Lessons Learned from the Loma Prieta, California, Earthquake of October 17, 1989

U.S. GEOLOGICAL SURVEY CIRCULAR 1045

AVAILABILITY OF BOOKS AND MAPS OF THE U.S. GEOLOGICAL SURVEY

Instructions on ordering publications of the U.S. Geological Survey, along with prices of the last offerings, are given in the current-year issues of the monthly catalog "New Publications of the U.S. Geological Survey." Prices of available U.S. Geological Survey publications released prior to the current year are listed in the most recent annual "Price and Availability List." Publications that are listed in various U.S. Geological Survey catalogs (**see back inside cover**) but not listed in the most recent annual "Price and Availability List" are no longer available.

Prices of reports released to the open files are given in the listing "U.S. Geological Survey Open-File Reports," updated monthly, which is for sale in microfiche from the U.S. Geological Survey, Books and Open-File Reports Section, Federal Center, Box 25425, Denver, CO 80225. Reports released through the NTIS may be obtained by writing to the National Technical Information Service, U.S. Department of Commerce, Springfield, VA 22161; please include NTIS report number with inquiry.

Order U.S. Geological Survey publications **by mail** or **over the counter** from the offices given below.

BY MAIL

Books

Professional Papers, Bulletins, Water-Supply Papers, Techniques of Water-Resources Investigations, Circulars, publications of general interest (such as leaflets, pamphlets, booklets), single copies of Earthquakes & Volcanoes, Preliminary Determination of Epicenters, and some miscellaneous reports, including some of the foregoing series that have gone out of print at the Superintendent of Documents, are obtainable by mail from

U.S. Geological Survey, Books and Open-File Reports
Federal Center, Box 25425
Denver, CO 80225

Subscriptions to periodicals (Earthquakes & Volcanoes and Preliminary Determination of Epicenters) can be obtained ONLY from the

Superintendent of Documents
Government Printing Office
Washington, D.C. 20402

(Check or money order must be payable to Superintendent of Documents.)

Maps

For maps, address mail orders to

U.S. Geological Survey, Map Distribution
Federal Center, Box 25286
Denver, CO 80225

Residents of Alaska may order maps from

Alaska Distribution Section, U.S. Geological Survey,
New Federal Building - Box 12
101 Twelfth Ave., Fairbanks, AK 99701

OVER THE COUNTER

Books

Books of the U.S. Geological Survey are available over the counter at the following Geological Survey Public Inquiries Offices, all of which are authorized agents of the Superintendent of Documents:

- **WASHINGTON, D.C.**--Main Interior Bldg., 2600 corridor, 18th and C Sts., NW.
- **DENVER, Colorado**--Federal Bldg., Rm. 169, 1961 Stout St.
- **LOS ANGELES, California**--Federal Bldg., Rm. 7638, 300 N. Los Angeles St.
- **MENLO PARK, California**--Bldg. 3 (Stop 533), Rm. 3128, 345 Middlefield Rd.
- **RESTON, Virginia**--503 National Center, Rm. 1C402, 12201 Sunrise Valley Dr.
- **SALT LAKE CITY, Utah**--Federal Bldg., Rm. 8105, 125 South State St.
- **SAN FRANCISCO, California**--Customhouse, Rm. 504, 555 Battery St.
- **SPOKANE, Washington**--U.S. Courthouse, Rm. 678, West 920 Riverside Ave..
- **ANCHORAGE, Alaska**--Rm. 101, 4230 University Dr.
- **ANCHORAGE, Alaska**--Federal Bldg, Rm. E-146, 701 C St.

Maps

Maps may be purchased over the counter at the U.S. Geological Survey offices where books are sold (all addresses in above list) and at the following Geological Survey offices:

- **ROLLA, Missouri**--1400 Independence Rd.
- **DENVER, Colorado**--Map Distribution, Bldg. 810, Federal Center
- **FAIRBANKS, Alaska**--New Federal Bldg., 101 Twelfth Ave.

Lessons Learned from the Loma Prieta, California, Earthquake of October 17, 1989

George Plafker and John P. Galloway, Editors

With contributions by

Michael J. Bennett
David M. Boore
Roger D. Borcherdt
William M. Brown III
Robert O. Burford
Mehmet Celebi
Malcolm M. Clark
James H. Dieterich
Donna M. Eberhart-Phillips
William L. Ellsworth
Thomas C. Hanks
Ralph A. Haugerud
Thomas L. Holzer
Malcolm J. Johnston
David K. Keefer
William J. Kockelman
Kenneth R. LaJoie
Michael Lisowski
Andrew J. Michael
Daniel J. Ponti
Carol S. Prentice
William H. Prescott
Paul A. Reasenberg
Michael J. Rymer
James C. Savage
David P. Schwartz
Robert V. Sharp
Paul C. Thenhaus
John C. Tinsley III
Peter L. Ward
Ray E. Wells

U.S. GEOLOGICAL SURVEY CIRCULAR 1045

DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

Catalog Card Number: 89–600786

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1989

Free on Application to the
Books and Open-File Reports Section,
U.S. Geological Survey
Federal Center, Box 25425
Denver, CO 80225

CONTENTS

FIGURES

TABLES

Lessons Learned from the Loma Prieta, California, Earthquake of October 17, 1989

George Plafker *and* John P. Galloway, *Editors*

INTRODUCTION

The magnitude 7.1 Loma Prieta earthquake (5:04 p.m. P.d.t., October 17, 1989) is the largest earthquake to strike the San Francisco Bay region and environs (fig. 1), home to more than 5.9 million people, since the great San Francisco earthquake of 1906. It was felt over an area of approximately 400,000 square miles, from Los Angeles on the south to the Oregon-California State line on the north, and to western Nevada on the east. Within about 15 seconds of seismic shaking of the region extending from Monterey Bay to northern San Francisco Bay, the Loma Prieta earthquake resulted in:

- 62 known deaths, 3,757 injuries, and more than 12,000 people homeless.[1]
- Over $6 billion property damage.[1]
- Disrupted transportation, utilities, and communications.

Losses in public and private property already place it near the top of the list of America's most expensive natural disasters, and it is the most costly earthquake since 1906. Coinciding with the third baseball game of the World Series in San Francisco, the first major league baseball game ever canceled on account of an earthquake, the Loma Prieta earthquake set a record for playing to the largest television audience ever to witness the direct effects of an earthquake. The only larger earthquakes to have affected the United States since 1906 are the magnitude 7.5 Kern County, California, earthquake of July 21, 1952 (12 dead; $49 million damage) and the magnitude 9.2 great Alaskan earthquake of March 27, 1964 (130 dead, $0.5 billion property damage in 1987 dollar-equivalent).

Manuscript approved for publication, November 22, 1989.

[1]State of California, Governor's Office of Emergency Services, written communication, November 21, 1989.

The Loma Prieta earthquake ruptured a segment of the San Andreas fault beneath the Santa Cruz Mountains—a segment that had been recognized as having the greatest chance (30 percent for the next 30 years) for producing a magnitude 6.5 to 7 earthquake of any fault segment north of the Mojave Desert in southern California (U.S. Geological Survey, 1988).

Just as the location and size of this earthquake were no surprise to earthquake specialists, neither were its principal effects—although, as in all large earthquakes, there were unexpected consequences and new lessons to be learned. Principal but preliminary findings are:

- Seismologic and geodetic data indicate that the earthquake in the Santa Cruz Mountains was accompanied by slip along a 25-mile-long segment of the San Andreas fault that ruptured the Earth's crust to a depth of about 11 miles. Displacement on the fault, which dips to the southwest at an angle of about 70°, amounted to about 6 feet horizontally and 4 feet vertically; the southwestern side moved northwestward and upward with respect to the northeastern side. The displacement differs significantly from the dominantly horizontal movements on near-vertical planes that have characterized seismicity and historical surface ruptures along most segments of the San Andreas fault.
- There were no known short-term seismic or strain precursors to warn of the impending earthquake.
- An unusual aspect of the earthquake is the absence of recognizable primary surface faulting; instead, a zone as much as 3 miles wide of numerous ground cracks along and near the surface trace of the San Andreas fault suggests strain was distributed over a broad area. Displacement across many of these cracks was large enough to damage houses and roads; many of them also appear to have been the locus for landsliding. Similar features were observed in this region in 1906. This type of distributed cracking constitutes a previously unappreciated category of earthquake hazard, one that can extend well beyond the well-defined and narrow fault trace that typifies most of the San Andreas fault.

• As observed in the 1906 earthquake, and predicted in maps of future earthquake effects, seismic shaking was locally amplified. Significant amplification occurred in areas of unconsolidated deposits and man-made fill over unconsolidated deposits that are widely distributed around the margins of Monterey Bay and

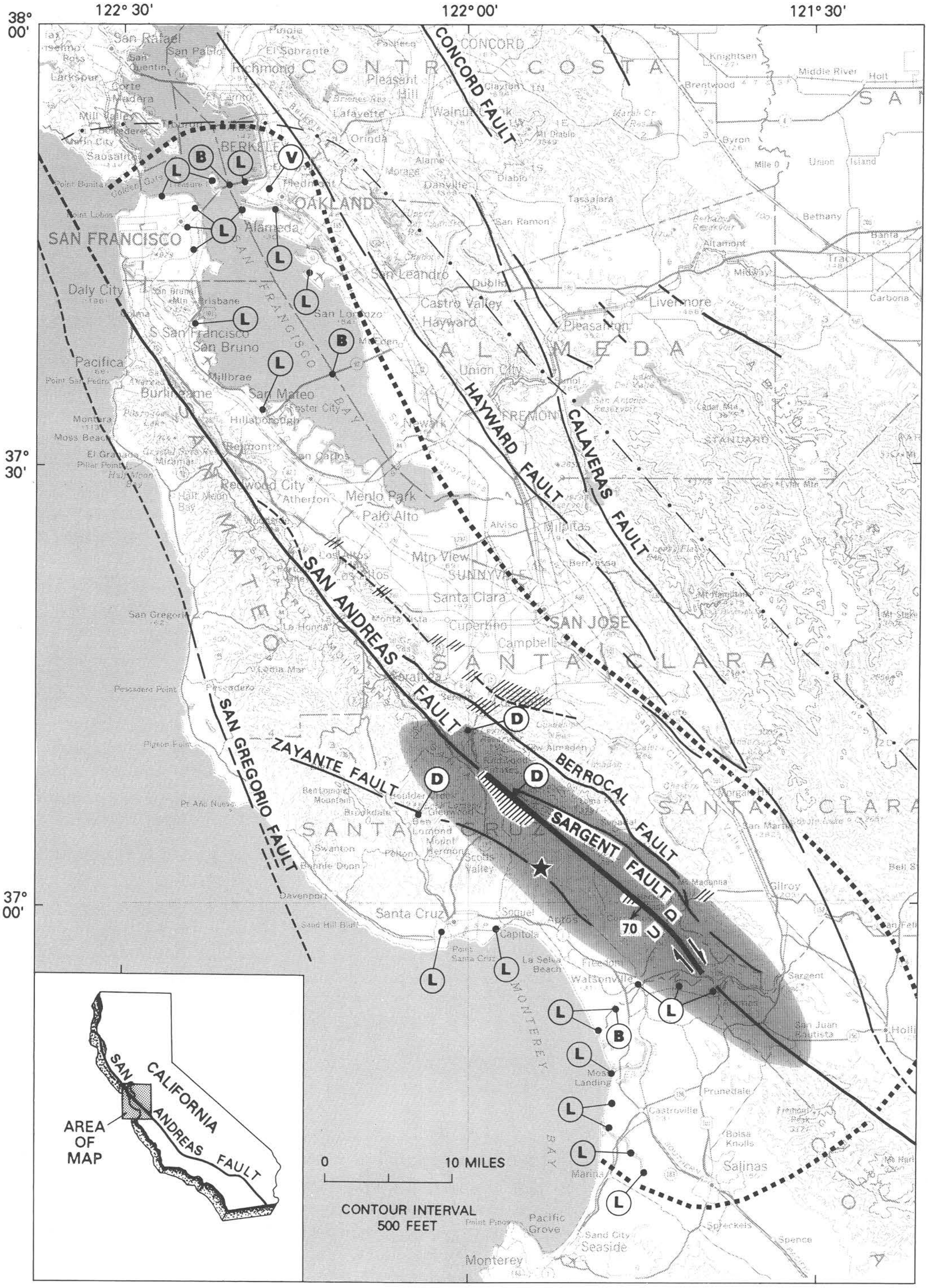


Figure 1. Mainshock epicenter of Loma Prieta earthquake and inferred fault rupture relative to areas of larger aftershocks, abundant ground cracks, and landslides and to limits of structural damage. Also shown are locations of major damaged structures and principal areas of ground cracks and liquefaction.

San Francisco Bay and along lakes, lagoons, and rivers. Amplified ground motion, which can affect structures on such deposits at great distances from the earthquake source, is suspected to be an important factor in damage to structures such as the Bay Bridge, the Cypress section of Interstate 880, and the Interstate 280 and Embarcadero viaducts.

- Areas underlain by thick deposits of water-saturated unconsolidated sand and mud were not only strongly shaken but were also affected by compaction and loss of strength in sediment that liquefied during the shaking; many of these same areas experienced similar processes in the 1906 earthquake. Sinking, tilting, and cracking of such deposits contributed greatly to the destruction, mainly in the same areas of amplified ground motion. This earthquake dramatically demonstrated that certain types of poorly engineered landfill, such as that which underlies the heavily damaged part of the Marina district in San Francisco, can fail at much lower levels of seismic shaking than might have been predicted.
- Seismic shaking triggered many landslides in areas of steep unstable slopes, including many manmade cuts and fills, throughout the region of strong ground motion. In addition to causing at least two deaths and extensive damage to buildings and utilities in rural mountain communities, landslides blocked many of the highways and roads, thereby hampering rescue and relief efforts.
- Damage to houses and multistoried buildings with foundations on good ground was minimal outside the epicentral region. Serious damage was largely restricted to older buildings that predate present building codes. Many failures can be linked to poor foundation connections, unreinforced masonry or brick facade construction, or multistory wood-frame buildings in which the first floor lacked sufficient lateral resistance to earthquake shaking.
- Part of downtown Los Gatos was destroyed in an area that was otherwise relatively undamaged. Small areas of enhanced damage appear to be present in a discontinuous zone that extends along the northeastern foothills of the Santa Cruz Mountains from Los Gatos to Palo Alto. Some of the damage is localized in areas of numerous ground cracks and surface deformation. The distribution of the damage and its relation to areas of surface cracking and warping suggest that damage may be related to the underlying geology, although this relation has yet to be proved.

This report summarizes our principal initial findings concerning the causes and effects of the Loma Prieta earthquake. It is addressed to the general public as well as to the earth scientists and researchers in related fields to provide information on this earthquake and an overview of the state of knowledge concerning future earthquakes in this region and their anticipated effects. In writing this report, we have tried to minimize use of scientific or technical terms and, for the benefit of the nontechnical reader, to explain concepts and terms as they are introduced. We have also converted most units of measurement from metric to English. A glossary of the commonly used terms in earthquake seismology and geology (appendix 1) is included at the end of the report to assist the nontechnical reader.

Many published reports, available from the U.S. Geological Survey and other sources, document risk from earthquake, landslide, and flood hazards. The list of references cited in this report and in appendix 2 includes a selected sample of these publications. In addition, appendix 2 cites publications of general interest on earthquakes as well as references of interest to engineers, planners, and decisionmakers and sources of the information.

The earthquake information presented in this preliminary report is based on less than 1 month of intensive postearthquake investigations. It derives chiefly from work by the staff of the U.S. Geological Survey, some of whom worked with scientists and engineers from several universities and private and public organizations and agencies. Prompt response to the earthquake was undertaken in order to (1) monitor aftershocks and postearthquake distortions of the Earth's surface because these phenomena diminish rapidly, (2) record the field evidence for ground failures before they were destroyed by emergency repairs or natural processes, (3) identify hazardous geologic situations, and (4) provide immedi-

EXPLANATION

	Explanation
D / U, 70	Fault rupture of Loma Prieta earthquake—Arrows show relative horizontal movement; small arrow and numeral show direction and amount of dip; U, upthrown side; D, downthrown side
———— - - -	Fault—Dashed where approximately located
★	Mainshock epicenter
(shaded area)	Area of aftershocks and abundant landslides
//////	Area of ground cracks possibly related to faulting
•••••••••••••••	Approximate limit of structural damage
— • — • — • —	Approximate limit of landslides
Ⓛ	Prominent area of liquefaction
Ⓑ	Damaged bridge
Ⓓ	Damaged dam
Ⓥ	Damaged two-story viaduct

Figure 1. Continued.

ate information on the earthquake and its effects to concerned citizens and public officials.

Investigations of the Loma Prieta earthquake will continue for years, for there is much to do to understand this reminder sent to citizens and scientists alike. Earthquakes of comparable size can be expected either on the segment of the San Andreas fault north of the Loma Prieta segment or on the Hayward fault. Such earthquakes will be far more disastrous to this growing and densely urbanized region unless we proceed vigorously to reduce the hazards.

GEOLOGIC SETTING

The San Andreas fault, which produced the Loma Prieta earthquake, first drew general attention in 1906 when it broke along a 280-mile stretch, causing the great San Francisco earthquake and fire. Since then, geologic mapping over many decades and the recent theories of plate tectonics have resolved that the San Andreas fault, which is about 800 miles long and extends to depths of at least 11 miles, is the major crustal boundary along which vast regions of the Earth's crust (known as the Pacific and North American plates) move past one another at rates of a few inches per year (fig. 2). Since the formation of the Pacific plate about 30 million years ago and on the basis of the offset of correlative rocks of known age on either side of the fault, the Pacific plate has moved northwestward relative to the North American plate as much as about 200 miles. In the San Francisco Bay area, the plate boundary is a broad, complex zone in which the horizontal slip is distributed over the San Andreas, Hayward, and Calaveras faults (figs. 1, 2), with additional slip on faults both seaward from the San Andreas and landward from the Calaveras. As a consequence, the San Andreas in this region takes up only about 40 percent of the relative plate motion, or an average of slightly less than one inch per year.

Sudden slippage that initiates large earthquakes usually happens on only one section of the fault at a time. Total offset along the fault accumulates unevenly, primarily by movement on first one and then another section of the fault. The widely accepted explanation of the process by which elastic strain gradually builds up and is suddenly released to produce an earthquake, the elastic rebound

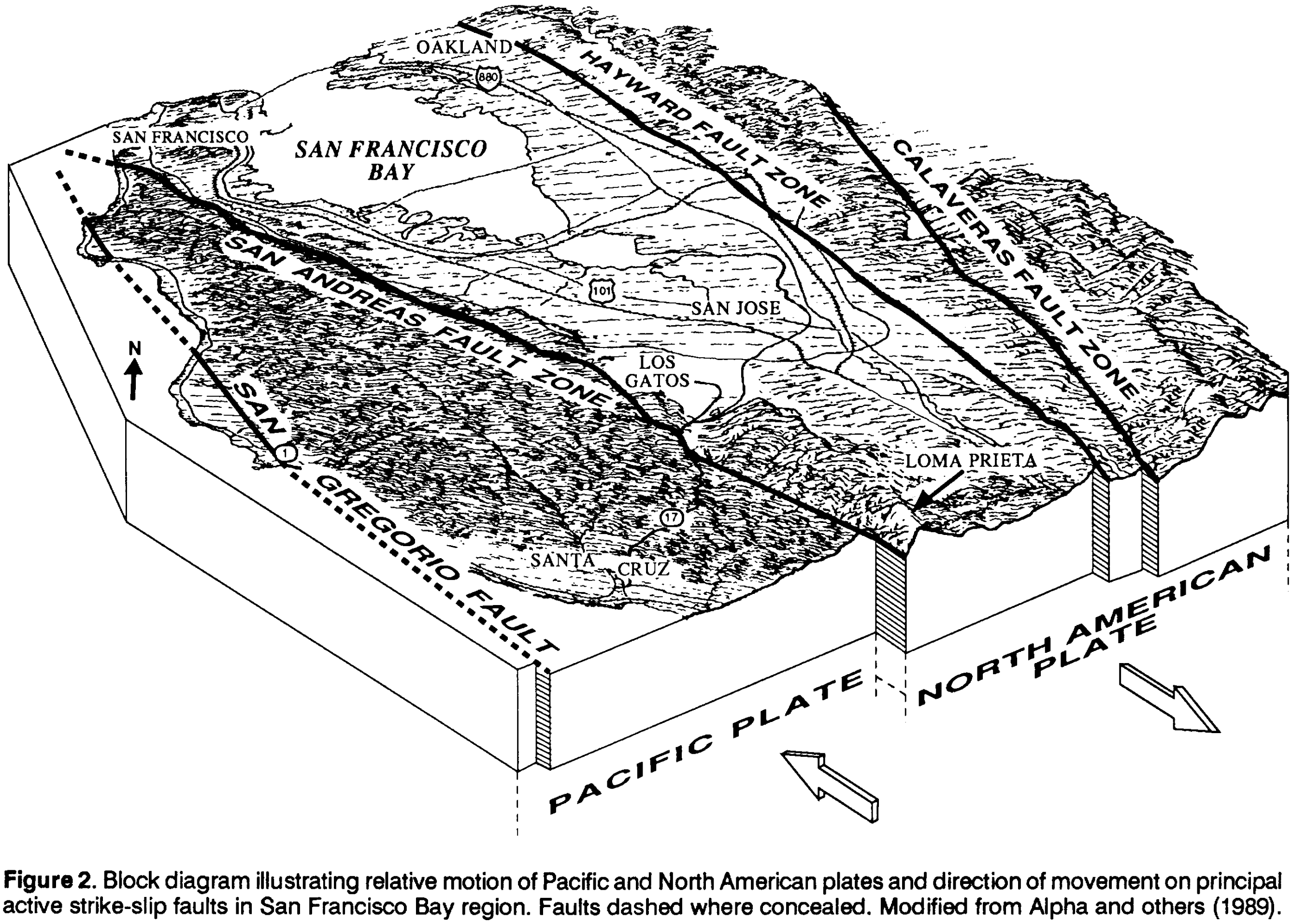


Figure 2. Block diagram illustrating relative motion of Pacific and North American plates and direction of movement on principal active strike-slip faults in San Francisco Bay region. Faults dashed where concealed. Modified from Alpha and others (1989).

theory, was developed as a result of studies of the fault displacement that accompanied the 1906 earthquake (Reid, 1910). According to this theory (see fig. 3), the sections that produce large earthquakes remain locked and quiet over periods of tens to hundreds of years while strain builds up by gradual deformation of the crust adjacent to the fault; this strain is relieved periodically in sudden fault displacements that produce earthquakes.

The break on the San Andreas fault that occurred during the Loma Prieta earthquake is in a sparsely inhabited part of the southern Santa Cruz Mountains, which attain their highest elevation (3,791 feet) at the nearby Loma Prieta (fig. 1). The Santa Cruz Mountains extend southeastward from San Francisco and separate the coastal communities of Santa Cruz and Watsonville from the San Francisco Bay area and the Santa Clara Valley. The mountains are underlain by deformed and variably consolidated bedrock, whereas the bay margins and the Santa Clara Valley are underlain by young unconsolidated sediment derived from the surrounding uplands (Helley and others, 1979). These stream deposits become progressively less compacted and less dense toward the bay, which is bordered and underlain by widely distributed estuarine deposits referred to as bay mud. During this century, man has placed many buildings, bridges, highways, airports, and other facilities on extensive areas of landfill over mud that can be especially susceptible to failure during seismic shaking.

Slight divergence between the present directions of crustal plate motions and the San Andreas fault produces a small component of compression perpendicular to the fault that is evident in the uplift of mountains and deformation of young rocks within the Santa Cruz Mountains. The southern Santa Cruz Mountains are bounded on the northeast by thrust faults along which the mountain side has moved upward and northeastward relative to the valley side. Both stratigraphic and seismic data show these faults to be active (McLaughlin, 1974). It is possible that similar, as yet unidentified, faults are present beneath the alluvial deposits of the Santa Clara Valley and San Francisco Bay.

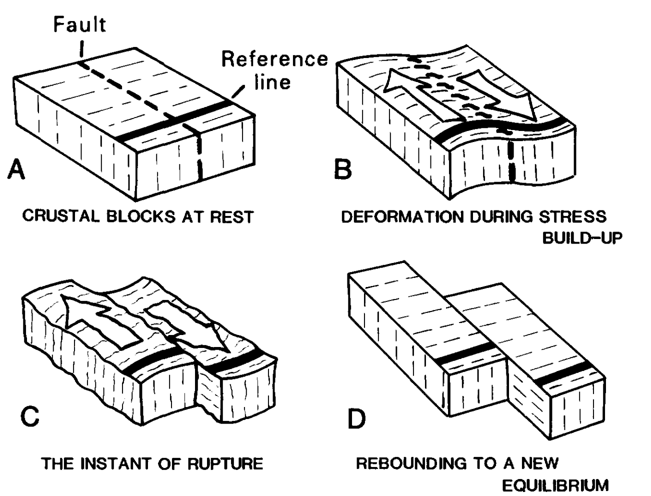


Figure 3. Block diagrams illustrating earthquake cycle for a right-lateral strike-slip fault according to elastic rebound theory.

THE EARTHQUAKE AND ITS AFTERSHOCKS

THE MAINSHOCK

The epicenter of the October 17 earthquake, at 37°02′ N. latitude, 121°53′ W. longitude in the Santa Cruz Mountains, is about 10 miles east-northeast of the city of Santa Cruz and 60 miles southeast of San Francisco (fig. 1). The main rupture began at 4 minutes 15 seconds after 5 p.m. (Pacific daylight time), at a depth of about 11 miles beneath the Earth's surface. During the next 7 to 10 seconds, the rupture spread about 25 miles northwest and southeast and upward about 8 miles, stopping about 3 to 4 miles below the surface. Although it failed to reach the Earth's surface, the earthquake rupture ultimately involved slip on a 190-square-mile area of the buried fault surface.

The magnitude of the earthquake is calculated to be 7.1 from surface waves recorded around the world, making it the largest earthquake on the San Andreas fault since 1906. The energy released as seismic waves by the earthquake (10^{22} ergs) was approximately equal to the total energy yield from one thermonuclear bomb (500,000 tons of TNT); additional energy was expended in fracturing rocks and in uplift of part of the Santa Cruz Mountains.

The earthquake is believed to have reruptured the southernmost 25-mile-long segment of the 1906 fault break. Because of the bend in the San Andreas fault and the compressional component noted previously, it is not surprising to find seismic evidence showing that the earthquake involved approximately equal amounts of right-lateral and reverse slip on a steeply inclined fault plane, with the Pacific plate moving up and northwestward relative to the North American plate (fig. 4). The fault-plane orientation was estimated to strike N. 50° W. ±8°, or approximately northwest, and dip 70°±10° southwest, with the direction of slip on this dipping plane estimated at 130°±15°, based on 267 observations of primary waves recorded in central California. Observations at Tsukuba, Japan, and at Pasadena, California, of surface and body waves give essentially the same result: strike N. 54° W., dip 72° southwest, and direction of slip in the fault plane of 132°. This orientation of slip is consistent with seismic observations of displaced survey monuments and with the 3-dimensional distribution of aftershocks.

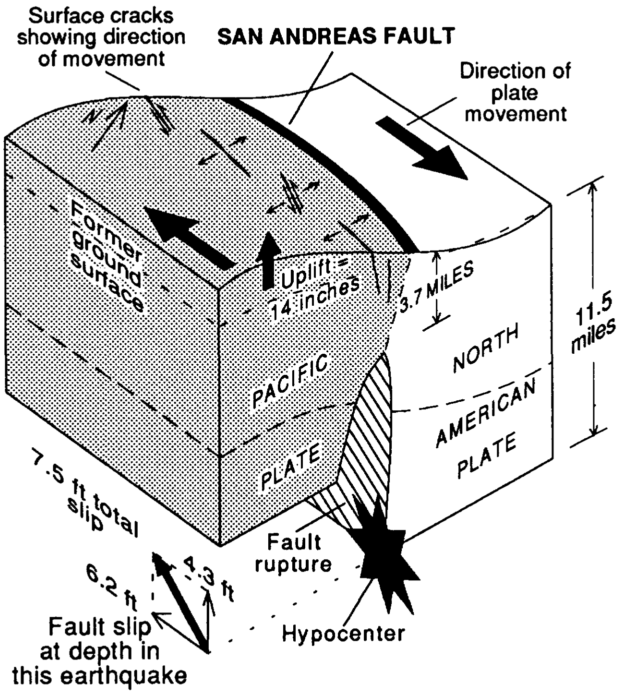


Figure 4. Schematic diagram showing inferred motion on San Andreas fault during Loma Prieta earthquake. Along southern Santa Cruz Mountains segment of fault, Pacific and North American plates meet along inclined plane that dips approximately 70° southwest. Plate motion is mostly accommodated by about 6.2 feet of slip along strike of this plane and by 4.3 feet of reverse slip, in which Pacific plate moves up fault and overrides North American plate. Amounts of fault slip and vertical surface deformation were determined from geodetic data. Modified from figure by M. J. Rymer.

BACKGROUND SEISMICITY

The earthquake occurred north of the creeping segment of the San Andreas fault in the locked segment that last had major movement in 1906. The contrasting behavior of the fault is apparent in the microseismicity recorded since 1969 (fig. 5). Between San Juan Bautista and Parkfield, the San Andreas fault moves by steadily creeping and produces numerous small earthquakes in an apparent absence of accumulated elastic strain. In contrast, north of Watsonville, the fault has remained relatively quiet, or aseismic, since 1906. What little seismicity that has occurred there over the last 20 years outlines an aseismic gap between about Watsonville and Los Gatos, a gap that was filled by aftershocks of the Loma Prieta earthquake. The Loma Prieta section is believed to be a transition zone, similar to the Parkfield segment, which begins about 124 miles to the south (fig. 5). These transition zones flank the creeping segment and sustain more frequent, but smaller, earthquakes than their respective neighboring segments to the north and south, where California's larger earthquakes are produced.

THE AFTERSHOCKS

Faults that ruptured during and after the mainshock are defined by the 3-dimensional distribution of the aftershocks (fig. 6). These aftershocks are caused by redistribution of stress following slip on the San Andreas fault during the mainshock. The mainshock hypocenter lies at the bottom and center of the aftershock distribution (fig. 6, section *A–A'*). Most of the aftershocks are

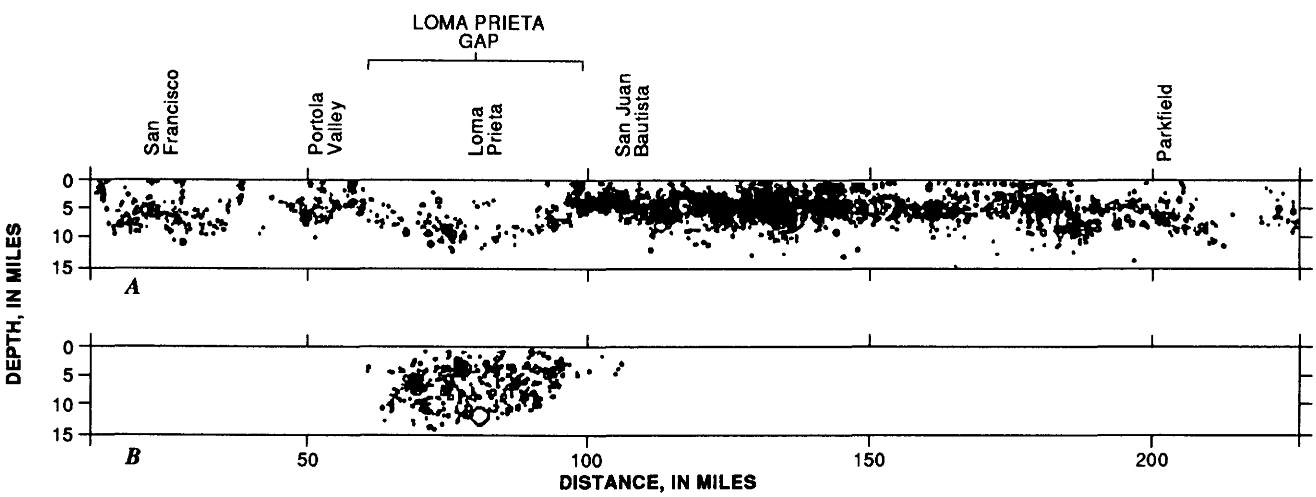
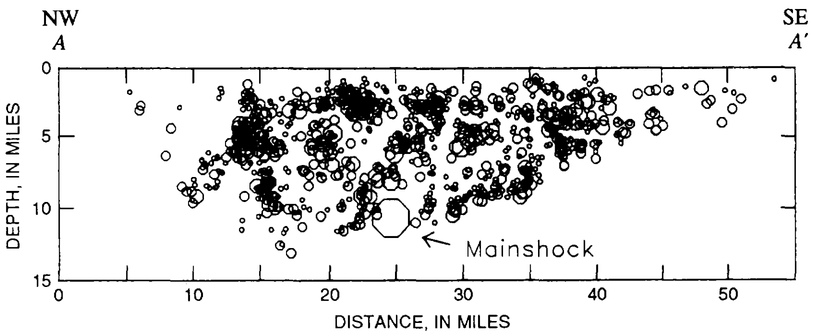


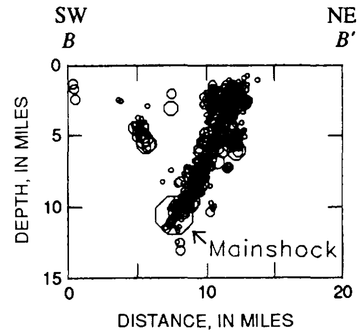
Figure 5. Cross sections showing seismicity along San Andreas fault from north of San Francisco to south of Parkfield. *A*, Background seismicity recorded during 20-year period before earthquake. Dense zone of activity south of San Juan Bautista is creeping segment of San Andreas fault. North of San Juan Bautista, San Andreas fault has been virtually aseismic since 1906. On Loma Prieta segment, what little seismicity has occurred has effectively outlined a U-shaped area (Loma Prieta gap) that has been virtually aseismic over the past 20 years. *B*, Aftershocks and mainshock (largest circle) almost completely filled former quiet zone of Loma Prieta gap.

confined to a plane that extends upward and laterally from the mainshock hypocenter with a dip of 70° southwest (fig. 6, section *B–B'*). This plane, the mainshock plane, projects to the surface between the traces of the San Andreas and Sargent faults. However, the dense clusters of shocks between 2 and 4 miles depth mark the inferred upper extent of the mainshock rupture. Above this point, the complex pattern of aftershocks probably represents movement on multiple branching faults, including shallow vertical segments of the San Andreas and Sargent faults. Thus, from the geometry of the deeper aftershocks, the primary rupture occurred on a dipping, buried portion of the San Andreas fault.

Southwest of the principal zone of aftershocks a distinct subparallel cluster of shocks was triggered by a magnitude 5.0 aftershock 33 hours after the mainshock. This cluster, which followed the second largest aftershock in the earthquake sequence, constitutes a secondary aftershock sequence associated with a separate episode of faulting in the upper (Pacific plate) block. The location of this aftershock cluster suggests the possibility of movement on the Zayante fault (see fig. 1); however, no displacement has yet been documented along the surface trace of this fault.

The rate of aftershock activity decreased rapidly with time after the mainshock, a pattern typical for a California earthquake sequence (fig. 7). A total of 51 aftershocks of magnitude 3.0 and larger occurred the day after the mainshock and 16 occurred the following day. After 21 days, 87 magnitude 3.0 and larger aftershocks had occurred. Extrapolation of the observed pattern, using a well-established law of aftershock decay, suggests that magnitude 3 or larger aftershocks will continue to be felt in the epicentral region for at least two years.





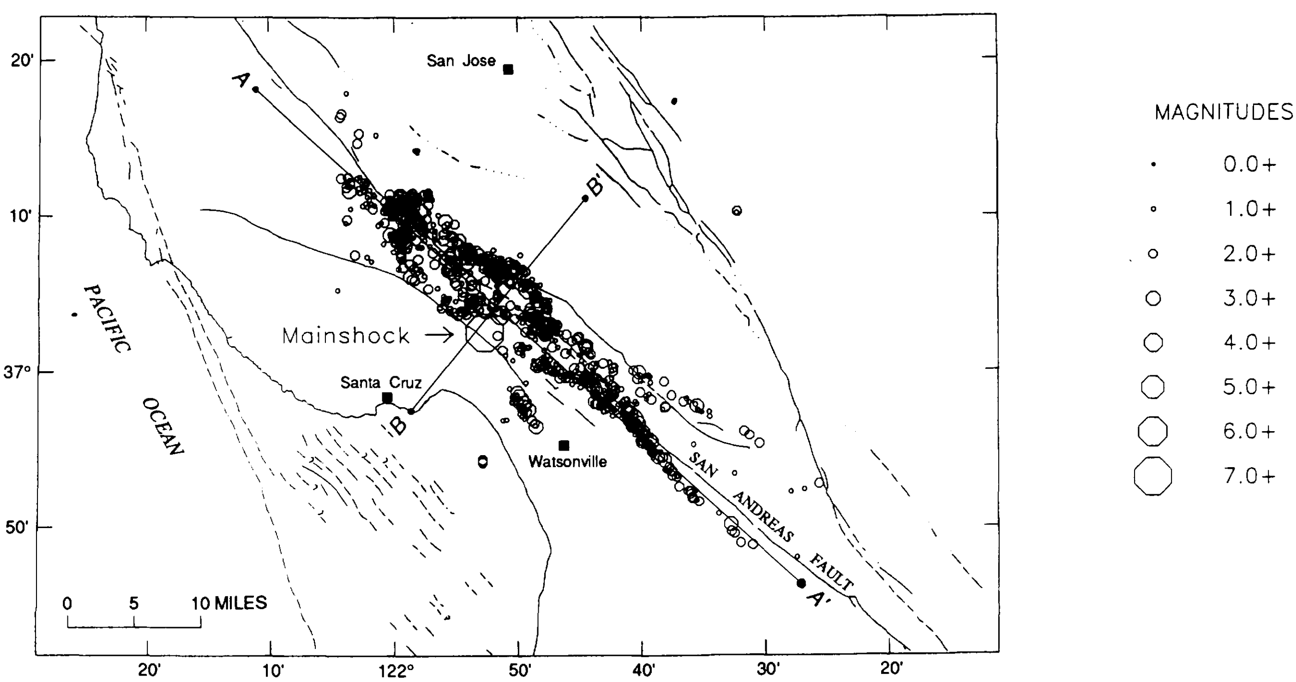


Figure 6. Spatial distribution of aftershocks of Loma Prieta earthquake in relation to San Andreas fault. Along-fault, or longitudinal, cross section *A–A'* and cross-fault, or transverse, cross section *B–B'* display depth distribution of aftershocks on vertical planes. Faults are dashed where approximately located, dotted where inferred, and queried where uncertain.

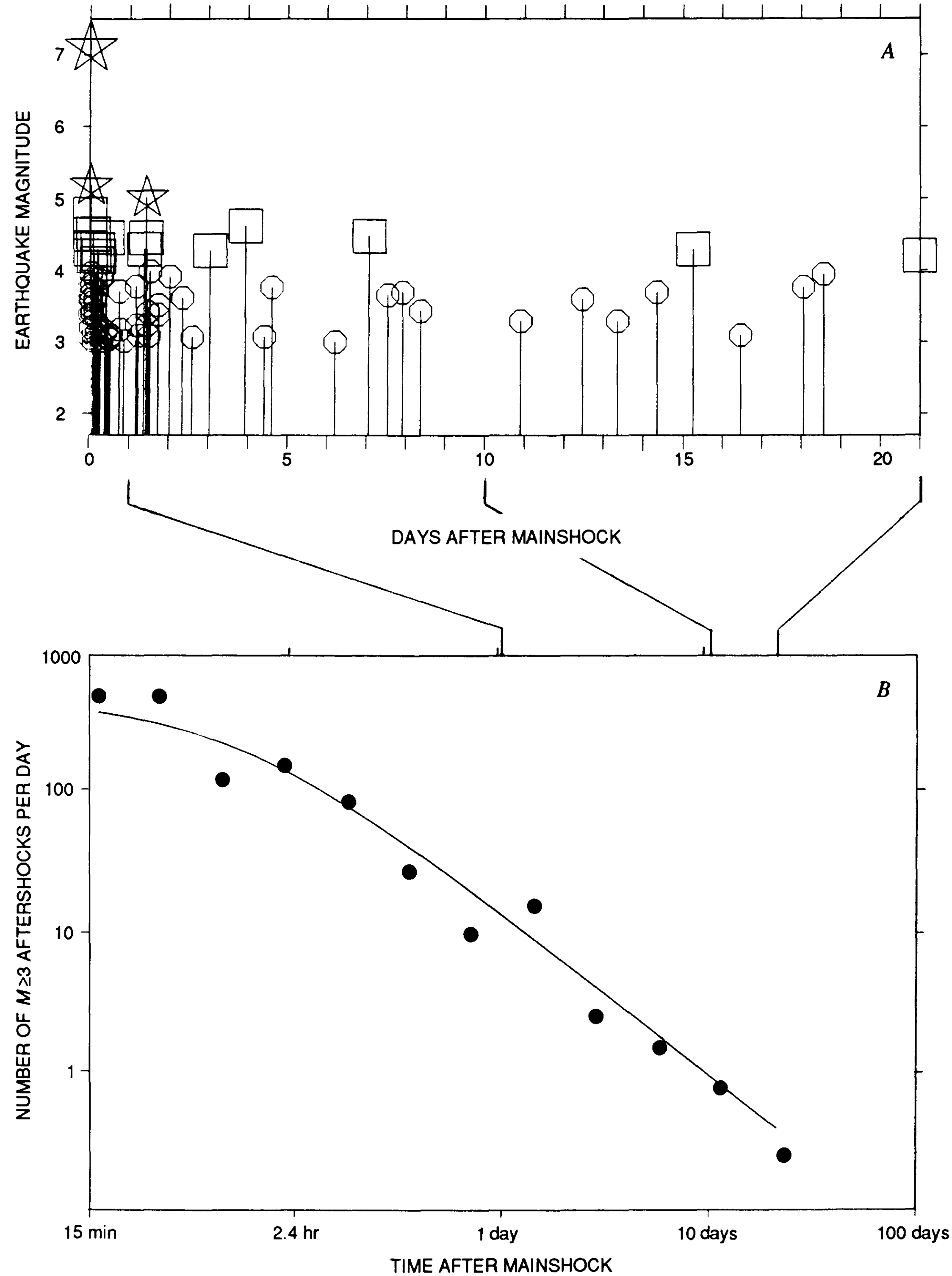


Figure 7. Time distribution of aftershocks of magnitude (*M*) 3 or greater of Loma Prieta earthquake. *A*, Aftershocks during first three weeks are represented by circles ($M \geq 3$), squares ($M \geq 4$), and stars ($M \geq 5$). Rate of aftershocks decreases rapidly in first week of sequence. *B*, Rate of $M \geq 3$ aftershocks as a function of time, shown on logarithmic scales. Points plotted represent rate observed in aftershock sequence. Solid line is theoretical curve representing expected aftershock rate. Earthquake sequence closely follows expected time behavior.

SURFACE DEFORMATION

Movement on the San Andreas fault during the Loma Prieta earthquake distorted the surface of the Earth. Earthquake-related changes in the positions of permanently marked sites (geodetic stations) can be used to infer the amount and distribution of fault slip.

The Loma Prieta earthquake occurred along the southwestern end of the 1906 rupture within an extensive and frequently measured network of geodetic stations. Since the early 1970's, the U.S. Geological Survey has monitored crustal deformation in the region near Loma Prieta by repeatedly measuring the distances between a network of geodetic stations. The distances, which range in length from 3 to 28 miles, are measured to an accuracy of better than 0.4 inch using a geodolite (a high-precision electro-optical distance-measuring instrument) according to procedures outlined by Savage and Prescott (1973). The network surveys were repeated at intervals of one to five years. Monthly measurements from Loma Prieta to stations located on Eagle Rock, Mount Allison, and Mount Hamilton (fig. 8) began in 1980. In 1985, the geodolite observations were supplemented by monthly observations of the relative position vectors between these same stations by observing a system of surveying satellites in Earth orbit—the so-called Global Positioning System (GPS) (Prescott and others, 1989). Since the October 17th Loma Prieta earthquake, much of this network has been, or is being, resurveyed.

On the basis of a preliminary analysis of the change observed in 11 geodolite distances and 4 GPS vectors surveyed immediately after the event, we have inferred that the rupture included about 6 feet of right-lateral strike slip and 4 feet of reverse slip on a fault surface that strikes N. 48° W. and dips 70° to the southwest (fig. 4). The best-fitting rupture surface extends about 25 miles along strike and at a depth of about 4 to 11 miles. The data suggest a broad uplift of the surface to a maximum of about +1.5 feet on the southwest block and a more limited area of subsidence to a maximum of –0.5 foot of the northeast block as depicted schematically by contours in figure 8. A buried rupture surface is consistent with the lack of surface offset associated with the earthquake. The slip in the plane of the fault, with a considerable component of reverse slip, is about the same as that inferred from the seismological data. The amount of reverse slip on the fault rupture is not well constrained by the geodolite and GPS data, which are most sensitive to horizontal deformation. A better estimate of the vertical deformation may be obtained from a resurvey of 124 miles of leveling routes in the Loma Prieta area. Most of the initial level surveys, several of which extend across the Santa Cruz Mountains near the fault rupture, were made in the 1940's and 1950's and, except for segments along the coast and in the Santa Clara Valley, none have been repeated.

PREMONITORY DEFORMATION

Although several monitoring systems for determining strain changes were operating continuously before, during, and after the Loma Prieta earthquake, no premonitory signals were observed.

SURFACE EXPRESSION OF FAULTING

SAN ANDREAS FAULT ZONE

Within 24 hours of the earthquake, U.S. Geological Survey personnel and others determined that no right-

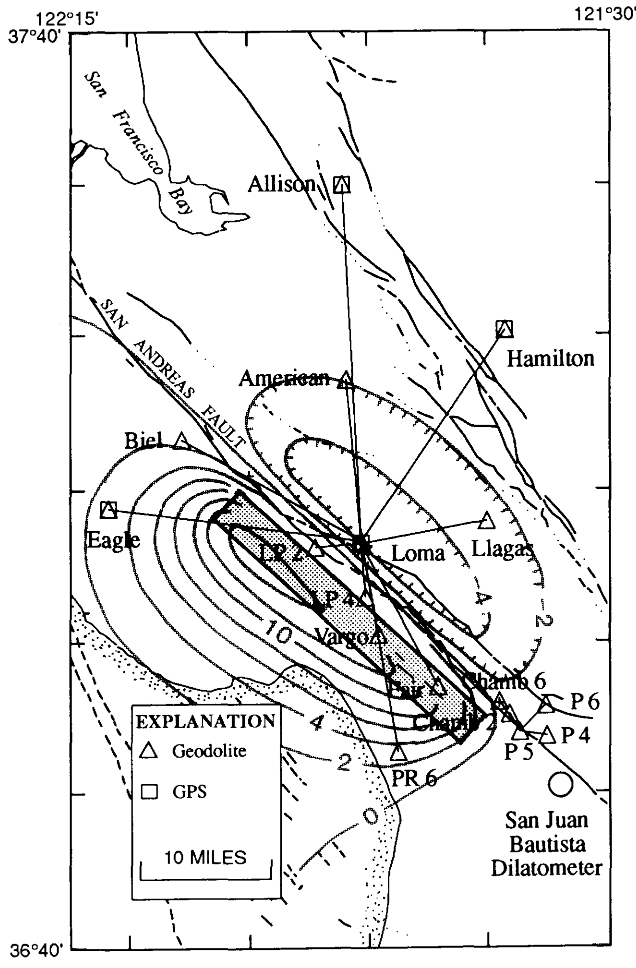


Figure 8. Geodolite lines and Global Positioning System (GPS) vectors that were observed following Loma Prieta earthquake. Projection of rupture surface, which extends to depths of about 4 to 11 miles, is shown by shaded rectangle. Contours show inferred uplift (gray lines) and subsidence (barbed gray lines) of surface due to oblique slip on fault plane; contour interval about 2 inches. Maximum uplift and subsidence were 1.5 and 0.5 feet, respectively. Location of San Juan Bautista Dilatometer is shown by circle. Faults (from Jennings, 1975) are dashed where approximately located and dotted where inferred.

lateral surface faulting occurred above the 25-mile-long deep rupture on the San Andreas fault. The nearby Sargent and Zayante faults also lacked clear evidence of tectonic rupture. On the basis of historical earthquakes along the San Andreas fault and crustal earthquakes of comparable magnitude on other strike-slip faults worldwide, we had anticipated through-going surface faulting with 3 to 6 feet of right lateral displacement (Bonilla and others, 1984).

In the aftershock zone, only local cracks and sets of cracks with small right-lateral offset were observed along the mapped trace of the San Andreas fault. The largest is near Mt. Madonna Road, where right-lateral en echelon cracks were traced for approximately 0.6 mile. Along the San Andreas fault, right-lateral offset measured in Mt. Madonna Road within 16 hours of the mainshock was approximately 3/4 inch. The cracks, which extend to the northwest from this site, consistently form left-stepping patterns within a 3- to 30-foot-wide zone. Repeated measurements made in the 17 days after the earthquake indicate slight additional right-lateral movement of about 1/20 inch across the San Andreas fault at Mt. Madonna Road.

AREAS OF EXTENSIONAL GROUND CRACKS

Sets of ground cracks that appear to be related to regional deformation, rather than local slumping, occur on the relatively upthrown southwest side of the San Andreas fault south of Highway 17 in an area about 5 miles long and 3 miles wide. A distinguishing characteristic of most of these cracks is that offsets across them are commonly combinations of extension and either left-lateral or right-lateral horizontal slip.

In the Summit Road area a zone of extensional and left-lateral cracks occurs just southwest of the main trace of the fault about 7 1/2 miles northwest of the epicenter. These cracks are distributed in a 5-mile-long, 1.5-mile-wide zone on a ridgetop traversed by Summit Road between Highway 17 and Old San Jose Road and on part of the next ridge to the south (fig. 9). Their continuity along trend, relatively large displacements, and (or) great length (up to 2,000 feet) distinguish them from abundant small cracks throughout the zone of strong ground shaking that are associated with local slumping of natural ground and pavement. These cracks trend northwesterly, and they vary from single large crack to en echelon, anastomosing, or discontinuous crack sets (figs. 10, 11). Displacement across these cracks is mainly extensional, generally with a component of left slip of as much as 2.5

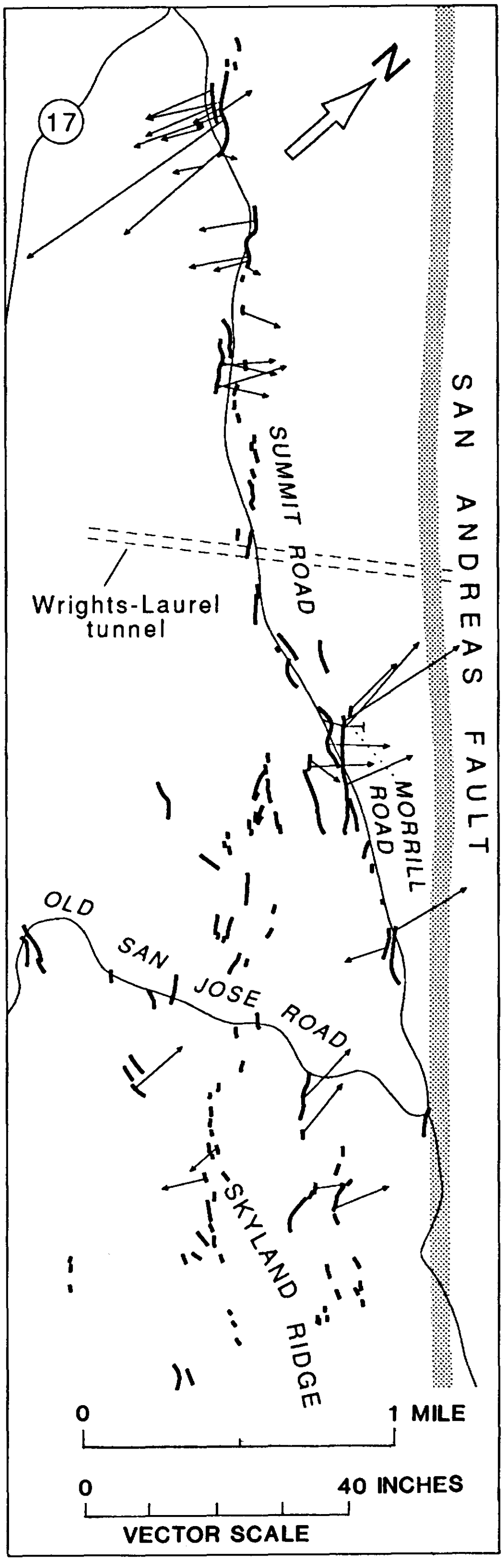
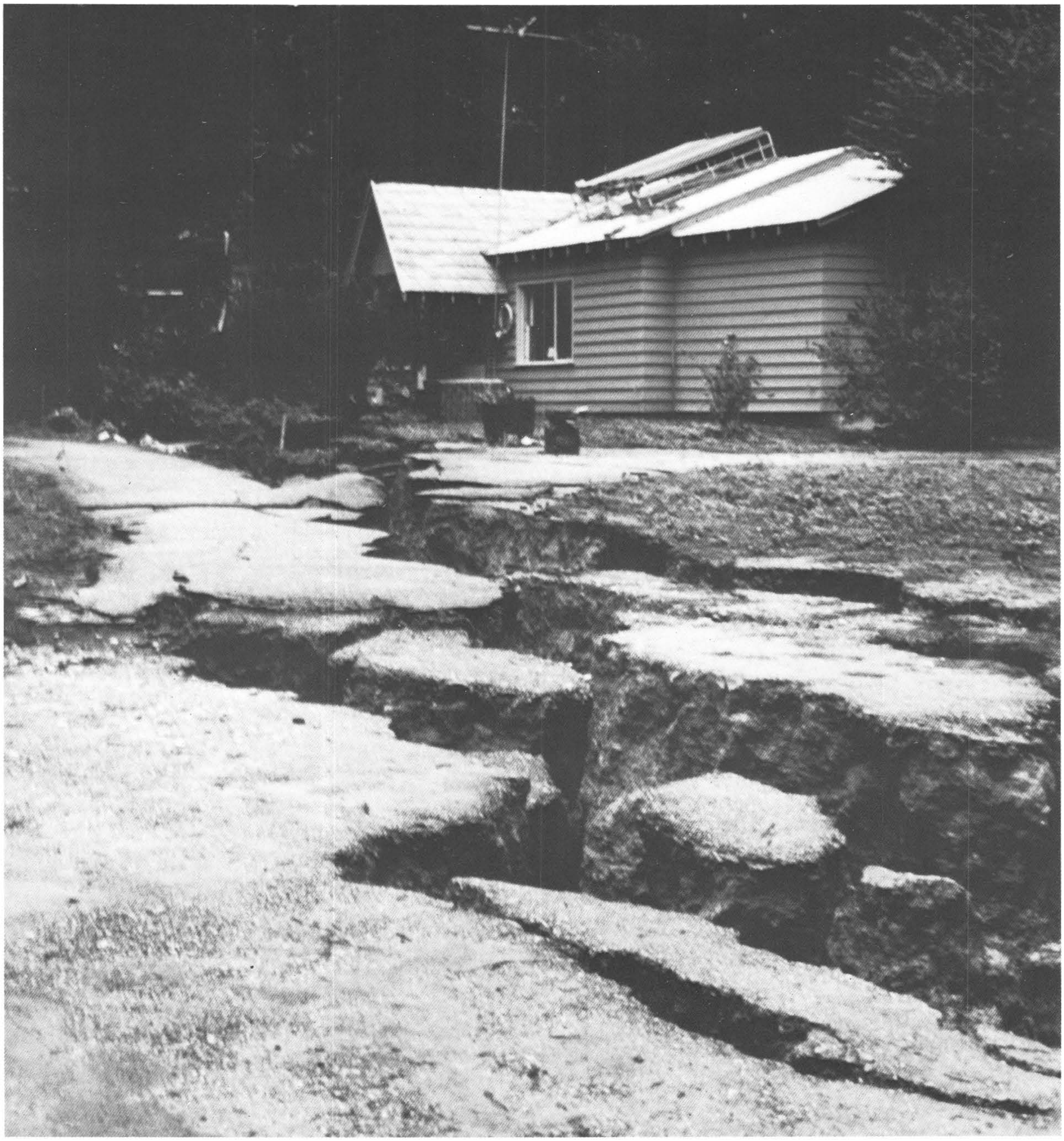


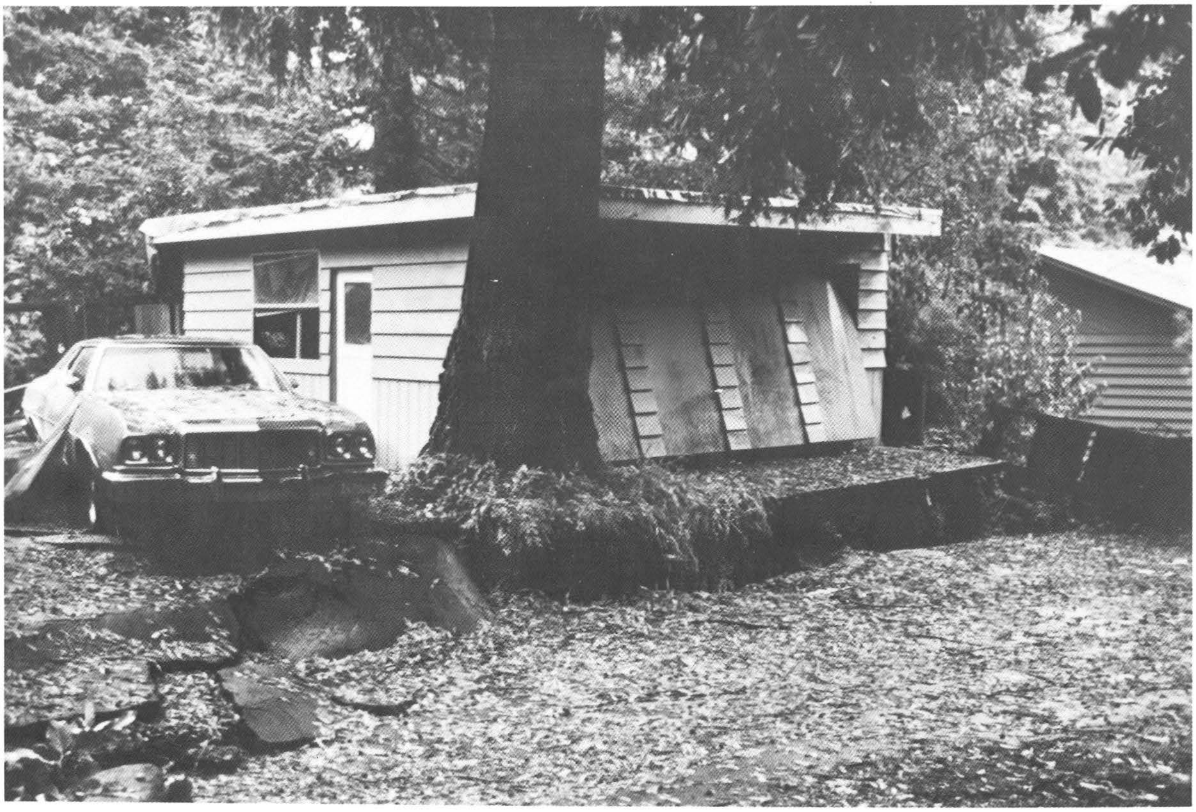
Figure 9. Zones of prominent surface cracks (heavy lines) and net-displacement vectors (arrows) near Summit Road, Santa Cruz Mountains. Open cracks obviously related to local ground failure or landslides are not shown. Only vectors greater than 5 inches long and next to Summit Road are shown. Wide gray band is approximate location of main trace of San Andreas fault as shown by 1906 offset in Wrights-Laurel tunnel and by topography along and beyond northwest and southeast boundaries of figure.

feet, and locally with a component of dip slip to 2 feet. Along some cracks the downslope side is consistently up, opposite the sense that would be expected for gravity slides. The direction of separation of opposite sides of the cracks (slip vectors) are consistently oriented roughly normal to the crest of the ridge along Summit Road (fig.



A

Figure 10. Crack system near Summit Road, ½ mile southeast of Highway 17. *A*, View northwest of wide zone of dominantly extensional cracks passing several feet in front of house. *B*, View southeast back toward house showing driveway dropped down relative to garage. *C*, Same crack where it crosses Summit Road; crack trends nearly north here rather than northwest and displays large component of left-lateral displacement. In general, upthrown block is on downhill side of this crack. Swale along crack on northeast side of Summit Road ridge in this area suggests similar displacement may have occurred in the past.



B

C

Figure 10. Continued.

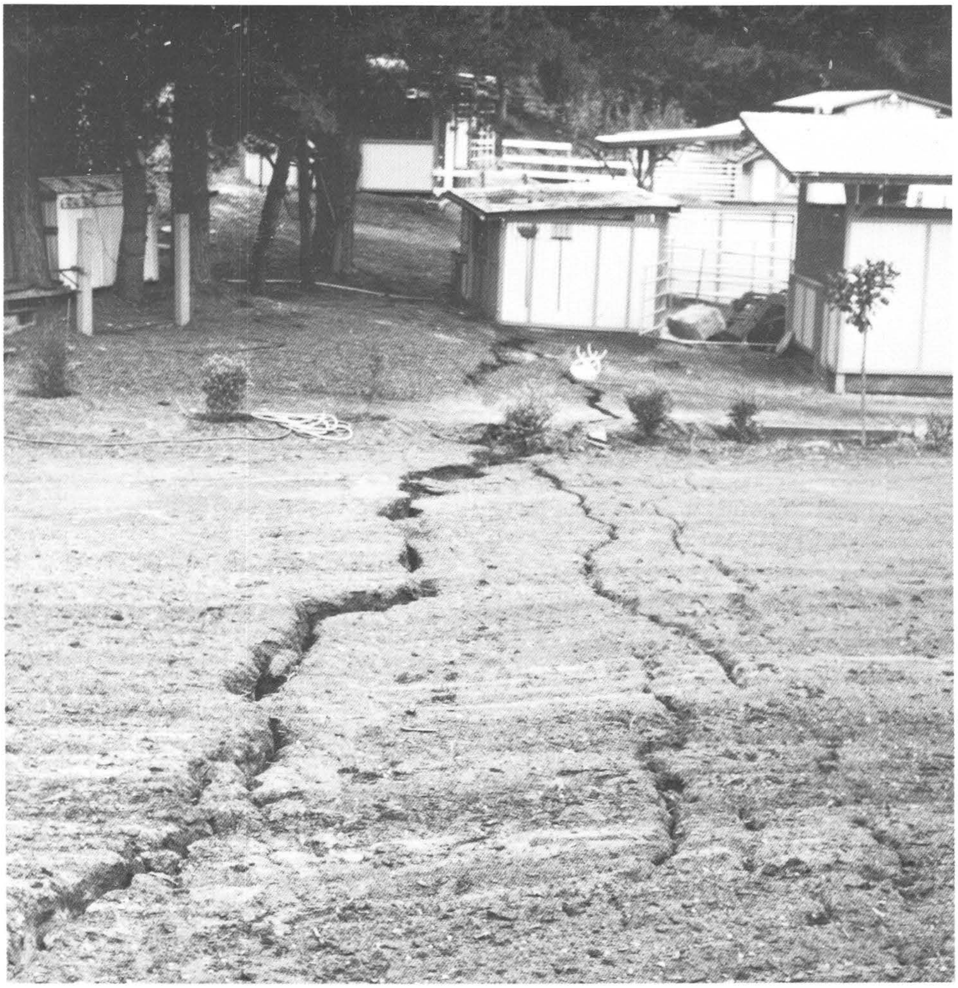


Figure 11. Cracks through corral near Summit Road, about 1.1 miles southeast of Highway 17, along southwest edge of elongate, closed depression. Cracks are also found along northeast edge of same depression. Displacements on both sets of cracks deepened depression.

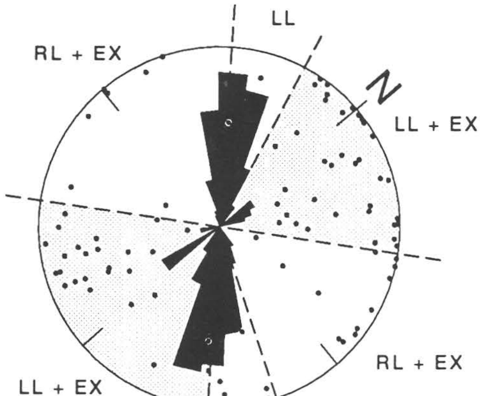
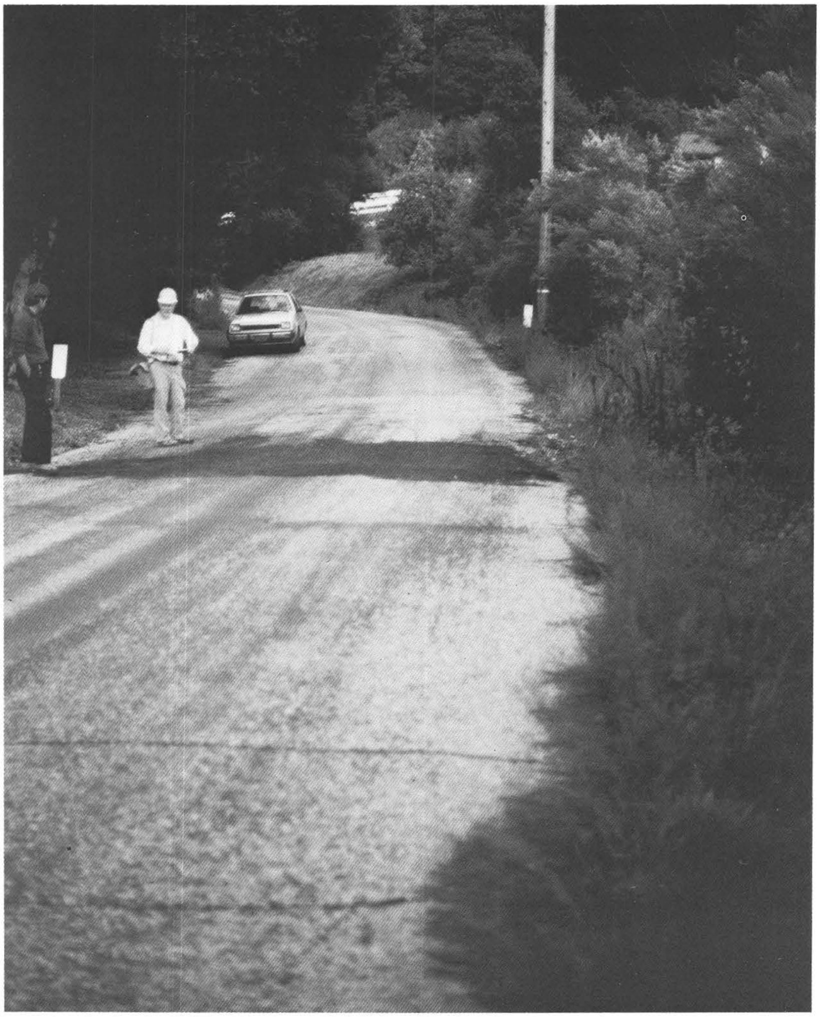


Figure 12. Crack trends and displacement vectors for 94 surface cracks in Summit Road area. Rose diagram (black) shows strike of cracks, which, on average, are subparallel to San Andreas fault. Dots are lower-hemisphere equal-area projection of slip vectors. Note that dominant sense of slip is within both mixed left-lateral and extensional (shaded) and right-lateral and extensional domains. LL, left lateral; RL, right lateral; EX, extensional. Modified from figure by Ze'ev Reches.

A

B

Figure 13. Larger of two cracks that broke Morrill Road by left-lateral motion in both 1906 San Francisco earthquake and 1989 Loma Prieta earthquake. *A*, View southwest across Morrill Road in 1906 showing left-lateral displacement of 3.6 feet (Lawson, 1908, plate 65A). *B*, Same crack on October 18, 1989, morning after earthquake, before road repairs, showing 1.1 feet of extension, 1.2 feet of left lateral displacement, and 0.3 feet of vertical displacement. Yardstick is aligned in direction of movement of opposite sides of crack. *C*, View of present-day Morrill Road (October 1989) similar to 1906 view after asphalt road had been patched, showing left-lateral displacement of edge of road.



C

Figure 13. Continued.

12). Repeated measurements across these cracks have detected no postearthquake displacement in 1 month after the earthquake.

Individual cracks within the zone generally follow existing topography and occur along slope breaks 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 similar movements along these ruptures. Some of the ruptures closely follow linear topographic trends identified by Sarna-Wojcicki and others (1975) and interpreted by them as elements of a complex fault pattern associated with this section of the San Andreas fault. The 1906 surface rupture and associated ground failure were poorly documented along this part of the San Andreas fault (Lawson and others, 1908). However, two of the 1989 Summit Road cracks coincide exactly with left-lateral offsets mapped during the field investigations following the 1906 earthquake. The larger of the two cracks showed left slip of about 4 feet in 1906 but 1.2 feet in the Loma Prieta earthquake (fig. 13). The 1989 cracks cross Morrill Road southeast of the axis of the now abandoned and closed Wrights-Laurel railroad tunnel, which passes 700 feet beneath the crest of the ridge. After the 1906 earthquake, the most reliable measurement of offset along this reach of the fault, 4.5 feet of right slip, was made in the tunnel about 3,000 feet north-northeast of these left-slip cracks. The offset, however, was not observed at the surface above the tunnel.

Ground cracks in the Skyland Ridge area (fig. 9) exhibit nearly the same trend and sense of displacement as the cracks located along Summit Road. Displacement of the Skyland Ridge cracks is largely extensional but with a component of left slip. Displacement is generally less than that observed near Summit Road, and the cracks are less continuous along trend. In contrast to the ridge-parallel cracks along Summit Road, many cracks in the Skyland area cut obliquely across the ridge crest. They tend to follow pre-existing linear scarps and troughs, suggesting repeated motion along the zone of cracking.

Along the San Jose-Soquel Road, asphalt road surfaces that are not obviously involved in slope failure are extensively cracked and extended to a distance of as much as 3 miles southwest of the San Andreas fault. These cracks show combinations of extension and crack-parallel left and right slip. Many cracks have the same combination of left slip and extension as those along Summit Road and Skyland Ridge, but they differ in that most of them trend northeasterly at a large angle to the San Andreas fault.

ORIGIN OF THE EXTENSIONAL CRACKS

The origin of the Summit Road cracks and similar cracks southwest of Summit road is complex. The large cracks are most abundant on northwest-trending ridgetops underlain by relatively soft, Tertiary sedimentary rocks. The cracks tend to follow the trend of bedding in the underlying strata and may be concentrated over weaker shale beds. Uplift of the block on the southwest side of the San Andreas fault resulted in extension or spreading near the surface of the block (as depicted schematically in figure 4), and slip on weak bedding planes in the Tertiary strata probably accommodated this extension. Cracking may have been enhanced by the severe ground shaking along some of the ridgetops (described in the following section). This strong shaking may have caused ridgetops to spread laterally as the slopes moved outward and downward toward the valleys under the influence of gravity. Ongoing detailed studies of the relation of the cracks to the underlying geology should help to further clarify the origin of these unusual features.

LOS GATOS-PALO ALTO ZONE OF DEFORMATION

Along the northeastern margin of the Santa Cruz Mountains there is a northwest-trending discontinuous zone of relatively intense damage to structures and local areas of ground cracks and deformation that extends northwestward from east of Los Gatos to Palo Alto (fig. 1).

In the town of Los Gatos, about 6.2 miles north of the Summit Road area, concrete sidewalks and curbs were systematically fractured and buckled on northeast-

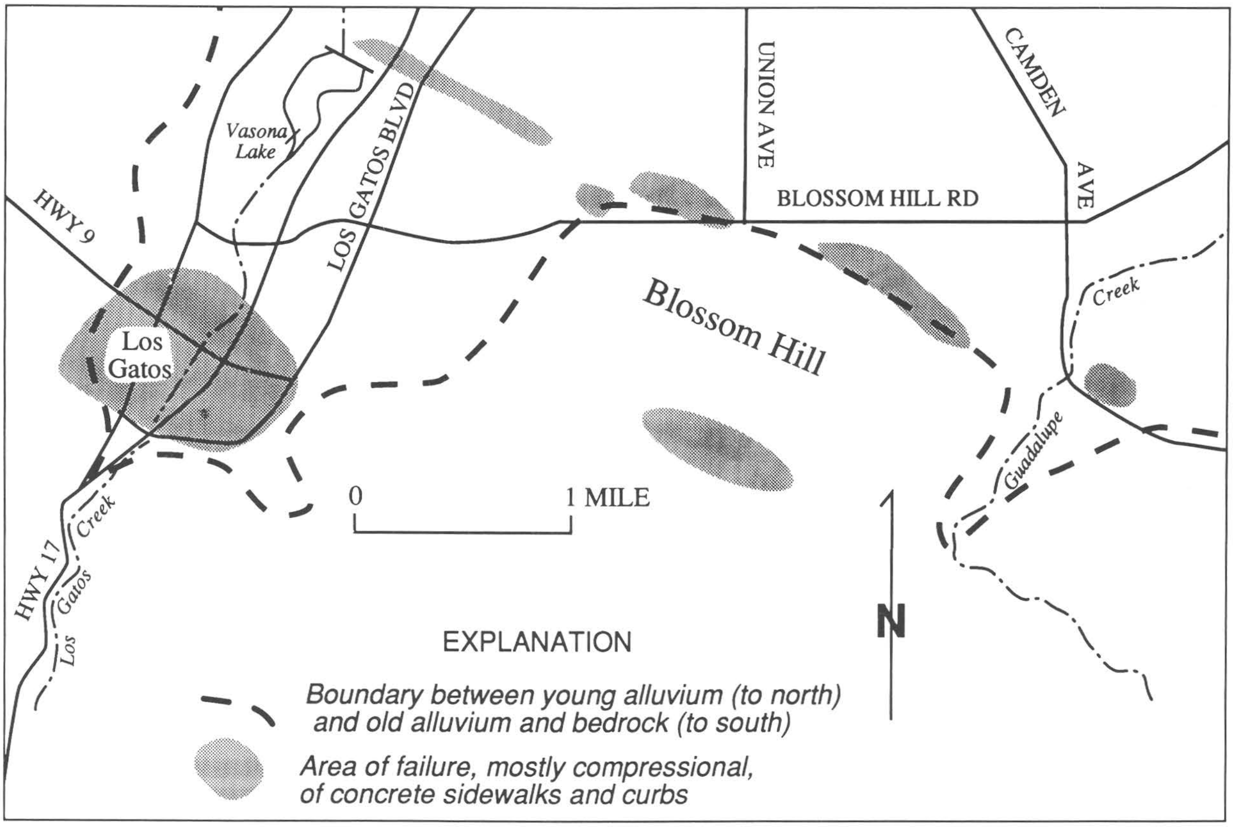


Figure 14. Areas of ground cracks and compressional deformation in Los Gatos and vicinity.

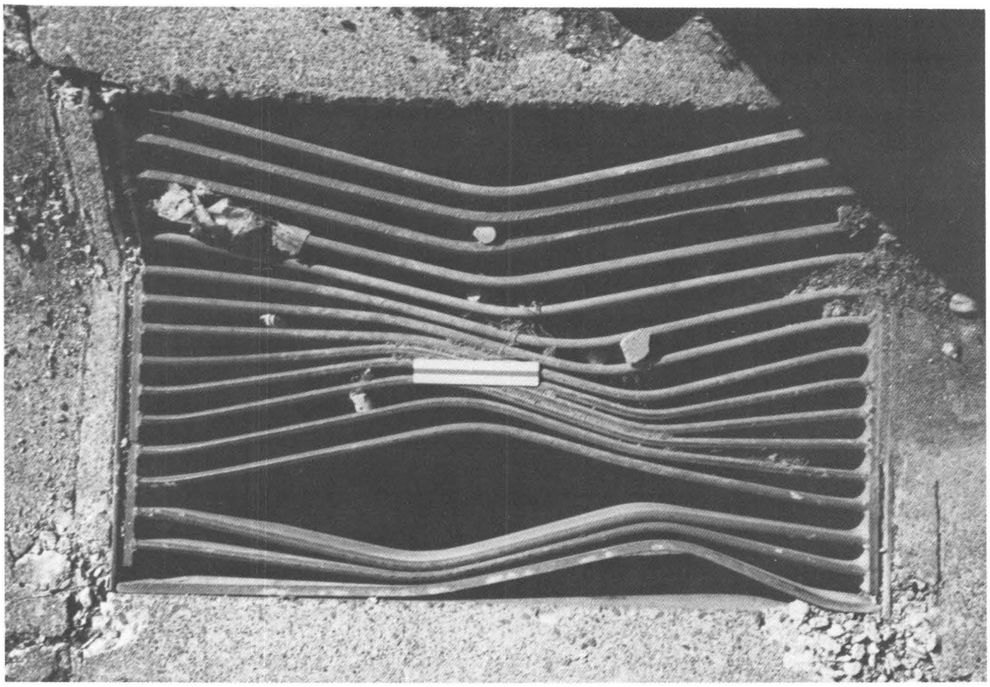


Figure 15. Sewer grate in Los Gatos showing effects of compression perpendicular to long direction of grate. Ruler is about 6 inches long.

trending streets throughout much of the downtown area (fig. 14). Broken concrete slabs lining Los Gatos Creek indicate about 10 inches of northeast-southwest compression.

Two miles to the northeast of Los Gatos, starting near Vasona Dam, a 3.7-mile-long, east-southeast-trending zone of freshly broken concrete sidewalks and curbs defines a similar zone of compression.

Pavement also broke in places along and near Interstate 280 as far northwest as Page Mill Road in Palo Alto. Some of these ruptures were at or near localities of isolated damage in areas that were otherwise relatively undamaged.

The cause of the relatively more intense damage to buildings along the northeastern foot of the Santa Cruz Mountains from Blossom Hill to Los Altos Hills, including Los Gatos, is uncertain. The distribution and nature of the surface deformation, especially the regional compressional features in Los Gatos and vicinity (fig. 15), suggest that they may be related to small secondary movement on one or more of the southwest-dipping thrust faults that parallel the Santa Cruz Mountain front in this area (fig. 1). Known faults include the Berrocal and Stanford faults (McLaughlin, 1974; Jennings, 1975); there may well be others in this area of generally poor exposure. Slip on a thrust fault at shallow depth, possibly triggered by the mainshock, would move the southwest block upward and northeastward along the dipping fault plane with resulting warping, cracking, and northeast-southwest compression of the surface and high intensity of shaking. Ongoing geologic studies, resurveys of geodetic control points, and a detailed analysis of the aftershocks in this region should resolve the origin of these enigmatic, but destructive, surface ruptures.

GROUND SHAKING

Seismic shaking at a given site from an earthquake is a complex function of distance to the earthquake source, size of the earthquake, and the type and thickness of the geologic materials that underlie the site (for instance, rock or unconsolidated deposits). Qualitative data on shaking intensity can be evaluated from observations of the effects on objects, buildings, and the ground as well as from eyewitness accounts using the modified Mercalli (MM) intensity scale. Because earthquake effects are pervasive, intensities can be ascribed to all localities within the region disturbed by the earthquake. In contrast, instrumental records of shaking are available only from those sites where accelerographs are located and thus from limited areas within the disturbed region. Quantitative records of the horizontal and vertical components of ground motion during large earthquakes are obtained with a special low-sensitivity seismograph (accelerograph). Understanding the response of the ground to strong shaking of the underlying bedrock is essential to reducing earthquake hazards in general and to the earthquake-resistant design of critical structures in particular.

SHAKING INTENSITY

A preliminary assessment of the regional distribution of modified Mercalli intensity resulting from the Loma Prieta earthquake is shown on figure 16. Except for the MM VI assessments in Brentwood, Banta, Manteca, and Vernalis, the evaluations are based on primary observations and data collected by the field parties. A secondary source of information for the above locations was early responses to a mail survey of postmasters, police, and fire departments routinely conducted by the National Earthquake Information Center following significant earthquakes.

The modified Mercalli (MM) intensity scale subjectively groups observations on earthquake effects into similar qualitative levels of shaking and then ranks the shaking levels into ascending order I through XII (table 1). Ground failure phenomena such as landsliding, sand blows, and liquefaction are generally relegated to MM level IX and higher. However, research and observations since the scale was developed shows that such effects can occur at lower shaking levels depending on a number of physical properties of the surficial materials, such as water content, permeability, and degree of consolidation, and on the slope angles of hillsides and bluffs. Therefore, MM intensity has been assessed on shaking damage to

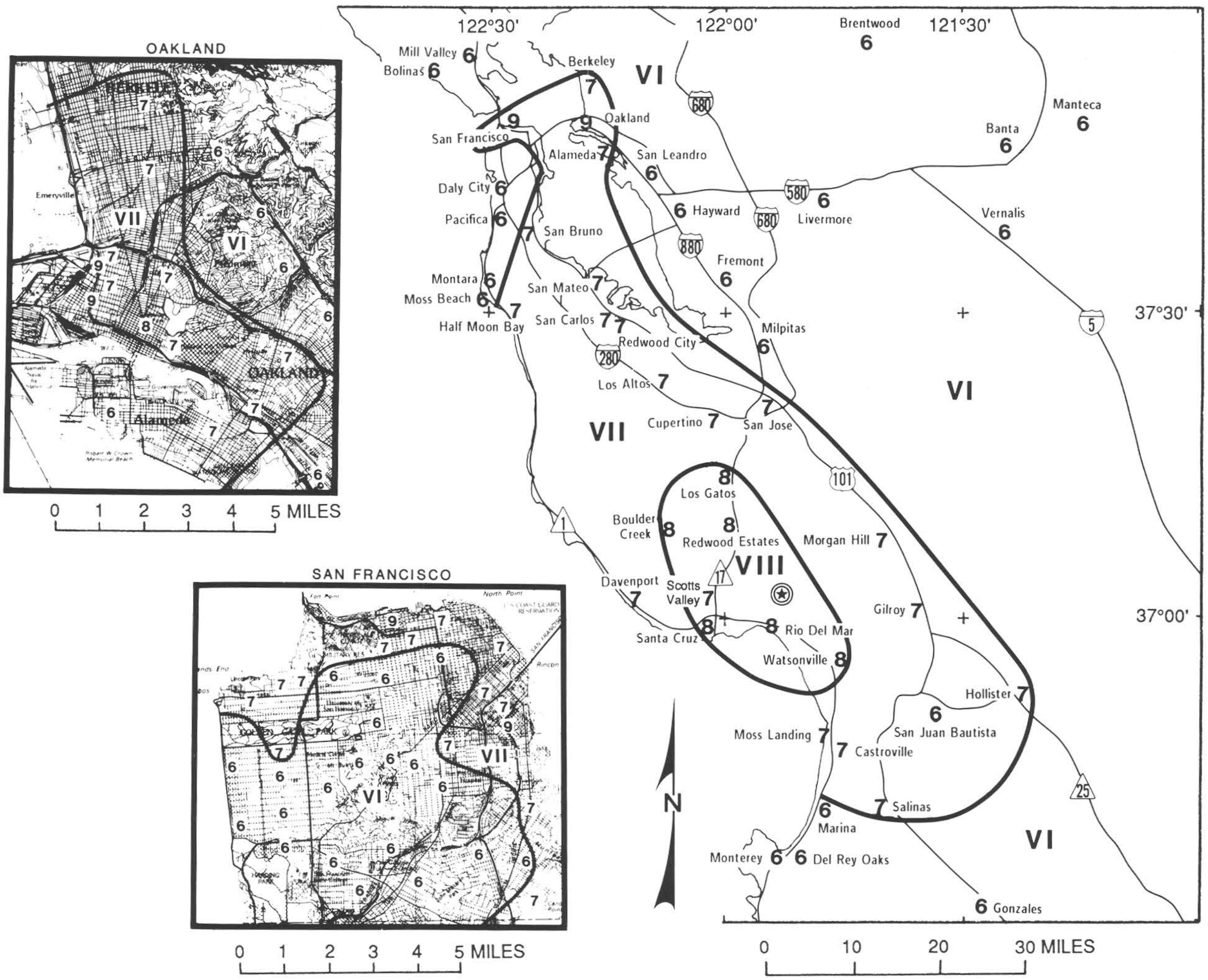


Figure 16. Preliminary map showing distribution of modified Mercalli intensity for Loma Prieta earthquake. Numbers indicate intensity values for localities where observations were made; Roman numerals represent intensity level between isoseismical lines. Location of mainshock epicenter is shown by circled star. Insets show more detailed assessments in cities of San Francisco and Oakland. See table 1 for descriptions of intensity levels.

Table 1. Modified Mercalli intensity scale

[The modified Mercalli scale measures the intensity of ground shaking as determined from observations of an earthquake's effect on people, structures, and the Earth's surface. This scale assigns to an earthquake event a Roman numeral from I to XII as follows:]

I	Not felt by people, except rarely under especially favorable circumstances.
II	Felt indoors only by persons at rest, especially on upper floors. Some hanging objects may swing.
III	Felt indoors by several. Hanging objects may swing slightly. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake.
IV	Felt indoors by many, outdoors by few. Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a heavy ball striking the walls. Standing automobiles rock. Windows, dishes, doors rattle. Wooden walls and frame may creak.
V	Felt indoors and outdoors by nearly everyone; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset; some dishes and glassware broken. Doors swing; shutters, pictures move. Pendulum clocks stop, start, change rate. Swaying of tall trees and poles sometimes noticed.
VI	Felt by all. Damage slight. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knickknacks and books fall off shelves; pictures off walls. Furniture moved or overturned. Weak plaster and masonry cracked.
VII	Difficult to stand. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary buildings; considerable in badly designed or poorly built buildings. Noticed by drivers of automobiles. Hanging objects quiver. Furniture broken. Weak chimneys broken. Damage to masonry; fall of plaster, loose bricks, stones, tiles, and unbraced parapets. Small slides and caving in along sand or gravel banks. Large bells ring.
VIII	People frightened. Damage slight in specially designed structures; considerable in ordinary substantial buildings, partial collapse; great in poorly built structures. Steering of automobiles affected. Damage or partial collapse to some masonry and stucco. Failure of some chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed pilings broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.
IX	General panic. Damage considerable in specially designed structures; great in substantial buildings, with some collapse. General damage to foundations; frame structures, if not bolted, shifted off foundations and thrown out of plumb. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground; liquefaction.
X	Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Landslides on river banks and steep slopes considerable. Water splashed onto banks of canals, rivers, lakes. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.
XI	Few, if any masonry structures remain standing. Bridges destroyed. Broad fissures in ground; earth slumps and landslides widespread. Underground pipelines completely out of service. Rails bent greatly.
XII	Damage nearly total. Waves seen on ground surfaces. Large rock masses displaced. Lines of sight and level distorted. Objects thrown upward into the air.

buildings and structures but intensities have not been assigned to sites of ground failure effects. This distinction becomes futile, however, where structural damage from ground failure and shaking are inextricably mixed, as was the case for certain structures located in the communities of Redwood Estates, Santa Cruz, and the Marina district of San Francisco. In these cases, the behavior of nearby buildings and other structures (such as water towers and telephone poles) apparently not influenced by local ground failure effects were used to corroborate our overall assessments. Damage resulting from the amplification of ground motion by surficial geologic materials and local topography is legitimately classed as shaking damage to the structures.

Though the intensity of the earthquake is tentatively rated to be MM VIII based on substantial damage to wood-framed dwellings and unreinforced masonry buildings in communities near the epicenter, the highest intensity levels (MM IX) are assigned to isolated sites in San Francisco and Oakland. The collapse of the elevated portion of Interstate 880 in Oakland and the considerable damage to Interstate 280 in San Francisco warrant MM IX. Both of the reinforced concrete freeway structures were built under seismic design requirements of the then-existing building codes. The Marina district in northern San Francisco also is assigned MM IX. Ground failure and shaking both played an apparent role in some apartment collapses in the district. However, other collapses occurred in areas of no apparent ground failure. The collapse and widespread structural damage to these substantial buildings is reason for the tentative MM IX assignment to the Marina district.

In all of the above areas, amplification of shaking on landfill and weak young deposits may have contributed significantly to the observed damage. Intensity levels in eastern and northern San Francisco underlain by alluvium and bay mud exhibit intensity levels one to three units higher than other areas of the city. Intensity levels in the extreme western margin of San Francisco, which also lies on thick sediments, are no higher than in the central area (fig. 16).

The maximum intensity assigned to the earthquake source region will be reevaluated as more reports of shaking effects from the sparsely populated southern Santa Cruz Mountains are analyzed. Severe shaking was reported in the Summit Road area south of Highway 17.

Many large trees had their tops broken off due to strong shaking. Residents reported the displacement of all household furniture by several feet, including one built-in oven that was ejected from its cabinet. Four residents, at three different locations, described being thrown through the air several feet by "explosion-like" forces. These three locations are situated on a narrow ridge where topography could have amplified the shaking.

A qualitative comparison of the Mercalli intensities from the Loma Prieta earthquake and those from the great 1906 earthquake clearly shows the much higher levels of shaking in 1906, particularly along the north Peninsula segment of the San Andreas fault and around the margins of San Francisco Bay. Direct comparisons are hampered by the fact that the 1906 damage was described in a different intensity scale which has to be converted to Mercalli intensity (J.F. Evernden, written commun., 1989; Borcherdt, 1975). For both earthquakes, intensity levels are comparable in the southern Santa Cruz Mountains and Monterey Bay region, areas closest to the source of the Loma Prieta earthquake. For the 1906 earthquake the equivalent MM VIII zone, centered on the San Andreas fault rupture, extends northward to the coast in an area that mainly was MM VII in 1989. Major differences, however, are apparent around the margins of San Francisco Bay, where there was a broad zone of equivalent MM VIII–X in 1906, mainly in areas of bay mud; these same areas in the Loma Prieta earthquake experienced intensity levels of only MM VI–VII, except for local pockets of MM IX in San Francisco and Oakland.

GROUND ACCELERATION

Instrumental records of the ground shaking from the Loma Prieta earthquake were obtained at more than 100

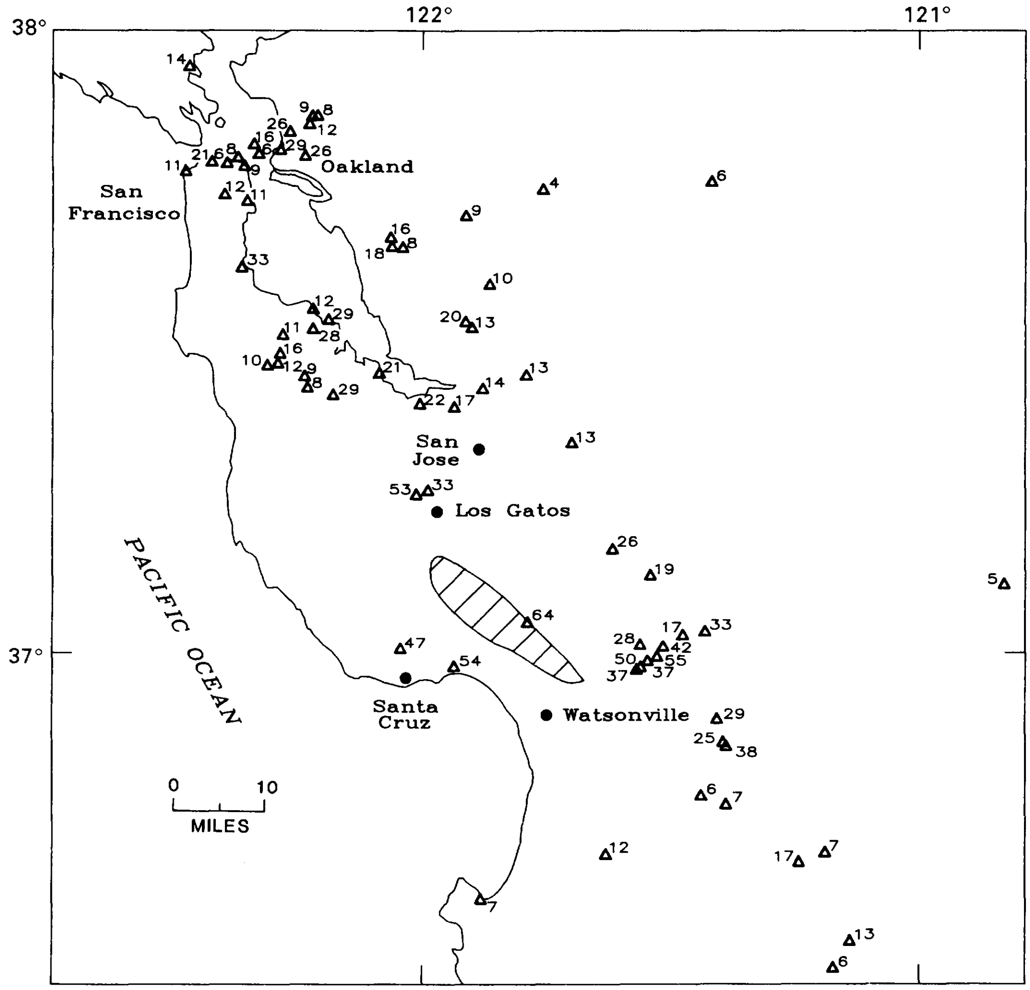


Figure 17. Free-field, peak horizontal acceleration, in percent gravity (32 feet per second per second), of ground motion during Loma Prieta earthquake measured from stations shown by triangles. Value plotted is larger peak acceleration of the two horizontal components of motion; vectorial peak motion would be even larger. Lined region is fault plane of mainshock projected to Earth's surface.

sites within 120 miles of the epicenter by accelerographs maintained by several agencies and groups, principally the California Division of Mines and Geology and the U.S. Geological Survey. For all practical purposes, the amplitudes of recorded earthquake motions are directly proportional to acceleration; this allows the peak acceleration to be rapidly obtained and analyzed. A map of peak horizontal accelerations, expressed in percent of gravity (fig. 17), shows that a station on the uplifted block within the focal region recorded 64 percent gravity a few miles south of the Summit Road area, where extremely hard shaking was inferred from damage and eyewitness accounts. Very high accelerations (47 to 55 percent gravity) were recorded at several localities within 12.5 miles of the focal region on both the relatively upthrown and downthrown sides of the San Andreas fault.

In several areas, the peak motions varied considerably over short distances (fig. 18). As an example, motions near Oakland range from 8 to 29 percent of gravity. These variations are almost certainly due to local changes in the geologic materials underlying the recording sites. In the Oakland area, two of the three highest values come from sites underlain by bay mud, the other high value is from a site underlain by alluvium, and the low values come from sites underlain by bedrock.

If all sites were underlain by similar materials, we would expect a map of peak ground motion to show a generally uniform decrease of motion with distance. Because of the masking effect of geologic variations, however, it is difficult to see the attenuation of peak acceleration from studying the map alone. This problem can be overcome by plotting the motions as a function of distance from the fault, after separating the recordings into three categories depending on the geologic materials underlying the recording sites. Such a plot is shown in figure 18, in which the equation of Joyner and Boore (1988) for the ground acceleration as a function of distance and magnitude serves as a convenient measure of the ground shaking of the Loma Prieta earthquake. The Joyner and Boore equation is widely used and is based on data from many past earthquakes.

As shown in figure 18, the accelerations from rock sites are in reasonable agreement with the predictions. Although there is considerable scatter in the data, which is an inherent feature of representing a complex physical process by a single number, the points cluster about the expected value (solid curve). The recordings at soil sites as a group are systematically greater than the predictions for rock sites, with the accelerations at bay mud sites much larger than those from most of the alluvium sites. Relative to rock sites, ground-motion records obtained on young, poorly consolidated, water-saturated alluvial deposits and bay mud tend to be deficient in high-frequency amplitudes and enriched in lower frequency motion, the frequency-dependent amplification being a function of rigidity contrasts in the local geology and basin geometry. The effect of local geologic conditions is shown in figure 19, where the record from 1295 Shafter Street in San Francisco is the only one written at a hard rock site. The Emeryville and 575 Market Street records

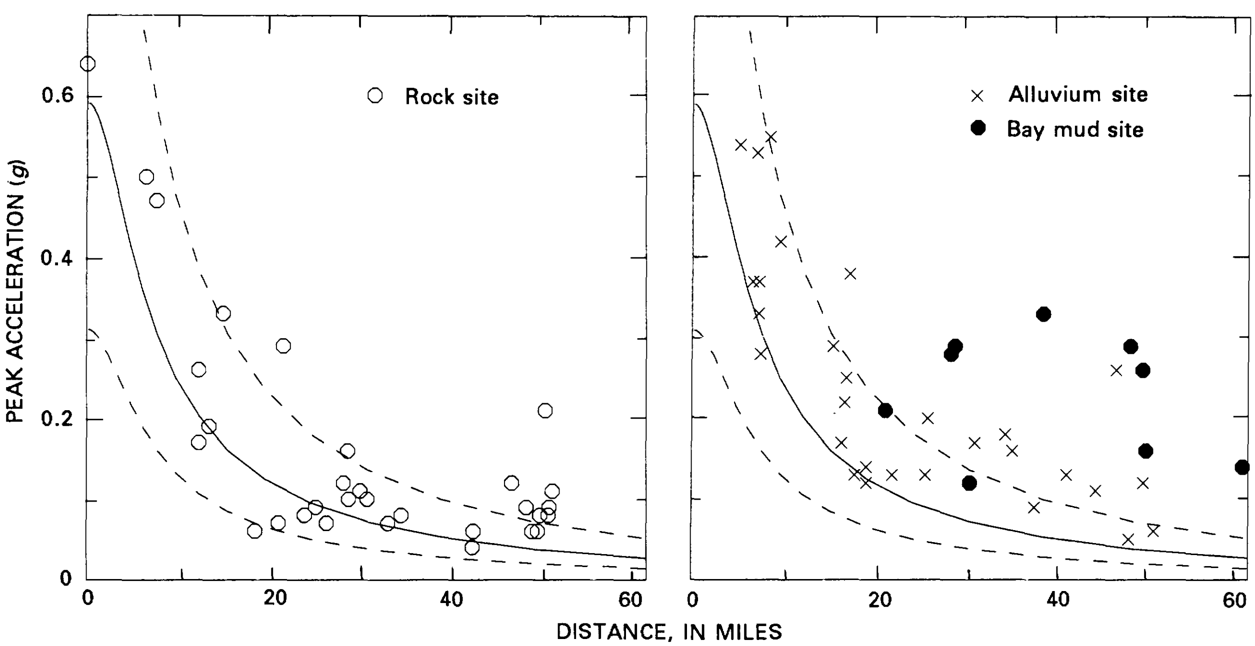


Figure 18. Peak horizontal accelerations of different geologic materials during Loma Prieta earthquake plotted as a function of closest distance from recording station to surface projection of fault (shown in fig. 17). Solid line is prediction of Joyner and Boore (1988); dashed lines indicate expected variation in individual observations. About two-thirds of observations should theoretically lie between dashed lines.

are from sites underlain by bay mud and dune sands, respectively. The Foster City and Redwood City records are both from areas of engineered artificial fill overlying bay muds, fill that performed well during the Loma Prieta earthquake.

The influence of the local geologic deposits on the amplitudes of the ground shaking and the extent of damage come as no surprise. Shortly after the 1906 San Francisco earthquake, H.O. Wood (1908) wrote "* * * the amount of damage produced by the

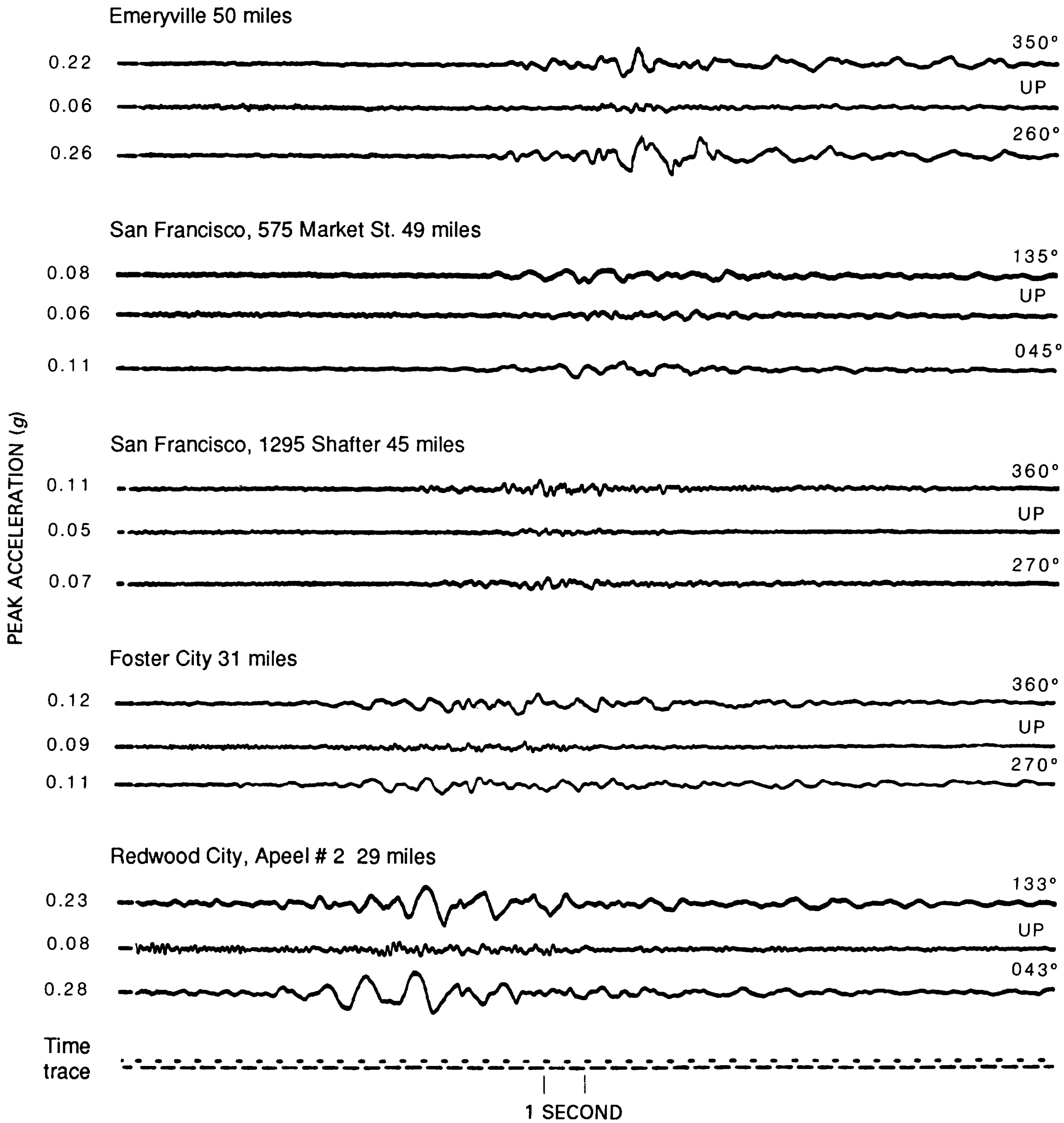


Figure 19. Three-component accelerograms from five stations, showing large difference in trace amplitudes between bedrock (1295 Shafter) and unconsolidated deposits (other sites). Stations arranged in order of decreasing distance from fault plane of mainshock. Directions of ground acceleration for upward trace motion are given above each trace, and peak accelerations scaled from records are given to left of each trace. Short raised lines of time trace occur every 0.5 s.

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 * * * ." During the late 1960's and early 1970's, instrumental recordings of local earthquakes and distant nuclear explosions were made at many tens of sites in and around the San Francisco Bay area to quantify spectral amplification ratios and resonant periods for these various geologic units relative to bedrock in this region.

Combined seismic and explosion data show that ground-motion amplitudes on firm alluvium can be amplified by factors of 2 to 4 in the frequency band of several seconds to several cycles per second, the frequency band of greatest engineering interest (Borcherdt, 1970). Similarly, amplification factors for the softer bay muds and artificial fill can be 5 to 10 and in some cases even more. Historical and instrumental data show that observed patterns of damage and strong ground motion for the Loma Prieta earthquake were both predictable and predicted (Borcherdt, 1975).

LANDSLIDES

Strong ground motions during the Loma Prieta earthquake triggered thousands of landslides throughout an area of 5,400 square miles. This region encompasses most of the San Francisco Bay area, the Santa Cruz-Monterey Bay area, adjacent parts of the California Coast Ranges, and the Big Sur coastline as far as 81 miles south of the epicenter (fig. 1). In addition to causing at least tens of millions of dollars of damage to houses, other structures, and utilities, landslides blocked many

Figure 20. Aerial photograph of rock slide near summit of Santa Cruz Mountains that has an estimated volume of 6,000 to 10,000 cubic yards. Slide nearly completely blocked northbound lanes of Highway 17 that links Santa Cruz and surrounding coastal area with San Francisco Bay region. This highway, which carried an estimated tens of thousands of commuters per day before Loma Prieta earthquake, was closed for more than 1 month for repairs.

transportation routes (fig. 20), thus greatly hampering rescue and relief efforts.

Landslides were most numerous around the earthquake source in the steep, rugged, and heavily vegetated Santa Cruz Mountains (fig. 1). These mountains, which receive as much as 60 inches of mean annual precipitation (Rantz, 1971), have historically produced abundant landslides both during earthquakes (Lawson and others, 1908) and during heavy winter rains (Keefer and others, 1987; Ellen and Wieczorek, 1988). Landslides were abundant during the Loma Prieta earthquake despite its occurrence after two dry years and at the end of the dry season during which only about 2 inches of rain had fallen in 5 months.

Landslides triggered during the earthquake included many types of downslope and lateral movements of the ground. The most common landslides were rock falls, rock slides, and soil slides, all of which were typically shallow (about 10 feet or less) and moved very rapidly down steep slopes, producing chaotic deposits of boulders and finer grained material (fig. 21). Most of these deposits have volumes of less than 100 cubic yards but several have volumes in the range of 1,000 to 10,000 cubic yards, and at least one has a volume of more than 52,000 cubic yards. Such landslides killed at least two people during the earthquake. Weakly cemented, deeply weathered, or intensely fractured rock materials exposed in roadcuts, near-vertical mountain cliffs, and coastal bluffs were especially prone to landslides of these types, as previous studies had predicted (Keefer, 1984).

Deeper seated (commonly 10 to 100 feet deep), slower moving blocks of ground also detached in hundreds of places during the earthquake to form rotational slumps or translational block slides. These typically moved a few inches or feet during the strong shaking, leaving scarps and cracks in roadways, residences, and other structures, and in natural ground (fig. 22). Slumps were especially common in manmade fill and thus were a source of significant and continuing disruption of roads in the heavily shaken region. Road fill had also been identified as a major potential source of such failures during previous studies (Keefer, 1984). At least some of the slumps and block slides showed evidence of continuing or renewed movement as a result of as much as 6 inches of rain that fell in the 10 days following the earthquake. Both existing slide blocks and adjacent slopes weakened by cracking, and removal of support are likely to be continuing hazards during large aftershocks or winter rains. The largest slump or block slide yet identified, located in the Santa Cruz Mountains near the

Figure 21. Small rock-fall deposit at roadcut, typical of those caused throughout Santa Cruz Mountains by Loma Prieta earthquake.

community of Laurel, encompasses more than 185 acres. This landslide contains within its borders several dozen houses, many of which have sustained substantial damage.

Other types of landslides associated with the earthquake include at least one very fluid mudflow (generated by increased flow from a spring that saturated hillside materials) and numerous lateral spreading failures in nearly flat lowland areas, which are discussed below in the section "Liquefaction and Related Effects."

LIQUEFACTION AND RELATED EFFECTS

Liquefaction, the transformation of loose saturated sandy material into a fluidlike condition, locally caused substantial damage to structures over a widespread area during the Loma Prieta earthquake (fig. 1). Particularly hard hit in the San Francisco Bay area were developments on manmade artificial sandy fills in San Francisco and Oakland. These areas included the Marina district and the area south of Market Street in San Francisco, the Oakland International Airport and port facility, the Alameda Naval Air Station, and Treasure Island. Elsewhere, damage caused by liquefaction was primarily in natural sediments. Most of this damage was south of the epicentral area in the flood plains of the Pajaro, San Benito, and Salinas Rivers and near the mouth of the San Lorenzo River in Santa Cruz. No liquefaction was noted either in the southern bay area in areas that liquefied in 1906 or at the extensive Foster City and Redwood Shores developments, which are built on engineered landfill over bay mud.

Damage from liquefaction results primarily from large horizontal and vertical displacements of the ground. These displacements occur because sands in a liquefied condition have virtually no strength and provide little or no resistance to compaction, lateral spreading, or downslope movement. Thus, ground on even the gentlest slopes can move toward free faces (or bluffs) such as shorelines, river banks, and manmade cuts. In addition to the downslope displacements, the ground above liquefied sediment commonly breaks into small blocks which may tilt and cause vertical displacements between adjacent blocks. This permanent movement of the land surface, known as lateral spreading (fig. 23), can be devastating to surface structures such as buildings, bridges, and river levees, as well as to buried underground utilities such as gas pipelines, water lines, and sewers.

SAN FRANCISCO AREA

The most intense damage from liquefaction occurred in the Marina district and in several multiblock areas south of Market Street, all of which were 50 miles or more from the closest part of the earthquake rupture zone. Many structures, including private residences, were damaged or destroyed (fig. 24). Although strong ground motion and vulnerable building design also may have contributed directly to damage in the Marina district, sand boils, which erupted into basements, streets, yards, and parks, and lateral spreading cracks demonstrate that liquefaction was widespread (figs. 25, 26). Presumably, most of the broken underground utilities, which left about a thousand homes without gas or water after the earthquake, were severed by movements associated with lateral spreading. One of the ironies of the devastation in the Marina district is that the heavily damaged part rests on fine sand fill that was hydraulically emplaced after the 1906 earthquake. Debris from buildings destroyed in 1906 may have been used as landfill also. This filled lagoon, where the district now stands, was the site of the International Exposition to celebrate San Francisco's postearthquake rejuvenation. On October 17, 1989, sand boils in the district erupted pieces of buried charred redwood, tar paper, and other debris in a poignant reminder of the city's earthquake history.

Aftershock data shed some light on the problem of whether damage in the Marina district was due to strong shaking or to foundation failure related to permanent deformation within the artificial fill. This is shown in figure 27, where seismograms of a magnitude 4.6 aftershock are shown at three sites. The top trace is from a station at Fort Mason (MAS), underlain by a competent sandstone member of the Franciscan assemblage. The middle trace is from a site underlain by clean dune sand just onshore of the pre-fill shoreline, near the eastern edge of the Marina district (PUC). Significantly, the structure here is a two-story brick building with a massive turret on its northwest corner, the San Francisco Gas and Light building constructed in 1893. This is not the sort of construction that performs well during strong shaking, yet it rode through the recent earthquake without a crack—and the great 1906 earthquake as well. The lower trace is from a site just $1^1/_2$ blocks away within the area covered by Marina bay fill (LMS). Here, houses are badly deformed by foundation failure, the north side of the street is now 1.6 feet lower than the south side. Both the LMS and PUC sites are amplified by comparable amounts relative to Fort Mason, but the local damage patterns are grossly different. This suggests that the problems in the Marina district are fundamentally due to permanent deformation of the manmade fill by liquefaction and are not the result of local amplification differences within the Marina district.

EAST BAY AREA

Substantial damage along the eastern margin of San Francisco Bay also occurred in areas underlain by sandy fill. Costly damage at the port facilities was due to compaction and lateral spreading of wharves. Sand boils erupted onto and around the major runway at Oakland

International Airport, and lateral spreading damaged the northern third of the runway (fig. 28). Liquefaction also occurred on Interstate 80 at the Bay Bridge toll plaza and the Alameda Naval Air Station, as shown by sand boils, ground cracks, and differential settlement of fill.

MONTEREY BAY AREA

Liquefaction-related ground failure was widespread from Santa Cruz to near Salinas in areas underlain by saturated late Holocene unconsolidated deposits of the

A

Figure 22. Scarps and cracks associated with movement of deep-seated slumps. *A*, Scarp at head of block slide in residential area of Brookdale in Santa Cruz Mountains. Block slide moved approximately 1.5 feet downslope (to right). Part of house to left of scarp remained on undisturbed ground while part to right moved downslope on slide block. Notebook on scarp is 8×10.5 inches. *B*, Home destroyed by landslide movement. Note cracks, from internal fissuring of landslide block, in pavement. Part of house on right has separated from part on left and tilted downslope as a result of differential movement within landslide block.

B

Figure 22. Continued.

San Lorenzo, Pajaro, and Salinas Rivers and spits, bars, and tidal channels along the coast. Liquefaction destroyed or disrupted flood-control levees, pipelines, bridge approaches, abutments and piers, roads, homes and utilities, and irrigation works, including gradients of irrigation ditches and irrigated fields (fig. 29).

Liquefaction began with the main shock, but several eye-witness accounts reported reactivation of sand boils during at least one aftershock. Liquefaction occurred primarily in geologically young deposits less than about 5,000 years old (late Holocene) and in present floodplain areas of coastal basins within 160 to 550 feet of the principal streamcourses. These areas are distinguished geologically by the presence of silt and sand and by the presence of shallow ground water. Lateral spreads caused displacements ranging from fractions of an inch to about 6.5 feet. The most widespread damage was to levees of the Pajaro and San Lorenzo Rivers, which suffered cracking due to differential settlements and small translational displacements at many locations of liquefaction.

Late Holocene river channels, now filled with fine sand and silt, proved to be especially prone to compaction. One zone of compaction that locally amounts to more than 1.5 feet across a zone tens to hundreds of feet in width extends in a meandering path for distances of up to about 1.2 miles through the town of Pajaro east of Watsonville. It is marked at the surface by a line of condemned structures, sand boils, low scarps, disrupted gradients in irrigated fields, and the damaged east abutment of the Main Street Bridge in Watsonville.

COMPARISON WITH 1906

Damage associated with liquefaction during the Loma Prieta earthquake comes as no surprise and should serve as a reminder of the consequences of building on loose saturated sands. Many of the areas that experienced liquefaction and unusually severe shaking damage in 1989 are known to have experienced ground failure in 1906 (Lawson and others, 1908; Youd and Hoose, 1978). This observation clearly demonstrates that liquefaction can affect the same areas in successive earthquakes. Areas of saturated sandy fill in San Francisco that failed in 1906 damaged the same types of structures and underground utilities that were damaged in 1989. In fact, Seawthorn and O'Rourke (1989) have documented how the fire that destroyed much of the Market Street area in 1906 raged out of control because watermains had been severed by lateral spreading. Again in 1989, the fires in the Marina district could not be fought with city water because of failed watermains. Fortunately there was no wind at the time and water could be pumped to the fire by a fireboat; otherwise the fire might have spread out of control. Similarly, liquefaction in the flood plains south of the epicentral area was anticipated. Maps of 1906 liquefaction areas outline the same areas that liquefied in 1989. In addition, maps showing the geology and relative susceptibility to liquefaction of parts of Santa Cruz and Monterey Counties, prepared about a decade ago by U.S. Geological Survey geologists (Dupré, 1975; Dupré and Tinsley, 1980), clearly distinguish those areas that experienced liquefaction-related ground failure in 1989 from those areas that did not.

DAMAGE TO BUILDINGS, TRANSPORTATION ROUTES, AND UTILITIES

The Loma Prieta earthquake is the first large seismic event to provide a real test for earthquake-resistant construction of buildings, transportation facilities, utilities, and communications systems in California and the San Francisco Bay area. Although the majority of facilities performed well, many failed the test. Of particular concern is the damage or failure of critical facilities at great distances from the earthquake source, such as those in San Francisco and Oakland. There are no major high-rise buildings, bridges, or freeway overpasses within about 7 miles of the mainshock rupture, and few within 15 or 20 miles of where the ground shaking was most violent; hence, this earthquake provided only a limited test for these types of structures.

Figure 23. Lateral spreading along Pajaro River banks due to liquefaction.

Comprehensive studies are underway by many groups into the causes of structural failures. The mainshock provided numerous accelerograms from strong-motion instruments that were emplaced in a variety of major structures throughout the San Francisco Bay region. When analyzed, these recordings will provide invaluable information on the response of modern engineered structures to strong shaking. Unfortunately, no accelerographs were installed on some critical structures such as the Bay Bridge and the Cypress structure, as strong-motion records would be invaluable in reconstructing the cause of failure.

The following subsections briefly highlight the more significant aspects of damage to the works of man that are not obviously related to failure of the ground on which they rest. Places referred to are shown on figure 1, unless otherwise indicated.

BUILDINGS

In general, the widespread shaking damage to buildings as far away as San Francisco and Oakland, about 50 miles from the closest part of the earthquake rupture zone, is unusual for an earthquake of magnitude 7.1. During the earthquake, no engineered structure built on the basis of the latest codes collapsed. However, there are many engineered structures throughout the earthquake-affected area that sustained damage without collapse, and a number of them are condemned and will have to be demolished. It should be realized that building codes aim to reduce, not prevent, damage to structures during the most severe shaking likely to occur in a region.

Wood-framed single-family dwellings on solid ground outside the epicentral region generally came through the earthquake without structural damage, although many lost brick or stone chimneys. However, in many areas that were subjected to extremely strong ground motions close to the earthquake source zone, even newer homes built to code had serious failures, mainly by shearing of the structure off its foundation supports. In Santa Cruz, Watsonville, Hollister, and Los Gatos, residential homes and older business buildings in downtown areas were severely damaged—some collapsed and others are beyond repair. Most of these buildings were older structures vulnerable because of one or more of the following reasons: (1) deterioration of structure, (2) lack of ties to foundation, (3) unreinforced masonry (brick or stone), (4) lack of shear resistance in

A

B

Figure 24. Structures damaged in Marina district. *A*, Damage due to ground failure of liquefied land fill. *B*, First story of this three-story building in Marina district was damaged because of liquefaction; second story collapsed. What is seen is third story.

ground floor, (5) pounding of adjacent structures, and (6) timber diaphragms not tied to unreinforced masonry walls, which allowed separation or pushing out of the walls.

In Watsonville, two adjacent buildings of a department store sustained extensive structural damage due to a weak first story, insufficient shear reinforcement of the columns, and possible pounding of the two structures. Recently constructed buildings with tilt-up walls in the area performed well.

Most structures in the southern Santa Clara Valley performed well. An exception in San Jose was damage to the trusses supporting the roof of a crucial machine shop at the FMC Corporation, which caused temporary layoffs of about 500 workers for almost one month until repairs were made.

At the Stanford University campus, 30 miles northwest of the epicenter, 60 buildings sustained varying degrees of damage, with an estimated repair cost of $160 million.

The new, three-winged 5-story Fluor Building in Redwood Shores on filled land about 35 miles from the closest part of the rupture zone had cracks in several of its shear walls. Nearby, the 22-story steel-framed building on fill at Foster City was not damaged.

In downtown San Francisco, modern high-rise buildings to 50 stories escaped without structural damage although several of them had nonstructural damage, and many were not occupied for several days after the earthquake due to loss of electrical power and the need to check for gas leakage. Many of the high-rise buildings are built on fill and bay mud, but their pile footings extend into high-bearing-strength layers at depth. South of Market Street, several buildings between 5 and 10 stories high were damaged. Old masonry buildings were badly damaged, including a four-story warehouse where collapse of exterior walls killed five people in the street. An older, masonry-walled 8-story building on Battery Street was damaged and later demolished.

The concentration of damage to 2- to 4-story homes in the Marina district received much attention. Although much of this damage can be attributed to liquefaction of the hydraulically emplaced silty sand foundation material, there were other contributing factors. Some had a structurally weak first story because the buildings had large garages without sufficient lateral resistance on the ground floor; others, particularly at the corners of the blocks, did not have the benefit of the stiffness and strength provided by adjacent structures on two sides. Notably, there were many nearby 2-story buildings that were not damaged (fig. 24*B*). Many buildings, such as 12-story apartment buildings around Lake Merced and a dormitory (Verducci Hall) on the San Francisco State University campus, came through the earthquake with insignificant structural damage although they sustained serious nonstructural damage.

Figure 25. Extension cracks in Marina district formed by lateral spreading of liquefied sandy landfill.

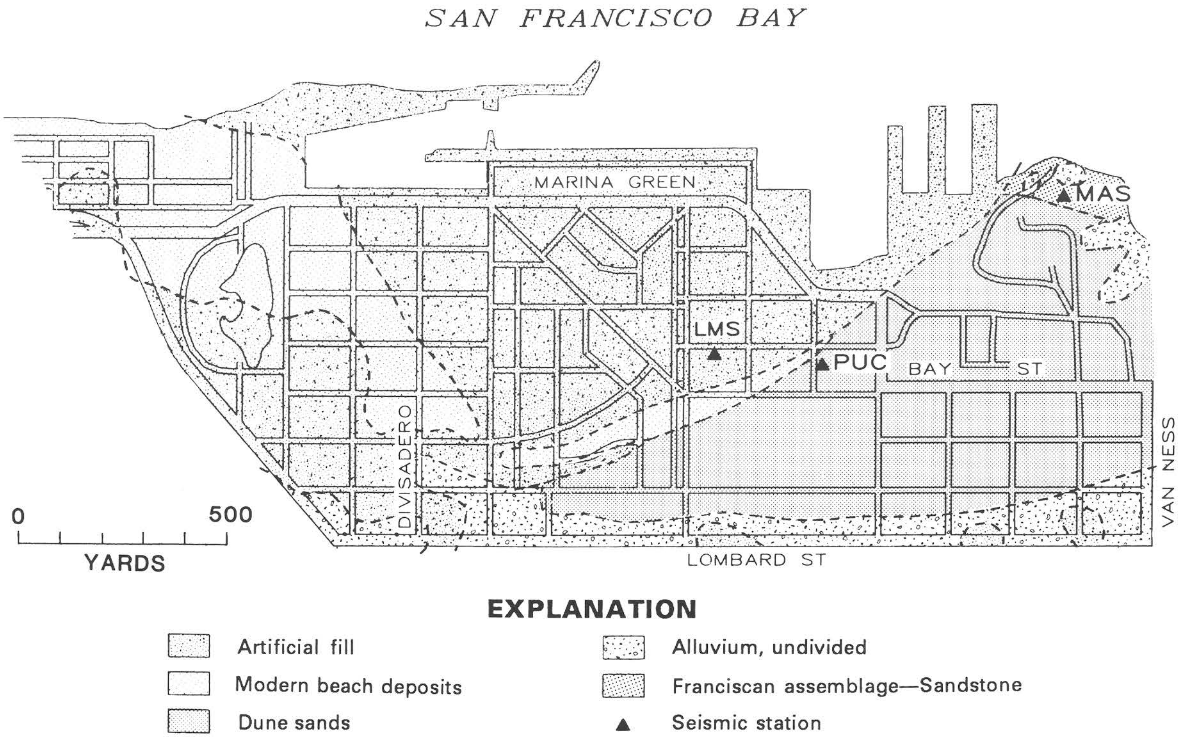
In Oakland, several midrise buildings were heavily damaged. Although none collapsed, some of them will have to be demolished.

BRIDGES, VIADUCTS, AND HIGHWAYS

Of the many arterial bridges in the San Francisco Bay area, only the double-deck Bay Bridge between San Francisco and Oakland was closed to traffic because of the collapse of one span of the upper deck. The cause of the collapse of the span is uncertain but appears to be due to differential lateral displacement of piers during shaking. In addition, many of the approaches to the Bay Bridge were damaged and were closed as of one month after the earthquake.

In Oakland, the Cypress Street viaduct of the Interstate 880 (Nimitz) Freeway is another important arterial structure that collapsed. Almost a 1.5-mile length of the double-decked reinforced-concrete viaduct collapsed onto unusually light commuter traffic, killing 41 people and injuring many others. The disaster may be attributed to the design and construction of the joint between the lower deck and the upper deck columns, to inadequate

Figure 26. Sand boils formed by liquefaction in Marina district.



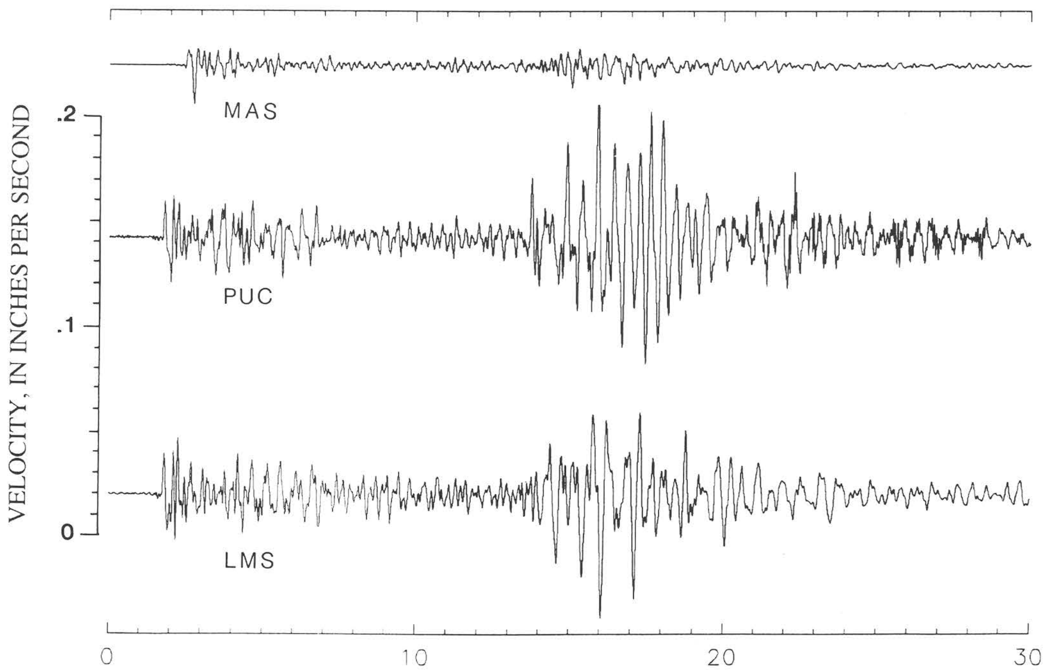


Figure 27. Three temporary seismograph stations in Marina district. *A*, Locations of stations and types of geologic material. *B*, Vertical velocities during a magnitude 4.6 aftershock on October 21, 1989, show amplification of ground motion in both damaged (LMS) and undamaged (PUC) areas in Marina district relative to ground motion on bedrock (MAS). Damage occurred in area underlain by artificial fill.

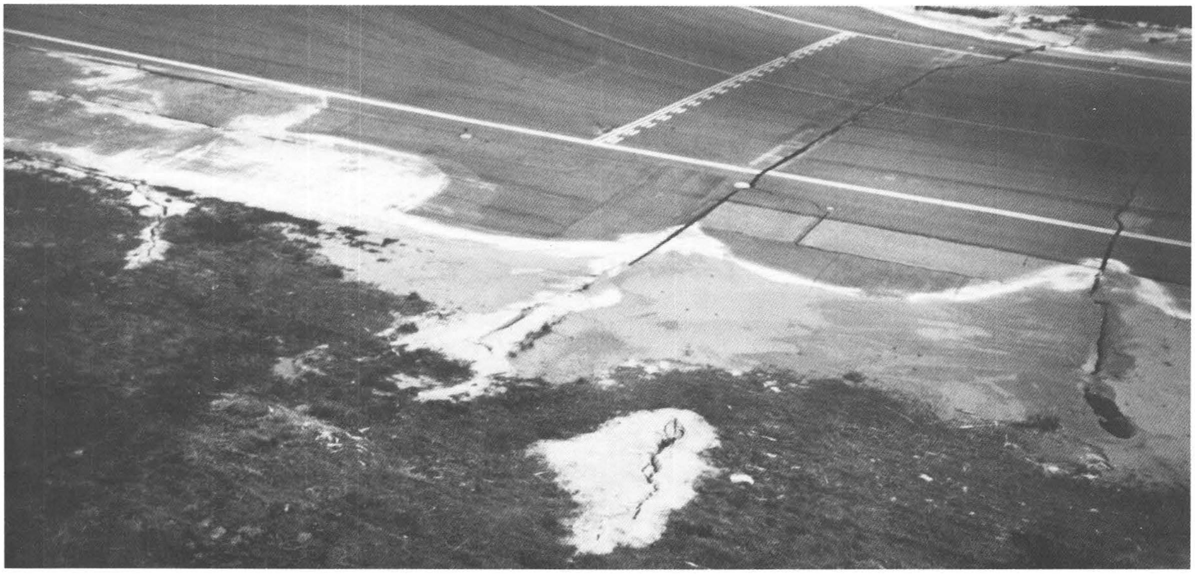


Figure 28. Sand boils at Oakland International Airport.

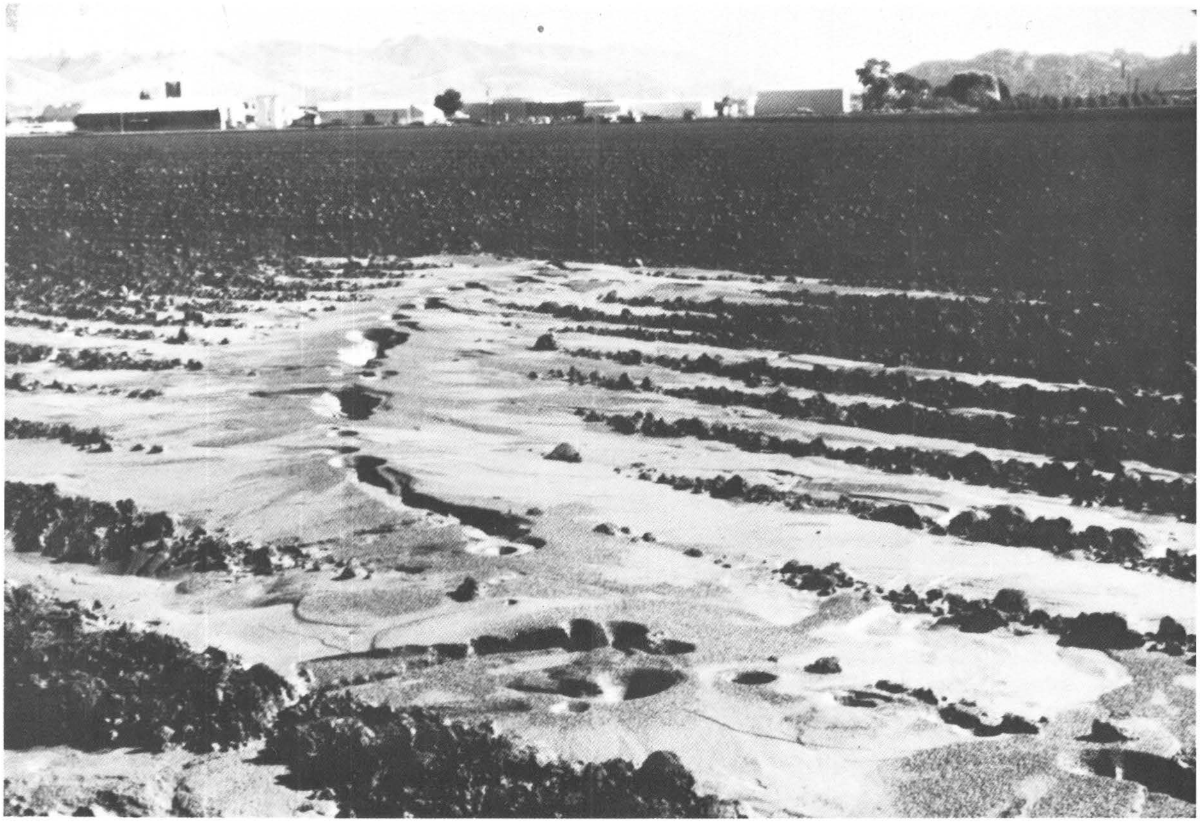


Figure 29. Sand boils in irrigated fields near Hollister.

shear reinforcement of the top end of the columns between the decks, and possibly to amplified ground shaking by local ground conditions (fig. 30). Retrofitting plans prepared prior to the earthquake were not implemented due to a lack of funds.

In San Francisco, three double-decked viaducts (Embarcadero Freeway, Highway 101 at Fell Street, and Interstate 280) were severely damaged and may have to be demolished. Their construction is similar to the Cypress structure, but with continuous column joints between decks.

The San Mateo Bridge was slightly damaged and was closed briefly for inspection and repairs immediately after the earthquake. The closure of this bridge, together with the Bay Bridge, added to the serious disruption of cross-bay traffic.

South of the epicentral area, on Highway 1 at Struve Slough, vertical movement of the concrete bridge deck slabs caused some support columns to punch through the deck with consequent tilting and collapse of the bridge (fig. 31).

Other transportation lifelines, although interrupted for inspection, performed well. The Bay Area Rapid Transit commuter train tunnel, which carries a significant burden of the traffic between San Francisco and Oakland, was not damaged. However, it was inoperative immediately after the earthquake because of power outage and for damage inspections.

AIRFIELDS, PIPELINES, AND STORAGE FACILITIES

San Francisco International Airport was closed to traffic for about 13 hours after the earthquake because of damage to the control tower. Part of a boarding ramp in one of the terminals was damaged, and a poorly designed 2-story structure was so badly damaged it will have to be demolished. There was extensive damage to nonstructural components, including rupture of sprinkler system water lines and collapse of ceilings. As previously discussed, runways at Oakland International Airport and the Alameda Naval Air Station were damaged by liquefaction and lateral spreading.

Damage to two dams within and close to the focal region (fig. 1) was reported by the New Civil Engineer (1989). Fortunately, their reservoirs were nearly empty at the end of the dry season. The 184-foot-high rockfill dam

A

Figure 30. Collapsed Cypress structure on Interstate 880. *A*, Second deck collapsed onto first deck. *B*, Closeup of failed column that supported second deck. Only four 2-in.-diameter, steel reinforcing bars were used in this joint (foreground).

at Lake Elsman was severely cracked and compacted and the spillway was damaged. Deep cracks developed in both shoulders of the dam that impounds Lexington Reservoir near Highway 17. No other dams in the region are known to have been damaged significantly. Peak accelerations at the crest of Anderson Dam (17 miles east-northeast from the epicenter) reached 43 percent of the acceleration of gravity.

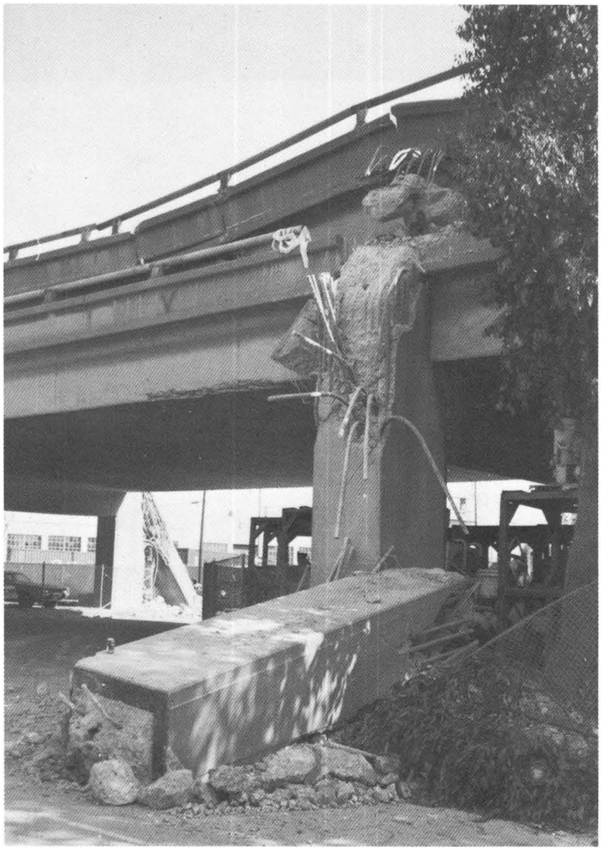
Widespread power outages occurred throughout the region, and some localities were without power for several days. The Moss Landing Pacific Gas and Electric fossil-fuel plant, which supplies much of the region, had damage to its electrical circuit breakers, and there was evidence of subsidence and liquefaction within the plant periphery.

THE POTENTIAL FOR FUTURE LARGE EARTHQUAKES

Without doubt, additional large earthquakes will occur along the major faults in the San Francisco Bay region, just as they have in the past (table 2). Of these faults, the most important are the San Andreas, Hayward, Calaveras, and San Gregorio (fig. 2). A large earthquake relieves stress on the fault segment that slips. Consequently, following an earthquake, the likelihood for another large earthquake on that fault segment is low for many years. However, as the time since the previous large earthquake along a particular fault segment becomes greater, the likelihood of an earthquake on that segment increases. Although the section of the San Andreas fault zone that slipped in the Loma Prieta earthquake is not expected to generate another major earthquake for many years, the Loma Prieta earthquake has not reduced the potential for large earthquakes along other fault segments in the San Francisco Bay area.

For well-studied fault segments, the long-term probabilities for occurrence of earthquakes can be computed. In 1988 a working group consisting of 12 scientists from the U.S. Geological Survey, academia, and private industry issued a report (U.S. Geological Survey, 1988) on the probabilities of large earthquakes on selected faults in coastal California. This report, which was reviewed and approved by the National Earthquake Prediction Evaluation Council, concluded that the segment of the San Andreas fault affected by the Loma Prieta earthquake had a 0.3 probability for a magnitude 6.5 to 7.0 earthquake over the interval 1988–2018. (Probabilities are expressed in numbers that range from 0 to 1, where 1 represents certainty that the event will occur and 0 indicates certainty that the event will not occur. A 0.3 probability corresponds to a 30 percent chance of the earthquake happening.) This was the highest probability the working group assigned to any fault segment in central California. Earlier studies by individual scientists (Lindh, 1983; Sykes and Nishenko, 1984) also concluded that this section of the San Andreas fault had a high probability for a large earthquake. For this fault segment, Lindh (1983) assigned a 0.47 probability for a magnitude 6.5 earthquake in a 30-year period.

Figure 32 shows long-term probabilities for large earthquakes on segments of the Hayward and San Andreas faults in the region, the only two faults for which the data are sufficient to support an estimate. Two sections of the Hayward fault, the northern and the southern segments, have been judged capable of producing magnitude 7 earthquakes comparable to the earthquakes of 1836 and 1868, respectively. The 30-year probability for each of those segments is 0.2. The San Francisco peninsula segment of the San Andreas fault also has a 30-year probability of 0.2 for a magnitude 7 earthquake. Because of the very large fault displacements in the great earthquake of 1906, the section of the San Andreas fault to the north of the San Francisco peninsula segment currently has a low probability for a magnitude 8 earthquake (less than 0.1 in 30 years). The total probability for one or more of the magnitude 7



B

Figure 30. Continued.

earthquakes on the Hayward and San Andreas faults is 0.5 in the next 30 years.

In addition to the San Andreas and Hayward faults, there are several other faults in the region that could produce damaging earthquakes. Consequently, the overall risk of destructive earthquakes in the region may be significantly greater than that posed by the San Andreas fault alone. A partial list of other faults of concern includes the Calaveras, San Gregorio, Concord, Green Valley, Healdsburg-Rodgers Creek faults and a number of poorly known thrust faults such as the Sargent-Berrocal and Stanford faults. Information concerning these faults is presently insufficient to compute probabilistic forecasts of future activity.

REDUCING EARTHQUAKE HAZARDS

The Loma Prieta earthquake amply illustrates that large earthquakes can seriously impact society and the Nation. To confront this problem, significant steps have been taken over the the last decade or two to help mitigate earthquake hazards (see appendix 2). With these steps substantial progress has been made toward better construction practice, improved building codes, identifying and strengthening dangerous structures, earthquake forecasting, mapping and evaluating earthquake-related geologic hazards, and better emergency preparedness and disaster response planning. However, important questions to be asked from an earth science perspective in the wake of the Loma Prieta experience are "Are the measures developed on the basis of the earth sciences sufficient? Are they being implemented? If not, what additional steps are needed to encourage active programs to reduce earthquake hazards in the San Francisco Bay region?"

An important lesson reaffirmed by the Loma Prieta earthquake is that damage to structures varied both with the quality of design and construction and with the behavior of the underlying ground. Geology influences earthquake damage by controlling:

- the potential location, size, and time of occurrence of damaging earthquakes;
- the potential rupture of the ground surface by faulting;
- the potential severity of ground shaking, including its intensity and duration;
- the potential shaking-induced failures and deformation of the ground surface resulting from landsliding or liquefaction; and
- the potential flooding from dike and dam failures, seiches, tsunamis, and tectonic changes of land level.

With the exception of flooding, each of these conditions contributed to the damage associated with the Loma Prieta earthquake. Consequently, success in reducing losses and damage in future earthquakes depends

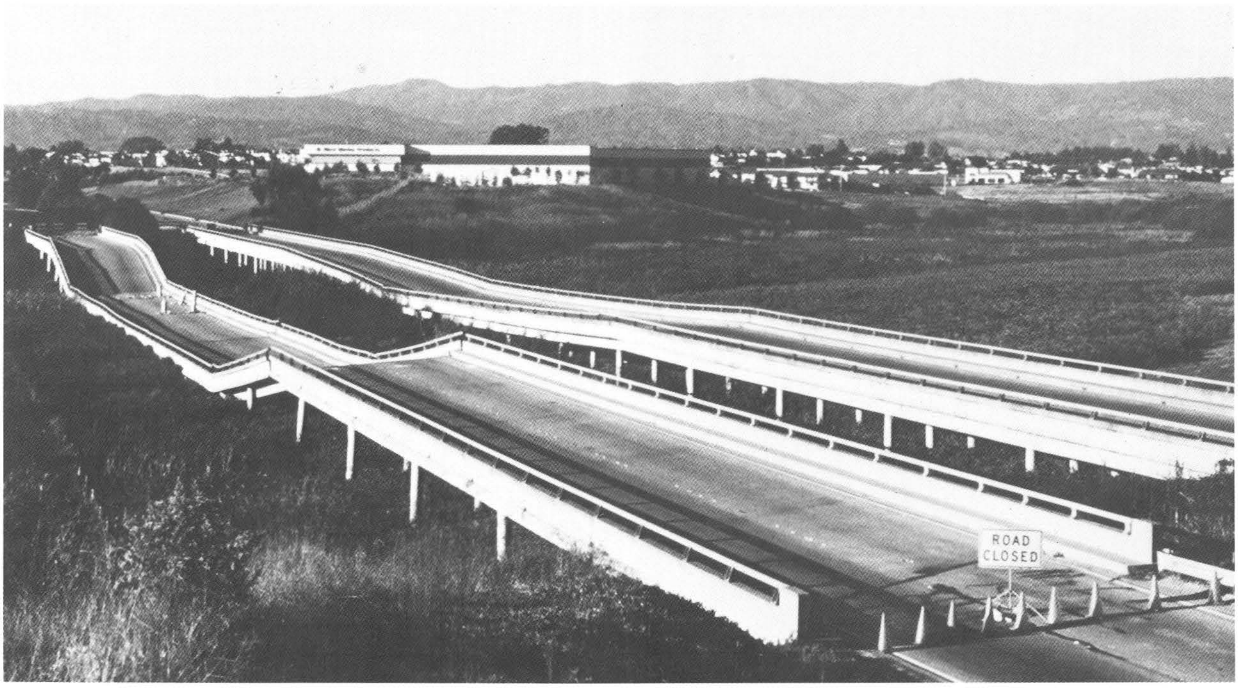


Figure 31. Highway 1 bridge destroyed by strong shaking and liquefaction of river deposits at Struve Slough.

Table 2. Chronology of historical earthquakes in the San Francisco Bay region

[--, no data; Do., ditto]

Date	Location	Magnitude	Lives lost	Estimated damage (in thousands of dollars)	Reference
1865	Santa Cruz Mountains	6.5	6	500	Sherburne, 1981
1868	Hayward	6.8	27	350	Do.
1892	Vacaville	6.8	1	225	Do.
1998	Mare Island	6.5	–	1,400	Do.
1906	San Francisco	8.3	700	[1]500,000	Do.
1955	Oakland-Walnut Creek	5.4	1	1,000	Do.
1957	San Francisco	5.3	1	1,000	Do.
1969	Santa Rosa	5.6	1	8,350	Do.
1980	Livermore Valley	5.5	–	3,934	Do.
1984	Morgan Hill	6.2	–	8,000	Bennett and Sherburne, 1984
1989	Loma Prieta	7.1	62	>~6,000,000	State of California, Governor's Office of Emergency Services, written communication, November 21, 1989

[1]Equivalent to 20 billion 1987 dollars.

Note: For a listing of historical earthquakes in California see Coffman, J.L., and von Hake, C.A., 1973, Earthquake history of the United States: U.S. Department of Commerce (NOAA), Publication 41-1 (revised edition through 1970), 208 p.

not only on sound engineering and construction, but also on our ability to predict the location, likelihood, and severity of geologic hazards on both a regional and a site-by-site basis.

SEISMIC ZONATION

Studies in the San Francisco Bay region (Borcherdt, 1975) showed that seismic zonation, or the delineation of geographical areas with different potentials for each of the various geologic hazards, was feasible. These studies, and the techniques developed therein, resulted in preparation of maps showing the potential for surface faulting, ground shaking, liquefaction, landsliding, and flooding; similar studies produced maps which formed the basis for the development of regional land-use policies to minimize future earthquake losses (Blair and Spangle, 1979). Some of this information has been incorporated into the public safety plans mandated by sec. 65302(g) of the California Government Code enacted in 1974 and into other plans of many cities and counties of the region. Examples of the use of the seismic zonation method for planning and regulation by three counties and three cities has been reported by Kockelman and Brabb (1979).

Laws already enacted have been major steps toward developing land-use policies to reduce the loss of life and property during future earthquakes. A State law of particular significance for mitigating hazards specifically related to surface faulting is the Alquist-Priolo Act of 1972 (California Public Resources Code, sec. 2621 and following). This law requires that a special-studies zone be prescribed along the traces of known active faults capable of earthquake offset. Unfortunately, much of the San Francisco Bay region growth took place prior to its enactment so that concentrated development exists on active traces of the Hayward fault and, to a lesser degree, on the San Andreas fault. Development also has spread to landfill areas underlain by bay mud, to other areas with high potentials for liquefaction, and to upland slopes subject to landsliding. Many buildings within this region predate modern building codes, which require earthquake-resistant design. Use of our current understanding of the causes of earthquake damage can reduce the impact of the next large earthquake. For example, many communities in this hilly region have implemented slope regulations that reduce the hazard of developing hillside sites. Few communities, however, have prepared similar guidelines for areas that are subject to unusually severe ground shaking, to ground deformation related to compaction or liquefaction, to flooding resulting from earthquake shaking, or to other causes.

The degree of vulnerability of the most densely urbanized part of the San Francisco Bay region, for large earthquakes originating on either the San Andreas or Hayward faults, is shown in figure 33. This map, based on the damage distribution of the 1906 earthquake, recent geologic information, and quantitative comparative ground-motion measurements, indicates that the damage from these large earthquakes will vary from weak to very violent depending on distance of the site from one of these major faults and on the type of underlying geologic unit. Such maps help identify the most vulnerable areas in the San Francisco Bay region and in turn those areas requiring special studies. A demonstration project conducted in San Mateo County has produced a folio of 1:62,500-scale maps showing the potential for surface

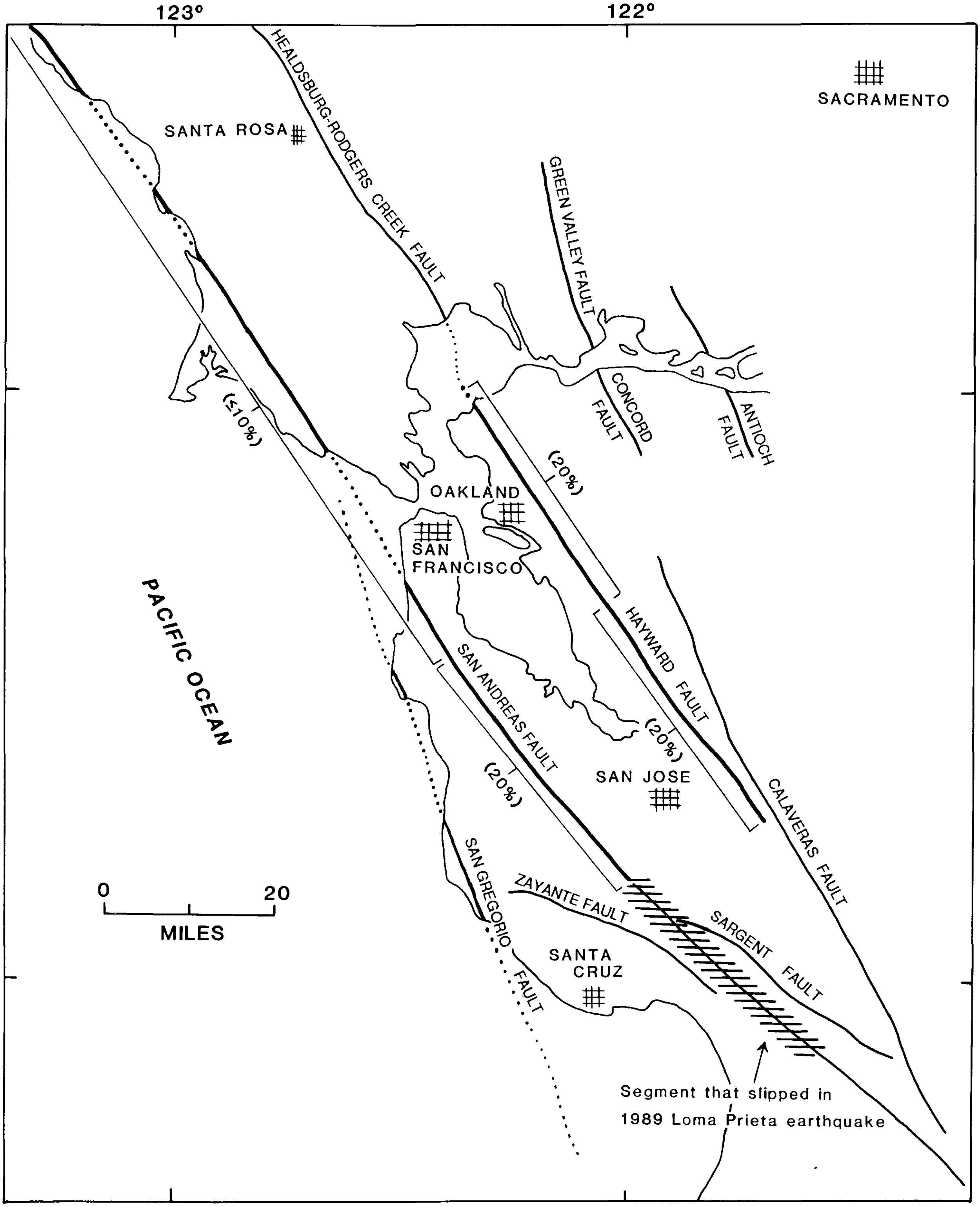


Figure 32. Segments of San Andreas and Hayward faults (heavy lines) showing chance of occurrence of an earthquake in the next 30 years (U.S. Geological Survey, 1988). Faults dotted where concealed.

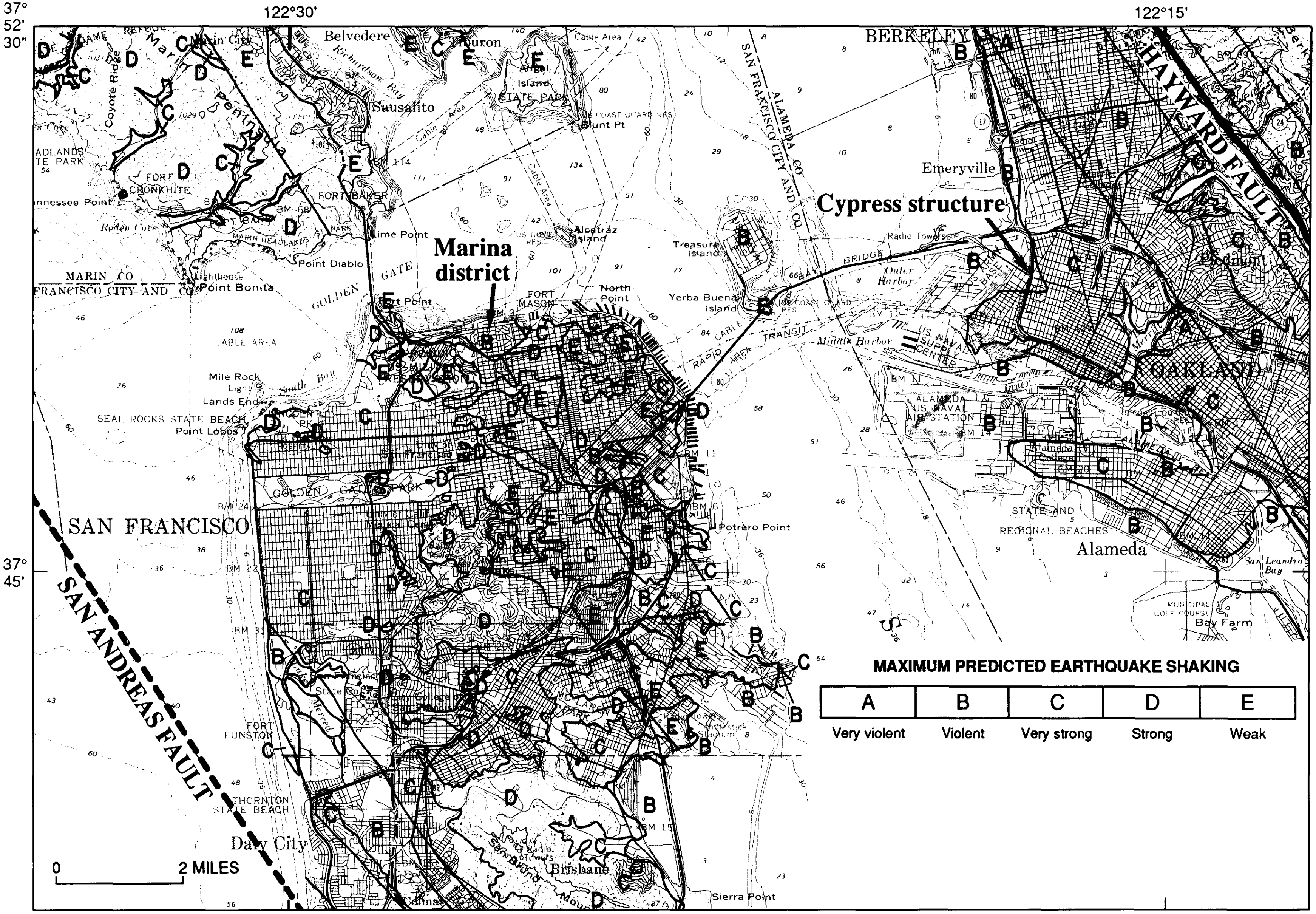


Figure 33. Predicted maximum intensity of ground shaking (lettered areas) from large earthquakes on San Andreas fault (heavy dashed line) and Hayward fault (heavy solid line). Map from Borcherdt and others (1975). Areas marked A apply to earthquake on Hayward fault but not to more distant Loma Prieta earthquake. Damage will be influenced not only by shaking but also by ground failure and design and construction quality of structures.

faulting, ground shaking, liquefaction, landsliding, and damage to various types of structures (Wieczorek and others, 1985; Brabb and Olson, 1986; Thomson and Evernden, 1986; Youd and Perkins, 1987; Perkins, 1987). These maps, which indicate the nature of the hazard and its potential severity, provide a rational basis for land-use and construction policies aimed at reducing the earthquake threat to public health and safety and the region's economy.

These geologic hazards are discussed and illustrated for the San Francisco Bay area by Brown and Kockelman (1983). In addition, six examples are presented on how various State, local, and private agencies have used this information to reduce hazards. Mader and Blair-Tyler (1988) recently described 30 actions that local governments can take to improve seismic safety. Many of them are drawn from innovative efforts already undertaken. Each action is divided into steps; sources of additional information are given. A brief but comprehensive checklist provides a format for assessing local preparedness and there are suggestions for selecting actions and combining them into a multiyear earthquake-safety program.

CONCLUSION

The recurring theme in this report on the Loma Prieta earthquake is that geologic conditions strongly influence damage. In other words, the geology determines where fault ruptures are likely to be, how hard the ground will shake, where landslides will occur, and where the ground will sink and crack.

A parallel theme is that the pattern of damage from shaking and geologic effects observed in 1989 is very similar to that witnessed in 1906. Thus, many of the lessons taught by the 1906 shock have been forgotten or ignored. As the philosopher-poet George Santayana aptly noted "Those who cannot remember the past are condemned to repeat it."

We *know* that an earthquake as large as, or larger than, the Loma Prieta earthquake is likely to shake the San Francisco Bay region within the lifetime of most of the present residents and of many of the existing buildings and facilities. We *know* that such an earthquake will probably occur in a more urbanized area, most likely on the Hayward fault or San Francisco Peninsula segment of the San Andreas fault, and that the casualties and damage are conservatively projected to be several times those just experienced. We *know* that shaking levels and geologic hazards of future earthquakes can be predicted with sufficient detail and confidence to guide policies and priorities for reducing future earthquake losses.

Good science and engineering are not enough to ensure reduction of earthquake hazards. Meaningful hazard reduction can be achieved only when a well-informed and well-prepared public insists upon such protection from government at local, county, State, and Federal levels. If society has the collective will, the effects of the next major earthquake can be minimized through wise land use, strengthening of weak structures, and proper design and construction practices. We can either proceed vigorously to apply the lessons learned from the Loma Prieta earthquake or be condemned to relearn them from the next earthquake.

ACKNOWLEDGMENTS

In addition to those who contributed directly to writing this report (listed on title page), many others contributed indirectly through their active involvement in the geological and geophysical studies of the earthquake, in analysis of the data, and in the typing, drafting, editing, technical review, and other facets of the team effort required for timely preparation of this report for publication. These contributors, listed below, are all with the U.S. Geological Survey, except as otherwise noted.

TECHNICAL STAFF:

A. Acosta, S.T. Algermissen, D.J. Andrews, Mary Andrews, C.A. Aviles, W.H. Bakun, F.W. Baldwin, R.L. Baum, J. Alan Bartow, J.D. Bicknell, Michael Blanpied, John Boatwright, Julian Bommer (Imperial College, London, England), M.G. Bonilla, G.A. Brady, Katherine Breckenridge, L.R. Brewer, Robert D. Brown, Jr., V. Brown, R. Bucknam, K.E. Budding, T.R. Burdette, Sandra Burford, F.L. Butler, R. Campbell, Mauro Cardinale (CNR, IRPI, Perugia, Italy), M.D. Carr, L. Carrol-Haar, D. Carver, K.W. Clark, J.A. Cotton, P. Cowil (Lamont-Doherty Observatory), E. Cranswick, C. Diass, C.M. Dietel, Lynn Dietz, Sam Donaldson, M.M. Donato, R.S. Dollar, J.P. Eaton, S.D. Ellen, F. Ellis, W.L. Ellsworth, E.C. Etheredge, F.G. Fischer, J.P. Fletcher, E.B. Fogelman, L. Foote, A. Frankel, P. Frieberg, G.S. Fuis, T.E. Fumal, J.F. Gibbs, G.N. Glassmoyer, P. Goldstein, W.K. Gross, Z. Guoxia, W.D. Hall, K.M. Haller, G.O. Hamilton, J.A. Hamilton, S.L. Hanson, D.H. Harlow, E.L. Harp, J.E. Healy, J.W. Herriot, Stephen Hickman, D.P. Hill, B.F. Hirschorn, M.G. Hopper, P.W. Irwin, E.G. Jensen, R. Jibson, D. Johnson, W.B. Joyner, B.R. Julian, R.M. Kaderabek, V.G. Keller, J.T. Kempe, Chi-Yu King, K., King, S.H. Kirby, F.W. Klein, W.M. Kohler, A.H. Lachenbruch, J.C. Lahr, J.O. Langbein, W.H. Lee, F.W. Lester, E.V. Leyendecker, R. Liechti, J. Lienkaemper, A.G. Lindh, Hsi-Ping Liu, J.H. Luetgert, N. Luttinger, N.G. MacGregor-Scott, M. Machette, R.P. Maley, R.K. Mark, S.M. Marks, G. Marshall, Robert McClearn, A.F. McGarr, R.J. McLaughlin, K. Meagher, Dan Meier, C.E. Mortenson, C.S. Mueller, R.J. Mueller, B.L. Murchey, D. Myron, J.E. Nielson, Tom Noce, Brendan O'Neill, Paul Okubo, J.A. Olson, E. Omodt, D.H. Oppenheimer, T. Parker, D.M. Perkins, S.F. Personius, D.W. Peterson, J.H. Pfluke, R. Porcella, B.G. Reagor, A. Records, D.B. Reneau, Pat Rice, James Rigby (Nevada Bureau of Mines and Geology), Anselmo Rodriquez, E. Roeloffs, M.J. Salsman, A.M. Sarna-Wojcicki, K.V. Schmidt, Linda Seekins, Paul Segall, E.D. Sembera, Joe Sena, Stan Silverman, R.W. Simpson, J.D. Sims, P.A. Spudich, J. Staude, R.S. Stein, C.D. Stephens, L. Stevens, S.W. Stewart, C.H. Stiffler, C.W. Stover, J.M. Sutton, G.L. Svarc, Joseph Svitek, J.C. Switzer, W.R. Thatcher, J.R. Van Schaack, R.E. Wallace, C. Walkingstick, A.W. Walter, S.R. Walter, R.E. Warrick, K.E. Wendt, Carl Wentworth, R.E. Westerlund, R.A. White, G. Wieczorek, R.C. Wilson, P. Wood (New Zealand Geological Survey), D. Worley, Ze'ev Reches (Stanford University), M.L. Zoback

SUPPORT STAFF:

G.L. Allen, N.E. Arp, R.K. Barnhart, L.E. Buchholz, R.M. Callahan, B.B. Charonnet, M.E. Coveau, C.J. Criley, P.J. Cuneo, R.R. Eis, D.D. Hirsch, L.D. Hodgen, L.M. Hollis, N.L. Hoskin, S. Hotop, T.C. Jackson, M.L. Jacobson, A.C. Jones, M.W. Kennedy, D.L. Knifong, L.W. Kohnitz, Linnea Larson, E.P. Lopez, J.S. Lull, A.M. Margrave, S.E. Mayfield, Lori Moore, C.C. Ramseyer, M.L. Sanders, G.M. Schumacher, S.L. Scott, W.H. Seiders, J.L. Siegman, Moses Smith, R.M. Trombley, R.E. Wood, J.F. Vigil

TECHNICAL REVIEWERS:

Robert D. Brown, Jr., and Robert A. Page

Although it is impossible to individually acknowledge everyone, we sincerely thank the many residents who graciously assisted us with our field investigations by providing access to their property and for their eyewitness accounts that helped us to better understand the earthquake and its effects.

REFERENCES CITED

Alpha, Tau Rho, Lahr, J.C., and Page, R.A., 1989, Oblique map of the northern half of the Loma Prieta, California earthquake rupture zone and environs: U.S. Geological Survey Open-File Report 89–633, 1 sheet.

Blair, M.L., and Spangle, W.E., 1979, Seismic safety and land-use planning—Selected examples from California: U.S. Geological Survey Professional Papaer 941–B, 82 p.

Bonilla M.G., Mark, R.K., and Lienkaemper, J.J., 1984, Statistical relations among earthquake magnitude, surface rupture length, and surface fault displacement: Bulletin of the Seismological Society of America, v. 74, no. 6, p. 2379–2411.

Borcherdt, R.D. 1970, Effects of local geology on ground motion near San Francisco Bay: Bulletin of the Seismological Society of America, v. 60, no. 29, p. 61.

Borcherdt, R.D., ed., 1975, Studies for seismic zonation of the San Francisco Bay region: U.S. Geological Survey Professional Paper 941–A, 102 p.

Borcherdt, R.D., Gibbs, J.F., and LaJoie, K.R., 1975, Maps showing maximum earthquake intensity predicted in the southern San Francisco Bay region, California, for large earthquakes on the San Andreas and Hayward faults: U.S. Geological Survey Miscellaneous Field Studies Map MF–709, scale 1:125,000.

Brabb, E.E., and Olsen, J.A., 1986, Map showing faults and earthquake epicenters in San Mateo County, California: U.S. Geological Survey Miscellaneous Investigations Series Map I–1257–F.

Brown, R.D., Jr., and Kockleman, W.J., 1985, Geology for decisionmakers—Protecting life, property, and resources: Berkeley, Regents of the University of California, Bulletin of the Institute of Governmental Studies, Public Affairs Report, v. 26, no. 1, 11 p.

Dieterich, J.H., 1983, Assessment of a prototype earthquake prediction network for southern California: U.S. Geological Survey Open-File Report 83–576, 27 p.

Dupré, W.R., 1975, Maps showing geology and liquefaction potential of Quaternary deposits in Santa Cruz County, California: U.S. Geological Survey Miscellaneous Field Studies Map MF–648, 2 sheets, scale 1:62,500.

Dupré, W.R., and Tinsley, J.C., III, 1980, Maps showing geology and liquefaction potential of northern Monterey and southern Santa Cruz Counties, California: U.S. Geological Survey Miscellaneous Field Studies Map MF–1199, 2 sheets, scale 1:62,500.

Ellen, S.D., and Wieczorek, G.F., eds., 1988, Landslides, floods, and marine effects of the storm of January 3–5, 1982, in the San Francisco Bay region, California: U.S.Geological Survey Professional Paper 1434, 310 p., 14 plates.

Helley, E.J., Lajoie, K.R., Spangle, W.E., and Blair, M.L., 1979, Flatland deposits of the San Francisco Bay region, California—Their geology and engineering properties, and their importance to comprehensive planning: U.S. Geological Survey Professional Paper 943, 88 p., 3 plates.

Jennings, C.W., 1975, Fault map of California, with locations of volcanoes, thermal springs, and thermal wells: California Division of Mines and Geology, Geologic Data Map 1, scale 1:750,000.

Joyner, W.B., and Boore, D.M. 1988, Measurement, characterization, and prediction of strong ground motion: Proceedings of Earthquake Engineering and Soil Dynamics, Park City, June 27–30, 1988, American Society Civil Engineers, no. 43, p. 102.

Keefer, D.K., 1984, Landslides caused by earthquakes: Geological Society of America Bulletin, v. 95, no. 4, p. 406–421.

Keefer, D.K., Wilson, R.C., Mark, R.K., Brabb, E.E., Brown, W.M., III, Ellen, S.D., Harp, E.L., Wieczorek, G.F., Alger, C.S., and Zatkin, R.S., 1987, Real-time landslide warning during heavy rainfall: Science, v. 238, p. 921–925.

Kockelman, W.J., and Brabb, E.E., 1979, Examples of seismic zonation in the San Francisco Bay region: U.S. Geolog-

ical Survey Circular 807, p. 73–84.
Lawson, A.C., and others, 1908, The California earthquake of April 18, 1906: Report of the California State Earthquake Investigation Commission: Washington, Carnegie Institution, Publication 87, v. 1, 2 parts, 451 p.
Lindh, A.G., 1983, Preliminary assessment of long-term probabilities for large earthquakes along selected segments of the San Andreas fault system in California: U.S. Geological Survey Open-File Report 83–63, p. 1–5.
Mader, G.G., and Blair-Tyler, Martha, 1988, California at risk—Steps to earthquake safety for local governments: Sacramento, California, Seismic Safety Commission Report SSC 88–01, 56 p.
McLaughlin, R.J., 1974, The Sargent-Berrocal fault zone and its relation to the San Andreas fault system in the southern San Francisco Bay region and Santa Clara valley, California: U.S. Geological Survey Journal of Research, v. 2, no. 5, p. 593–598.
New Civil Engineer, 1989, The race to repair dams: New Civil Engineer, no. 896, November 2, p. 26–27.
Perkins, J.B., 1987, Maps showing cumulative damage potential from earthquake ground shaking, in San Mateo County, California: U.S. Geological Survey Miscellaneous Investigations Series Map I–1257–I.
Prescott, W.H., Davis, J.L., and Svarc, J.L., 1989, Global positioning system measurements for crustal deformation: Precision and accuracy: Science, v. 244, p. 1337–1340.
Rantz, S.E., 1971, Mean annual precipitation and precipitation depth-duration-frequency data for the San Francisco Bay region, California: U.S. Geological Survey Open-File Report, 23 p., 1 plate.
Reid, H.F., 1910, The California earthquake of April 18, 1906: Report of the California State Earthquake Investigation Commission: Washington, Carnegie Institution, Publication 87, v. 2, The mechanics of the earthquake, 192 p.
Sarna-Wojcicki, A.M., Pampeyan, E.H., and Hall, N.T., 1975, Recent active breaks along the San Andreas fault between the central Santa Cruz Mountains and northern Gabilan Range, California: U.S. Geological Survey Miscellaneous Field Studies Map MF–650, scale 1:24,000.
Savage, J.C., and Prescott, W.H., 1973, Precision of geodolite distance measurements for determining fault movement: Journal of Geophysical Research, v. 78, p. 6001–6008.
Seawthorn, C., and O'Rourke, T.D., 1989, Effects of ground failure on water supply and fire following earthquake: The 1906 San Francisco earthquake: Proceedings of 2nd U.S.-Japan Workshop on Liquefaction, Large Ground Deformation and Their Effects on Lifeline Facilities, September 26–28, 1989, Buffalo, New York.
Sherburne, R.W., 1981, Seismology Program: California Geology, v. 34, no. 1, p. 3–6.
Sherburne, R.W., and Bennett, J.H., eds., 1984, The Morgan Hill, California, earthquake: Sacramento, California Division of Mines and Geology Special Publication 68, 271 p.
Sykes, L.R., and Nishenko, S.P., 1984, Probabilities of occurrence of large plate-rupturing earthquakes for the San Andreas, San Jacinto, and Imperial faults, California, 1983–2003: Journal of Geophysical Research, v. 89, p. 5905–5927.
Thatcher, W., 1975, Strain accumulation and release mechanism of the 1906 San Francisco earthquake: Journal of Geophysical Research, v. 84, p. 4862–4872.
Thatcher, W., and Lisowski, M., 1987, Long-term seismic potential of the San Andreas fault southeast of San Francisco, California: Journal of Geophysical Research, v. 92, p. 4771–4784.
Thomson, J.M., and Evernden, J.F., 1986, Map showing predicted seismic-shaking intensities of an earthquake in San Mateo County, California: U.S. Geological Survey Miscellaneous Investigations Series Map I–1257–H.
U.S. Geological Survey, 1988, Probabilities of large earthquakes occurring in California on the San Andreas fault: U.S. Geological Survey Open-File Report 88–398, 62 p.
Wieczorek, G.R., Wilson, R.C., and Harp, E.L., 1985, Map of slope stability during earthquakes in San Mateo County, California: U.S. Geological Survey Miscellaneous Investigations Map I–1257–E.
Wood, H.O., 1908, Distribution of apparent intensity in San Francisco, *in* The California earthquake of April 18, 1906: Washington, Carnegie Institution, Publication 87, v. 1, p. 220–246.
Youd, T.L., and Perkins, J.B., 1987, Map showing liquefaction susceptibility of San Mateo County, California: U.S. Geological Survey Miscellaneous Investigations Series Map I–1257–G.

APPENDIX 1. GLOSSARY

[Terms set in bold type are defined elsewhere in the glossary]

Acceleration. The time rate of change of velocity of a reference point during an **earthquake**. Commonly expressed in percentage of gravity (*g*, equal to 32 feet per second per second.

Active fault. A **fault** that is considered likely to undergo renewed movement within a period of concern to humans. Also referred to as a "capable" fault.

Alluvium. Loosely compacted gravel, sand, silt, or clay deposited by streams.

Aftershock. Secondary tremors that may follow the largest shock or mainshock of an **earthquake** sequence. Such tremors can extend over a period of weeks, months, or years.

Amplification. An increase in **seismic** signal **amplitude** within some range of **frequency** as waves propagate through different earth materials.

Amplitude. Zero-to-peak value of any wavelike disturbance.

Aseismic. Not associated with an **earthquake**.

Attenuation. A decrease in **seismic** signal **amplitude** as waves propagate from the seismic source. Attenuation is caused by geometrical spreading of **seismic wave** energy and by the absorption and scattering of seismic energy in different earth materials.

Bedrock. Relatively hard, solid rock that commonly underlies softer rock, sediment, or soil.

Body wave. A **seismic wave** that travels through the interior of the Earth and is not related to a boundary surface. **Primary** and **secondary waves** are examples of body waves.

Creep. Slow, more or less continuous movement that may occur either along faults owing to ongoing **tectonic** deformation or along slopes owing to gravitational forces.

Crust. The outermost major layer of the Earth, ranging from about 6 to 40 miles thick worldwide and about 12 miles thick in coastal California; characterized by **primary wave** velocities less than 5 miles per second.

Dip. Inclination of a planar geologic surface (for example, a **fault** or a bed) from the horizontal.

Displacement. The difference between the initial position of a reference point and any later position. (1) In seismology, displacement is typically calculated by integrating an accelerogram twice with respect to time and is expressed in centimeters. (2) In geology, displacement is the permanent offset of a geologic or manmade reference point along a **fault** or landslide.

Earthquake. Groups of **elastic waves** propagating in the Earth, set up by a sudden disturbance of the elastic equilibrium of a portion of the Earth.

Earthquake hazard. Any physical phenomenon associated with an **earthquake** that may produce adverse effects on human activities.

Elastic rebound theory. In seismology, the theory stating that faulting arises from the sudden release of elastic energy which has slowly accumulated in the Earth. Just before the rupture, the energy released by the faulting is entirely potential energy stored as the elastic **strain** in the rocks. At the time of the rupture the rocks on either side of the **fault** spring back to a position of relatively little or no strain.

Elastic wave. A wave that is propagated by some kind of elastic deformation, that is, a deformation that disappears when the forces are removed. A **seismic wave** is a type of elastic wave.

Epicenter. That point on the Earth's surface vertically above the **hypocenter** of an **earthquake** (where a **seismic** rupture initiates).

Fault. A fracture or fracture zone along which there has been displacement of the sides relative to one another parallel to the fracture plane or planes.

Fault-plane solution. An analysis to determine the attitude of the causative **fault** and its direction of slip from the radiation pattern of **seismic waves** for an **earthquake**. The analysis most commonly uses the direction of first motion of **primary waves** recorded at numerous stations and yields two possible orientations for the fault rupture and the direction of seismogenic slip. From these data, inferences can be made concerning the principal axes of **stress** in the region of the earthquake.

Fault-trace. Intersection of a **fault** with the ground surface; also, the line commonly plotted on geologic maps to represent a fault.

Focus. The source of a given set of **elastic waves**. The true center of an **earthquake**, within which the **strain** energy is first converted to elastic wave energy. See also **Hypocenter**.

Focal zone. The rupture zone of an **earthquake**. In the case of a great earthquake (**magnitude** > 7.5), the focal zone may extend several hundred miles in length.

Foreshock. A small tremor that commonly precedes a larger **earthquake** or mainshock by seconds to weeks and that originates at or near the **focus** of the larger earthquake.

Free face. A sloping surface exposed to air or water such that there is little or no resistance to lateral movement of adjacent earth material.

Frequency. Number of cycles occurring in unit time. Hertz (Hz), the unit of frequency, is equal to the number of cycles per second.

Geodetic measurements. Controls on location (vertical or horizontal) of positions on the Earth's surface of a high order of accuracy, usually extended over large areas for surveying and mapping operations.

Geophysical surveys. The use of one or more techniques of physical measurement to explore earth properties and processes.

Geotechnical. Refers to the use of scientific methods and engineering principles to acquire, interpret, and apply knowledge of earth materials for solving engineering problems.

Ground motion. General term referring to the qualitative or quantitative aspects of shaking of the Earth's surface from **earthquakes** or explosions.

Hypocenter. The point within the Earth where an **earthquake** rupture initiates. See also **Focus**.

Intensity. A subjective measure of the force of an **earthquake** at a particular place as determined by its effects on persons, structures, and earth materials. The principal scale used in the United States today is the modified Mercalli intensity scale (see table 1).

Isoseismal. A line connecting points on the Earth's surface at which **earthquake intensity** is the same. It is usually a closed curve around the **epicenter**.

Liquefaction. Process by which water-saturated sediment temporarily loses strength, usually because of strong shaking, and behaves as a fluid.

Magnitude. A number that characterizes the size of an **earthquake**, usually based on measurement of the maximum **amplitude** recorded by a **seismograph** for earthquake waves of a particular **frequency**. Scales most commonly used are (1) local magnitude (M_L, commonly referred to as "Richter magnitude"), (2) surface-wave magnitude (M_S), and (3) body-wave magnitude (m_b). None of these scales satisfactorily measures the largest possible **earthquakes** because each relates to only certain frequencies of **seismic waves** and because the spectrum of radiated seismic energy changes with the earthquake size. The recently devised moment magnitude (***M***) scale, based on the concept of seismic moment, is uniformly applicable to all sizes of earthquakes.

> **Body-wave magnitude** (m_b): Measures the type of waves that pass through the interior—the body—of the planet and that have a period of between 1 to 10 seconds.
>
> **Local magnitude** (M_L): A scale most accurately applied when dealing with California earthquakes. It is still quite useful today for describing smaller and more moderate earthquakes, but is not useful in larger earthquakes.
>
> **Surface-wave magnitude** (M_S): Scale formulated to describe earthquakes at distant locations. The scale principally measures **surface waves** with a 20-second period, or a wavelength of approximately 37 miles.
>
> **Moment magnitude** (***M***): This is today perhaps the most meaningful scale for large and great earthquakes, in that it measures total energy released. The measurement takes into account the surface area of the fault that moved to cause the earthquake, plus the average displacement of the fault plane, and the rigidity of the material of the fault. A seismic moment, M_o, is the result, and when that is combined with an energy-magnitude formula, the outcome is a common means of measuring the greatest earthquakes on the planet, such as in Alaska, 1964, and Chile, 1960. This scale was developed very recently, which is why great earthquakes, such as that in Alaska in 1964, which were once related in the M_S 8.5 range have been upgraded to an ***M*** rating in the low 9's.

Major earthquake. An **earthquake** having a magnitude of 7 or greater on the Richter scale.

Microseismic event. **Earthquake** or man-induced vibrations observable only with instruments.

Plate tectonics. A widely accepted theory that considers the Earth's **crust** and upper mantle to be composed of a number of large, relatively thin and rigid plates that move relative to one another. Interaction along their boundaries commonly results in **earthquakes** and volcanic activity.

Primary wave (*P*-wave). That type of **seismic body wave** which is propagated by alternating compression and expansion of material in the direction of propagation. It is the fastest of the **seismic waves** (traveling 3.7 to 4.2 miles per second in the **crust** and 5 to 5.3 miles per second in the upper mantle below the crust), and it is the type which carries sound. The *P* stands for primary; it is so named because it arrives before the slower *S* wave (**secondary wave**).

Remote sensing. The acquisition of information or measurement of some property of an object by a recording device that is not in physical or intimate contact with the object under study. The technique employs such devices as the camera, lasers, infrared and ultraviolet detectors, microwave, and radio frequency receivers, and radar systems.

Reverse fault. A steeply to slightly inclined **fault** in which the block above the fault has moved relatively upward or over the block below the fault.

Right-lateral movement. Generally horizontal movement in which the block across the **fault** from an observer has moved to the right.

Sand boil. Sand and water ejected to the ground surface as the result of **liquefaction** at shallow depth; the conical or ridge-shaped sediment deposit that remains is evidence of liquefaction.

Scarp. A cliff or steep slope formed by a **fault** or landslide, generally by one side moving up relative to the other.

Secondary wave (*S*-wave). That type of **seismic body wave** which is propagated by a shearing motion of material, so that there is oscillation perpendicular to the direction of propagation. It does not travel through liquids or through the outer core of the Earth. Its speed is 1.8 to 2.5 miles per second in the **crust** and 2.7 to 2.8 miles per second in the upper mantle below the crust. The *S* stands for secondary; it is so named because it arrives later than the faster *P*-wave.

Seiche. Oscillation of the surface of an enclosed body of water owing to **earthquake** shaking.

Seismic. Pertaining to an **earthquake** or earth vibration, including those that are artificially induced.

Seismic risk. The probability of social or economic consequences of an **earthquake.**

Seismic wave. An **elastic wave** generated by an impulse such as an **earthquake** or an explosion. Seismic waves may propagate either along or near the Earth's surface or through the Earth's interior.

Seismic zonation. Geographic delineation of areas having different potentials for hazardous effects from future **earthquakes.** Seismic zonation can be done at national, regional, and local scales.

Seismicity. The geographical and historical distribution of **earthquakes.**

Seismogram. A record of **ground motion** or of vibration of a structure caused by an **earthquake** or an explosion.

Seismograph. An instrument that scribes a permanent continuous record of earth vibrations.

Separation. The distance between any two parts of a reference plane (for example, a sedimentary bed or a geomorphic surface) offset by a **fault** measured in any plane. Separation is the apparent amount of fault **displacement** and is nearly always less than the actual slip.

Shear. A mode of failure whereby two adjacent parts of a solid slide past one another parallel to the plane of failure.

Shear wave. A distortional, secondary or transverse wave.

Slip rate. The average **displacement** at a point along a **fault** as determined from geodetic measurements, from offset man-made structures, or from offset geologic features whose age can be estimated. It is measured parallel to the dominant slip direction or estimated from the vertical or horizontal **separation** of geologic, geodetic, or other markers.

Strain. The amount of any change in dimensions or shape of a body when subjected to deformation.

Stress. Force per unit area acting on a surface within a body. Six values are required to characterize completely the **stress** point: three normal components and three shear components.

Strike-slip fault. Fault in which movement is principally horizontal.

Strong motion. Ground motion produced by a "strong" **earthquake** or one capable of producing damage to structures. The **magnitude** of such an earthquake may vary considerably according to the character of the earthquake and the nature of the ground.

Subsidence. Downward settling of the Earth's surface with little or no horizontal motion. May be caused by natural geologic processes (such as sediment compaction or **tectonic** activity) or by human activity (such as mining or withdrawal of ground water or petroleum).

Surface faulting. Displacement that reaches the ground (or sea floor) surface during slip along a **fault.** Commonly accompanying moderate and large **earthquakes** having focal depths to 12 miles. Surface faulting also may accompany **aseismic tectonic creep** or natural or man-induced **subsidence.**

Surface wave. Seismic wave that propagates along the Earth's surface.

Tectonic. Refers to crustal rock-deformation processes that affect relatively large areas.

Travel time curve. A graph of arrival times of **primary** or **secondary waves** recorded at different points as a function of distance from the seismic source. Seismic velocities can be computed from the slopes of the resulting curve.

Water table. The upper surface of a body of unconfined ground water at which the water pressure is equal to the atmospheric pressure.

SOURCES:

Bates, R.L., and Jackson, J.A., editors, 1987, Glossary of Geology [3d ed.]: Alexandria, Virginia, American Geological Institute, 788 p.

Nance, John, J., 1989, On shaky ground: America's earthquake alert: New York, Avon Books, 440 p.

Ziony, J.I., ed., 1985 Evaluating earthquake hazards in the Los Angeles Region—An Earth-Science perspective: U.S. Geological Survey Professional Paper 1360.

APPENDIX 2. GENERAL REFERENCES AND SOURCES OF INFORMATION ON EARTHQUAKES

Earthquakes, by Bruce Bolt, 1988, New York, W.H. Freeman, 282 pages. *A primer on earthquakes—their causes, measurement, precursors, and effects written by a leading researcher and teacher at University of California, Berkeley.*

Earthquakes, by Don DeNevi, 1977, Millbrae, California, Celestial Arts, 230 pages. *An overview of historic earthquakes, earthquake hazard reduction, and earthquake prediction.*

Earthquake Survival Guide: Emergency planning for family, home, workplace, and school, 1989, Prepared as a Public Service by Artichoke Joe's, 659 Huntington Avenue, San Bruno, Calif. 94066, Artichoke Enterprises, Inc., 2nd ed., 24 p.

Earthquakes and Volcanoes, United States Geological Survey, bimonthly publication available yearly for $9.00 from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402. *This magazine provides short articles and many illustrations for nonscientists on different aspects of research on earthquakes and volcanoes.*

Earthquakes and Volcanoes, Readings from Scientific American, 1980, San Francisco, California, W.H., Freeman and Company 154 pages. *Eleven articles on earthquake properties, earthquakes and earth structure, and volcanoes.*

Earthquake Country, by Robert Iacopi, 1971, A Sunset Book, Menlo Park, California, Lane Books, 160 pages. *An explanation as to why California has earthquakes and a guide to faults in California.*

On Shaky Ground: America's Earthquake Alert, by J.J. Nance, 1989, New York, Avon Books, 440 pages.

Peace of Mind in Earthquake Country, by Peter Yanev, 1974, San Francisco, California, Chronicle Books, 304 pages. *Describes earthquake hazards and practical steps to take before, during, and after earthquakes.*

Seismicity Map of California 1808–1987, 1:1,000,000 scale, U.S. Geological Survey Open-File Report 88–286, available for $5.00 per map plus $2.00 shipping from National Earthquake Information Center, U.S. Geological Survey, 1711 Illinois Avenue, Golden, Colorado 80401.

SOME LOCAL SOURCES FOR EARTHQUAKE INFORMATION

The Community Access Pages of Your Local Telephone Book.

Your Community Library.

Your County or City Planning Office.

Association of Bay Area Governments (ABAG), P.O. Box 2050, Oakland, California 94604–2050, phone (415) 464–7900. *Maps that show ground-shaking probabilities, technical assistance in planning, publications on preparedness, and training courses for businesses.*

Bay Area Regional Earthquake Preparedness Project (BAREPP), Metro Center, 101 8th Street, Suite 152, Oakland, California 94607, phone (415) 540–2713. *Publications, videotapes, scripted slide shows, and lectures on earthquake preparedness.*

California Division of Mines and Geology, Department of Conservation, P.O. Box 2980, Sacramento, California 95812–2980, phone (916) 445–5716. *Earthquake planning scenarios, maps, and other publications.*

Earth Science Information Centers, U.S. Geological Survey, 555 Battery Street, Room 504 Customs House, San Francisco, California 94111, phone (415) 705–1010; 345 Middlefield Road, Menlo Park, California 94025, phone (415) 329–4390. *USGS publications and information on other products and data bases.*

Federal Emergency Management Agency (FEMA), Building 105, The Presidio, San Francisco, California 94129, phone (415) 923–7100. *Pamphlets on how to prepare for an earthquake and what to expect.*

OVERVIEW AND ISSUES

[This is a modified list of references that recently appeared in an Earthquake Engineering Research Institute Newsletter (EERI), September, 1989, v. 23, no. 9]

Archuleta, R.J., Joyner, W.B., and Boore, D.M., 1979, A methodology for predicting ground motion at specific sites, *in* Brabb, E.E., ed., Progress on seismic zonation in the San Francisco Bay region: U.S. Geological Survey Circular 807, p. 26–36.

Brown, R.D., Jr., and Kockelman, W.J., 1983, Geologic principles for prudent land use: A decisionmakers guide for the San Francisco Bay region: U.S. Geological Survey Professional Paper 946, 97 p.

———1985, Geology for decisionmakers: Protecting life, property and resources: Berkeley, University of California, Bulletin of the Institute of Governmental Studies, Public Affairs Report, v. 26, no. 1, 11 p. [Condensed version of USGS Professional Paper 946]

Hank, T.C., 1985, The National Earthquake Hazards Reduction Program—Scientific Status: U.S. Geological Survey Bulletin 1659, 40 p.

Nichols, D.R., and Buchanan-Banks, J.M., 1974, Seismic hazards and land-use planning: U.S. Geological Survey Circular 690, 33 p.

U.S. Office of Science and Technology Policy, 1978, Earthquake hazards reduction: Issues for an implementation plan: Washington, D.C., Executive Office of the President, 231 p.

SEISMIC ZONATION

Arnold, Christopher, and Eisner, R.K., 1984, Planning information for earthquake hazard response and reductions: San Mateo Calif., Building Systems Development, Inc., 79 p.

Blair, M.L., and Spangle, W.E., 1979, Seismic safety and land-use planning: Selected examples from California: U.S. Geological Survey Professional Paper 941–B, 83 p.

Borcherdt, R.D., ed., 1975, Studies for seismic zonation of the San Francisco Bay region: U.S. Geological Survey Professional Paper 941–A, p. A1–A102.

Brabb, E.E., Pampeyan, E.H., and Bonilla, M.G., 1972, Landslide susceptibility in San Mateo County, California: U.S. Geological Survey Miscellaneous Field Studies Map MF–360, scale 1:62,500.

Brown, R.D., Jr., and Wolfe, E.W., 1972, Map showing recently active breaks along the San Andreas fault between Point Delgada and Bolinas Bay, California: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-692, 2 sheets, scale 1:24,000.

Hays, W.W., 1980, Procedures for estimating ground motions: U.S. Geological Survey Professional Paper 1114, 77 p.

Jafee, Martin, Butler, JoAnn, and Thurow, Charles, 1981, Reducing earthquake risks: A planner's guide: Chicago, American Planning Association, Planning Advisory Service Report 364, 82 p.

Kockelman, W.J., and Brabb, E.E., 1979, Examples of seismic zonation in the San Francisco Bay region: U.S. Geological Survey Circular 807, p. 73–84.

Perkins, J.B., 1987, The San Francisco Bay area: On shaky ground: Oakland, Calif., Association of Bay Area Governments, 32 p.

Williams, J.W., and Rogers, T.H., 1978, Relative seismic stability map, Santa Clara County, California (revised ed.): San Jose, Calif., Santa Clara County Environmental Management Agency, scale 1:250,000.

Wesson, R.L., Helley, E.J., Lajoie, K.R., and Wentworth, C.M., 1975, Faults and future earthquakes, *in* Borcherdt, R.D., ed., Studies for seismic zonation of the San Francisco Bay region: U.S. Geological Survey Professional Paper 941-A, p. A5-A30.

Youd, T.L., and Hoose, S.N., 1978, Historic ground failures in northern California triggered by earthquakes: U.S. Geological Survey Professional Paper 993, 177 p.

Youd, T.L., Nichols, D.R., Helley, E.J., and Lajoie, K.R., 1975, Liquefaction potential, *in* Borcherdt, R.D., ed., Studies for seismic zonation of the San Francisco Bay region: U.S. Geological Survey Professional Paper 941-A, A68-A74.

SEISMIC SAFETY PLANNING

Foster, H.D., 1980, Disaster planning: The preservation of life and property: New York, Springer-Verlag, 275 p.

Helley, E.J., LaJoie, K.R., Spangle, W.E., and Blair, M.L., 1979, Flatlands deposits of the San Francisco Bay region, California—Their geology and engineering properties, and their importance to comprehensive planning: U.S. Geological Survey Professional Paper 943, 88 p.

Mader, G.G., Spangle, W.E., Blair, M.L., Meehan, R.L., Bilodeau, S.W., Degenkolb, H.J., Duggar, G.S., and Williams, Norman, Jr., 1980, Land use planning after earthquakes: Portola Valley, Calif., William Spangle and Associates, Inc., 158 p.

Nilsen, T.H., Wright, R.H., Vlasic, T.C., and Spangle, W.E., 1979, Relative slope stability and land-use planning in the San Francisco Bay region, California: U.S. Geological Survey Professional Paper 944, 96 p.

PLAN IMPLEMENTATION

Atwater, Brian, 1978, Central San Mateo County, California—Land-use controls arising from erosion of seacliffs, landsliding, and fault movement, *in* Robinson, G.D., and Spieker, A.M., eds., "Nature to be commanded...": Earth-science maps applied to land and water management: U.S. Geological Survey Professional Paper 950, p. 11–21.

Blair-Tyler, Martha, and Gregory, P.A., 1988, Putting seismic safety policies to work: Oakland, Calif., Bay Area Regional Earthquake Preparedness Project, 40 p.

Bolton, P.A., Heikkala, S.G., Greene, M.R., May, P.J., and Wolfe, M.R., 1986, Land use planning for earthquake hazard mitigation: A handbook for planners: Boulder, University of Colorado, Natural Hazards Applications Information Center Special Publication 14, 121 p.

Kockelman, W.J., 1985, Using earth-science information for earthquake hazard reduction, *in* Ziony, J.I., ed., Evaluating earthquake hazards in the Los Angeles region: U.S. Geological Survey Professional Paper 1360, p. 443–469, 502–505.

Mader, G.G., and Blair-Tyler, Martha, 1988, California at risk: Steps to earthquake safety for local government: Sacramento, California Seismic Safety Commission Report SSC 88–01, 56 p.

San Jose Board of Realtors, 1977, Map of Santa Clara County, California, special studies zones and flood hazard area: San Jose, Calif., Barclay Maps.

San Mateo-Burlingame Board of Realtors, 1979, Midpeninsula cities map; special studies zones and flood hazard area: San Jose, Calif., Barclay Maps.

EVALUATING EFFECTIVENESS

Alesch, D.J., and Petak, W.J., 1986, The politics and economics of earthquake hazard mitigation: Boulder, University of Colorado, Institute of Behavioral Science, Program on Environment and Behavior Monograph 43, 273 p.

Kockelman, W.J., 1979, Use of USGS earth-science products by selected regional agencies in the San Francisco Bay region, California: U.S. Geological Survey Open-File Report 79–221, 173 p.

May, P.J., and Bolton, P.A., 1986, Reassessing earthquake hazard reduction measures: Chicago, American Planning Association Journal, v. 52, no. 4, p. 443–451.

Mintier, J.L., and Stromberg, P.A., 1983, Seismic safety at the local level: Does planning make a difference?: California Geology, v. 36, no. 7, p. 148–154

☆ U.S. GOVERNMENT PRINTING OFFICE: 785

SELECTED SERIES OF U.S. GEOLOGICAL SURVEY PUBLICATIONS

Periodicals

Earthquakes & Volcanoes (issued bimonthly).
Preliminary Determination of Epicenters (issued monthly).

Technical Books and Reports

Professional Papers are mainly comprehensive scientific reports of wide and lasting interest and importance to professional scientists and engineers. Included are reports on the results of resource studies and of topographic, hydrologic, and geologic investigations. They also include collections of related papers addressing different aspects of a single scientific topic.

Bulletins contain significant data and interpretations that are of lasting scientific interest but are generally more limited in scope or geographic coverage than Professional Papers. They include the results of resource studies and of geologic and topographic investigations; as well as collections of short papers related to a specific topic.

Water-Supply Papers are comprehensive reports that present significant interpretive results of hydrologic investigations of wide interest to professional geologists, hydrologists, and engineers. The series covers investigations in all phases of hydrology, including hydrogeology, availability of water, quality of water, and use of water.

Circulars present administrative information or important scientific information of wide popular interest in a format designed for distribution at no cost to the public. Information is usually of short-term interest.

Water-Resources Investigations Reports are papers of an interpretive nature made available to the public outside the formal USGS publications series. Copies are reproduced on request unlike formal USGS publications, and they are also available for public inspection at depositories indicated in USGS catalogs.

Open-File Reports include unpublished manuscript reports, maps, and other material that are made available for public consultation at depositories. They are a nonpermanent form of publication that may be cited in other publications as sources of information.

Maps

Geologic Quadrangle Maps are multicolor geologic maps on topographic bases in 7 1/2- or 15-minute quadrangle formats (scales mainly 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering geology. Maps generally include brief texts; some maps include structure and columnar sections only.

Geophysical Investigations Maps are on topographic or planimetric bases at various scales; they show results of surveys using geophysical techniques, such as gravity, magnetic, seismic, or radioactivity, which reflect subsurface structures that are of economic or geologic significance. Many maps include correlations with the geology.

Miscellaneous Investigations Series Maps are on planimetric or topographic bases of regular and irregular areas at various scales; they present a wide variety of format and subject matter. The series also includes 7 1/2-minute quadrangle photogeologic maps on planimetric bases which show geology as interpreted from aerial photographs. Series also includes maps of Mars and the Moon.

Coal Investigations Maps are geologic maps on topographic or planimetric bases at various scales showing bedrock or surficial geology, stratigraphy, and structural relations in certain coal-resource areas.

Oil and Gas Investigations Charts show stratigraphic information for certain oil and gas fields and other areas having petroleum potential.

Miscellaneous Field Studies Maps are multicolor or black-and-white maps on topographic or planimetric bases on quadrangle or irregular areas at various scales. Pre-1971 maps show bedrock geology in relation to specific mining or mineral-deposit problems; post-1971 maps are primarily black-and-white maps on various subjects such as environmental studies or wilderness mineral investigations.

Hydrologic Investigations Atlases are multicolored or black-and-white maps on topographic or planimetric bases presenting a wide range of geohydrologic data of both regular and irregular areas; principal scale is 1:24,000 and regional studies are at 1:250,000 scale or smaller.

Catalogs

Permanent catalogs, as well as some others, giving comprehensive listings of U.S. Geological Survey publications are available under the conditions indicated below from the U.S. Geological Survey, Books and Open-File Reports Section, Federal Center, Box 25425, Denver, CO 80225. (See latest Price and Availability List.)

"Publications of the Geological Survey, 1879-1961" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the Geological Survey, 1962-1970" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the U.S. Geological Survey, 1971-1981" may be purchased by mail and over the counter in paperback book form (two volumes, publications listing and index) and as a set of microfiche.

Supplements for 1982, 1983, 1984, 1985, 1986, and for subsequent years since the last permanent catalog may be purchased by mail and over the counter in paperback book form.

State catalogs, "List of U.S. Geological Survey Geologic and Water-Supply Reports and Maps For (State)," may be purchased by mail and over the counter in paperback booklet form only.

"Price and Availability List of U.S. Geological Survey Publications," issued annually, is available free of charge in paperback booklet form only.

Selected copies of a monthly catalog "New Publications of the U.S. Geological Survey" available free of charge by mail or may be obtained over the counter in paperback booklet form only. Those wishing a free subscription to the monthly catalog "New Publications of the U.S. Geological Survey" should write to the U.S. Geological Survey, 582 National Center, Reston, VA 22092.

Note.--Prices of Government publications listed in older catalogs, announcements, and publications may be incorrect. Therefore, the prices charged may differ from the prices in catalogs, announcements, and publications.

Plafker and Galloway, eds.—LESSONS LEARNED FROM THE LOMA PRIETA, CALIFORNIA, EARTHQUAKE OF OCTOBER 17, 1989—U.S. Geological Survey Circular 1045