab foundations. Both the Mission and South of Market Street districts experienced severe liquefaction-induced ground failure and resultant structural damage during the 1906 earthquake.

Significantly, no obvious ground failure occurred in numerous other extensive land fills along the central and southern shores of the bay. Most of these consist of hydraulically emplaced silt and clay, dumped earth and rock, or solid waste covered by compacted earth. There is also no evidence of ground failure along the collapsed section of I-880 in Oakland.

From Santa Cruz to Salinas, liquefaction-related ground failure was widespread but restricted to areas underlain by water-saturated, late Holocene alluvial deposits of principally the San Lorenzo, Pajaro, and Salinas rivers, including spits and bars and tidal channels in the Moss Landing area. Lateral spreads and differential settlements disrupted or destroyed flood-control levees; pipelines; approaches, abutments, and piers of bridges; roads, homes, and utilities; and irrigation works, including gradients of irrigated fields.

Implications for Future Earthquakes

In the past, the occurrence of a major earthquake has confronted earthquake scientists and engineers with major surprises. The Loma Prieta earthquake was exceptional, for the likelihood of its coming had been evaluated well in advance of the earthquake, and the damage and destruction it wrought occurred in those areas and to those structures known to be at greatest risk. For the San Francisco Bay Area, the lessons of this earthquake differ only in the degree to which we will ultimately measure them from those of every other major historic earthquake in this area.

The strong ground motion generated by the Loma Prieta earthquake was neither particularly long, scarcely a third of the duration of the 1906 earthquake, nor unusually violent. Indeed, areas just north of Oakland and San Francisco that suffered liquefaction-induced ground failure in 1906 did not this time; this distribution indicates that the liquefaction threshold was only slightly exceeded even in heavily damaged parts of San Francisco during the Loma Prieta earthquake (*32*). When a similar or stronger earthquake strikes closer to the center of the Bay Area, as will happen, the hazard can only be greater. The real question is will its effects be more damaging?

Earthquake intensities previously predicted for the San Francisco Bay region (Fig. 8) for large earthquakes on either the San Andreas or Hayward faults reveal that the potential for damage can vary on a block by block basis depending on the geological character of the ground. The Loma Prieta earthquake served to identify only the most vulnerable structures located at sites underlain by poor soil conditions.

Now that a portion of the 1906 earthquake fault break has reruptured, there can be little doubt that the hazard is real along other active faults in the San Francisco Bay Area. Both the adjacent segment of the San Andreas fault on the San Francisco Peninsula and the Hayward fault, in repose since 1868, are recognized as possible sites for another *M* 7 earthquake in the coming decades. The aggregate probability of at least one *M* 7 event from these two faults alone had been judged as 0.5 over the next 30 years (*5*), and the occurrence of the Loma Prieta earthquake has not lowered that probability (*33*).

We have known for some time that meaningful reduction of earthquake hazards cannot be achieved through science alone (*34*). It requires a well-informed and well-prepared public to insist upon mitigation of the hazards before the next earthquake strikes.

REFERENCES AND NOTES

1. Loma Prieta, "the dark rolling mountain," highest point in the Santa Cruz mountains at 1157 m, has played a central role in geodetic measurements of crustal deformation in the San Andreas fault system since 1851, including the measurement of fault slip in the 1906 earthquake and the development of the elastic rebound theory of earthquakes [H. F. Reid, *Carnegie Inst. Washington Publ. 87*, vol. 2 (1910)].
2. California Office of Emergency Services estimates as of 9 November 1989.
3. A. G. Lindh, *U.S. Geol. Surv. Open-File Rep. 83-63* (1983).
4. L. R. Sykes and S. P. Nishenko, *J. Geophys. Res.* **89**, 5905 (1984).
5. Working Group on California Earthquake Probabilities, *U.S. Geol. Surv. Open-File Rep. 88-398* (1988).
6. Geologic effects of the 1906 earthquake were generally well documented [A. C. Lawson *et al.*, *Carnegie Inst. of Washington Publ. 87*, vol. 1 and atlas (1908)]. The investigation in the southern Santa Cruz Mountains, however, is an exception. The investigators apparently veered away from the main trace of the San Andreas fault and may have missed a long section of the main trace between Summit Road ridge and Pajaro Gap. The locations of most of the surface fractures described in the report are poorly documented. The report mentions only four sites of horizontal offset in the source region of the 1989 earthquake: Wrights-Laurel tunnel, Morell ranch, Pajaro River railroad bridge, and a fence halfway between Chittenden and San Juan Bautista. The report from Wrights-Laurel tunnel clearly indicates that there was about 1.5 m of right-lateral offset in the tunnel but not on the surface above. At Morell ranch, left-lateral displacements are described across two fractures. The report describes damage to the Pajaro River bridge but does not clearly document actual fault displacement. The report describes 1.2 m of horizontal offset

of the fence located between Chittenden and San Juan Bautista but does not give the sense of offset nor characterize its relation to the fault trace. Except for the Wrights-Laurel tunnel, we have little evidence of right-lateral surface faulting in the southern Santa Cruz Mountains during the 1906 earthquake, either because there was none or the investigator did not look in the right places. However, the report does mention extensive fracturing in the Summit Road and Skyland Ridge areas, as we observed in the same areas after the Loma Prieta earthquake. At least one, and probably many, of the 1906 fractures were reactivated in the 1989 earthquake.
7. K. Shimazaki and T. Nakata, *Geophys. Res. Lett.* 7, 279 (1980).
8. W. Thatcher and M. Lisowski, *J. Geophys. Res.* **92**, 4771 (1987).
9. C. H. Scholz, *Geophys. Res. Lett.* **12**, 717 (1985).
10. The mainshock epicenter is at 37°2.19'N and 121°52.98'W. The $M_s = 7.1$ is based on the average amplitude of 0.05-Hz surface waves at 18 selected stations between 22° and 142° from the mainshock. The hypocentral depth of 17.6 km is deeper than essentially all previously documented events on the San Andreas fault proper and is unusually deep for other faults of the San Andreas system as well.
11. The *P*-wave first-motion solution for the mainshock defines a fault plane striking N50° ± 8°W, dipping 70° ± 10° to the southwest, with a rake of 130° ± 15°. The southwestern side of the fault, or hanging-wall block, moved to the northwest (right-lateral slip) and upward (reverse slip), relative to the northeast, or footwall block. This solution was determined from 267 *P*-wave first motions recorded on the U.S. Geological Survey Central California Seismic Network. Centroid-moment-tensor (CMT) inversion of 3.5- to 7-mHz surface waves and 12- to 20-mHz body waves recorded at Pasadena, California; Cambridge, Massachusetts; and Tsukuba, Japan, by H. Kawakatsu of the Geological Survey of Japan (personal communication) gives an almost identical result for the best double couple with a strike of N54°W, a dip of 72° to the southwest, and a rake of 132°. The CMT inversion gave a seismic moment of 2.2×10^{19} N-m. Geodetic data collected the day after the earthquake with a Geodelite and meteorological measurements made by aircraft at the time of ranging and with two global positioning systems give a seismic moment of 3.8×10^{19} N-m.
12. The slip deficit accumulated in the 83.5 years since the 1906 earthquake equals the time interval times the mean slip rate. Estimates of the slip rate range from a low value of 1.2 ± 0.4 cm per year [W. H. Prescott and J. C. Savage, *J. Geophys. Res.* **86**, 10853 (1981)] to 2 cm per year (*3*) and imply that the slip deficit is between 1.0 m and 1.7 m, in comparison to the geodetically determined right-lateral slip of ~1.9 ± 0.2 m.
13. Movement along the San Andreas fault in a restraining fault bend requires the removal of crust if the horizontal motion direction is controlled by the fault orientation outside the bend. If one side of the fault is fixed and the other maintains a horizontal velocity $\dot{u}$, then the kinematic solution for a block sliding along a fault plane striking θ with respect to its constrained motion direction and dipping ϕ beneath it gives a horizontal (strike-slip) velocity of $\dot{u}\cos\theta$ and a vertical (reverse-slip) velocity of $\dot{u}\sin\theta/\cos\phi$ in the plane of the fault. The average difference in fault strike between the Loma Prieta fault plane and adjacent segments is 10° to 15°. For a dip of 70°, this difference implies that the ratio of strike slip to reverse slip on the fault plane is 2 : 1 to 1.3 : 1.
14. The high near-term seismic potential of the seismic gap considered by Lindh (*3*) was first delineated by A. G. Lindh, B. L. Moths, W. L. Ellsworth and J. Olson [*U.S. Geol. Surv. Open-File Rep. 82-180* (1981), p. 45] on the basis of the seismically quiet zone along the southeasternmost 45 km of the 1906 rupture, assignment of the 1865 earthquake to this fault segment, and (inferred) restoration of the strain released in the 1906 earthquake. Although the 1989 event was larger than anticipated, its intensity pattern closely corresponds the 1865 event. As the magnitude of the 1865 earthquake is based solely on the interpretation of its intensity pattern, the two events are probably more similar in size than their 0.6 difference in magnitude would suggest.
15. W. H. Bakun and A. G. Lindh, *Science* **229**, 619 (1985). Analyses of line-length changes on geodetic networks near Parkfield indicate that the 1966 rupture surface has not slipped significantly since 1966 and that the strain released in 1966 will most likely be restored by 1989. These considerations lend independent support for the prediction of the next Parkfield earthquake [P. Segall and R. Harris, *Science* **233**, 1409 (1986)].
16. The State of California issued public advisories following the 27 June 1988 (*M* 5.0) and 8 August 1989 (*M* 5.2) Lake Elsman earthquakes. These advisories noted that there was a small but significant chance of a larger earthquake during the next 5 days. All earthquakes have a finite probability of being foreshocks to larger events [P. A. Reasenberg and L. M. Jones, *Science* **243**, 1173 (1989)]. The decision to issue these advisories was driven by their location at the intersection of the Sargent and San Andreas faults, at the northern end of Lindh's (*3*) postulated earthquake.
17. These results constrict the limit on the seismic moment of possible preseismic deformations by a factor of 10 compared to earlier limits [M. S. J. Johnston, A. T. Linde, M. T. Gladwin, R. D. Borcherdt, *Tectonophysics* **144**, 189 (1987)].
18. W. H. Prescott, J. L. Davis, J. L. Svarc, *Science* **244**, 1337 (1989).
19. The unusual surface breaks occur in an 8-km-long, 1.5-km-wide zone on a ridge top traversed by Summit Road between Highway 17 and Old San Jose Road and on part of the next ridge to the south (Fig. 4). Their continuity along trend or relatively larger displacements or greater length distinguish these from the abundant small cracks throughout the zone of strong ground shaking that are associated either with obvious local ground failures or failures in asphalt and concrete pavement. The Summit Road fractures trend northwesterly, and the longest is about 700 m. They vary from single fractures to roughly en echelon, anastomosing or discontinuous cracks. Displacement across these fractures is mainly extensional, generally with a component of left slip of as much as 75 cm, and locally with a component of dip slip as large as 60 cm. Along some fracture sets, the downslope side is consistently up. Net displacement vectors for the fractures show consistent trends approximately normal to the crest of the ridge (Fig. 4). Repeated measurements across these fractures have detected no post-seismic creep.
20. A. M. Sarna-Wojcicki, E. H. Pampeyan, N. T. Hall, *U.S. Geol. Surv. Misc. Field Stud. Map MF-650* (1975).
21. Although fractures of this geometry and sense of displacement can be accounted for with special circumstances—for example, if surface materials were stress-free until the deep rupture imposed tractional stresses, or if the shear stress beneath the fracture zone was oriented anticlockwise in plan from the local strike of the fault trace—contrary arguments and the lack of corroborative evidence renders such explanations unattractive. Dislocation models suggest that the observed surface displacements are possible south of the San Andreas fault trace, but other explanations are also possible. Failure at depth on weak bedding planes, modified by near-surface topography, may also explain the displacements.
22. Similar phenomena have frequently been documented elsewhere in California [C. R. Allen, M. Wyss, J. N. Brune, A. Grantz, R. E. Wallace, *U.S. Geol. Surv. Prof. Pap.* 787 (1972), p. 87]. In the city of Los Gatos, about 10 km north of the rupture, concrete sidewalks and curbs on northeast-trending streets deformed throughout much of the downtown area. Broken concrete slabs lining Los Gatos Creek indicate about 25 cm of northeast-southwest tectonic shortening. About 3 km northeast of downtown, a 4.5-km-long, east-southeast-trending zone of broken concrete sidewalks and curbs defines a coseismic thrust or reverse fault. Possibly analogous zones of cracks and concentrated damage also occurred in Los Altos Hills.
23. Studies of recurrent liquefaction in the geologic record provide data for dating prehistoric earthquakes and are of particular importance in the central and eastern United States [P. Talwani and J. Cox, *Science* **229**, 379 (1985); S. F. Obermeier *et al.*, *ibid.* **227**, 408 (1985)].
24. R. D. Borcherdt, Ed., *U.S. Geol. Surv. Prof. Pap. 941-A* (1975).
25. H. O. Wood, in (*2*), p. 241.
26. R. D. Borcherdt, *Bull. Seismol. Soc. Am.* **60**, 29 (1970).
27. The bulk of the data are from the Strong Motion Instrumentation Program of the California Division of Mines and Geology [*Calif. Dept. Conserv., Rep. OSMS-89-06* (1989)] and the U.S. Geological Survey [*U.S. Geol. Surv. Open-File Rep. 89-568* (1989)]. Other data are from the University of California Santa Cruz, the California Department of Water Resources, and the U.S. Bureau of Reclamation.
28. W. B. Joyner and D. M. Boore, *Proceedings of the Conference on Recent Advances in Ground-Motion Evaluation Earthquake Engineering and Soil Dynamics II*, Park City, Utah, 27 to 30 June 1988 (*Geotech. Spec. Publ. 20*, American Society of Civil Engineers, New York, 1988), p. 43. The peak acceleration, a, is given by $\log a = 0.49 + 0.23(M - 6) - \log r - 0.0027r$, where r is the slant distance to the nearest point on the rupture at 8 km depth.
29. The area, maximum epicentral distance of effects, and geologic environments of landsliding in this earthquake are generally consistent with earlier predictions based on worldwide data and theoretical considerations [D. K. Keefer *et al.*, *Science* **238**, 921 (1987)].
30. Liquefaction is the process in which sediment composed chiefly of loose, noncohesive, water-saturated sand and silt is temporarily transformed to a slurry of water and sediment by earthquake shaking. It then has scant resistance to flow or to shear forces. So long as excess fluid pore pressure persists, water and sediment may escape to the ground surface and be expressed as sand boils, or the ground may spread laterally downslope, and carry unliquefied overburden, including man-made structures. Structures sited above zones of liquefaction also may suffer differential lateral displacement and subsidence if bearing capacity is reduced or if the ground settles beneath the foundation.
31. T. L. Youd and S. N. Hoose, *U.S. Geol. Surv. Prof. Pap* **993** (1978).
32. Repeat liquefaction at sites known to have failed in the 1906 earthquake demonstrates that the ground localities such as the Marina District or Treasure Island, which failed by liquefaction in the Loma Prieta earthquake but not the 1906 earthquake, could fail again in future earthquakes. Locations that have experienced liquefaction in earlier earthquakes, but not this time, cannot be assumed to be immune in future earthquakes.
33. The National Earthquake Prediction Evaluation Council has formed a working group charged with the evaluation of the 1988 report (*5*) in light of new knowledge derived from the Loma Prieta earthquake. Although this work has just begun, it is clear that the stress transferred to the adjacent segments of the San Andreas brings them closer to failure.
34. J. I. Ziony, Ed., *U.S. Geol. Surv. Prof. Pap. 1360* (1985);W. W. Hays, Ed., *U.S. Geol. Surv. Open-File Rep. 88-13-B* (1988).
35. R. D. Borcherdt *et al.*, *U.S. Geol. Surv. Misc. Field Stud. Map MF-709* (1977).
36. We thank the many individuals and institutions for their assistance in collecting data during the hectic days following the earthquake used in this report. In particular, we thank J. B. Berrill, P. Cowie, K. Hudnut, M. Jackson, H. Kawakatsu, S. Larsen, Z. Reches, F. Webb, and P. Wood.