SPECIAL PUBLICATION 104

THE LOMA PRIETA (SANTA CRUZ MOUNTAINS), CALIFORNIA, EARTHQUAKE OF 17 OCTOBER 1989

CALIFORNIA
DEPARTMENT
OF CONSERVATION

Division of Mines and Geology

THE RESOURCES AGENCY
GORDON K. VAN VLECK
SECRETARY FOR RESOURCES

STATE OF CALIFORNIA
GEORGE DEUKMEJIAN
GOVERNOR

DEPARTMENT OF CONSERVATION
RANDALL M. WARD
DIRECTOR

DIVISION OF MINES AND GEOLOGY
JAMES F. DAVIS
STATE GEOLOGIST

Cover Photo:

View to the south of Hazel Dell Road, located in the Santa Cruz Mountains about 8.5 kilometers north of Watsonville. The large fissures in the road were caused by lateral spreading due to liquefaction of saturated sediments in Simas Lake and intense shaking associated with the M_S 7.1 Loma Prieta earthquake (note leaning telephone pole). Simas Lake, located just west of Hazel Dell Road, is a closed depression formed by recurring surface fault rupture along the San Andreas fault. *Photo by W. A. Bryant, 10/18/89.*

THE LOMA PRIETA (SANTA CRUZ MOUNTAINS), CALIFORNIA, EARTHQUAKE OF 17 OCTOBER 1989

Edited by

Stephen R. McNutt and Robert H. Sydnor

Special Publication 104

1990

Department of Conservation
Division of Mines and Geology
1416 Ninth Street, Room 1341
Sacramento, CA 95814

Oblique high-altitude U-2 photograph of the damaged San Francisco-Oakland Bay Bridge (A) and collapsed Cypress segment of I-880 Nimitz Freeway (B) taken on October 18, 1989, the morning after the earthquake (courtesy of USAF). The image was captured by an IRIS-II panoramic aerial camera looking northeast from an altitude of about 65,000 feet (see article by Real and others, this volume).

CONTENTS

INTRODUCTION

by

Stephen R. McNutt and Robert H. Sydnor

The Loma Prieta earthquake of 17 October 1989 did more to make people in California aware of earthquake hazards than any other single event of the last 18 years. The event killed 63 people, injured 3,757, left over 12,000 homeless, and caused over $5.9 billion in damage (California Office of Emergency Services, written communication, April 12, 1990). Damage occurred over a wide area (Figure 1) and included effects of strong shaking and various forms of ground failure including liquefaction. The earthquake has provided a wealth of new data, has prompted new legislation, and has refocused discussions on numerous topics related to hazards mitigation.

A significant earthquake always provides an opportunity to learn, to respond, and to refocus hazard mitigation efforts. This Special Publication primarily documents actions of the California Department of Conservation's Division of Mines and Geology (DMG) to respond to and study the earthquake. The report contains a variety of information on seismological and geological features of the event. The intended readers are primarily other researchers and government agencies, but much of the information provided will also be useful to the media and the public.

DMG ROLE AND ORGANIZATION

DMG is the State geological survey, with a staff of 144 people and an annual budget of approximately $12 million. It has three primary functions: (1) Geologic Hazards Reduction - to prevent loss of life and property from geologic phenomena including earthquakes, fault movements, volcanic eruptions, landslides, and erosion; (2) Mineral Resources Conservation - to promote the development, use and reclamation of land and mineral resources consistent with sound conservation practices; and (3) Basic Investigations - to establish and maintain a baseline of geological, geophysical, and seismological information.

The organization consists of five main programs, four of which responded to the 17 October 1989 earthquake. The five are: (1) Environmental Protection; (2) Geologic Hazards Assessment; (3) Earthquake Engineering; (4) Geologic Information and Support; and (5) Mineral Resource Development (no response). Response consisted of collecting, compiling, analyzing, and interpreting a wide variety of data and communicating results to many levels of users.

DMG has produced Special Publications and other books on significant earthquakes since the Kern County earthquake of 1952 (Oakeshott, 1955). The most recent such efforts were Special Publication 66 on the 1983 Coalinga earthquake (Bennett and Sherburne, 1983) and Special Publication 68 on the 1984 Morgan Hill earthquake (Bennett and Sherburne, 1984). DMG produces such reports when specific circumstances warrant the effort.

CONTENTS OF THIS REPORT

This report is a collection of 14 papers representing the efforts of 35 authors. Most of the papers are by DMG staff members and thus provide a record of DMG actions. The editorial philosophy was to allow each paper to stand alone and to include the appropriate and necessary papers so that the pertinent information was contained in one volume. The time frame of the publication (about 4 to 6 months after the earthquake) permitted the information contained to be more complete than initial reports that were prepared about one month after the event. Many results, however, cannot yet be regarded as definitive.

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 (source: Plafker and Galloway, 1989).

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

Main shock epicenter

Area of aftershocks and abundant landslides

Area of ground cracks possibly related to faulting

Approximate limit of major structural damage

Approximate limit of landslides

(L) Prominent area of liquefaction

(B) Damaged bridge

(D) Damaged dam

(V) Damaged two-story viaduct

Figure 1. Continued

This Special Publication is divided into three sections. The first focuses on the earthquake itself and its geologic and seismologic setting. The second section focuses on selected effects of the earthquake and study by several DMG programs. Key contributions are those on strong ground motion, landslides, and fault evaluation. The third section focuses on response and evaluation.

Special effort has gone into providing many high quality figures and complete tables throughout the publication. This was done to make the volume useful as a reference work on the Loma Prieta earthquake and on related geologic phenomena. For example, much of the information contained in the volume will be useful as background information when the next M≥ 7 earthquake strikes California.

The choice of topics was made to highlight DMG activities and to provide balance. However, it was not possible to cover every aspect of the earthquake. For example, liquefaction and several engineering aspects of the event have received only limited attention here. These have received adequate attention elsewhere (e.g., Plafker and Galloway, 1989).

GENERAL INFORMATION

The Loma Prieta earthquake epicenter is located in the Laurel quadrangle, U.S. Geological Survey 7.5-Minute Series (Topographic), and immediately adjacent to the Loma Prieta quadrangle of the same series. The epicenter was located in the Forest of Nisene Marks State Park. The event occurred in the southern Santa Cruz Mountains, a physiographic feature which appears in most world atlases; Loma Prieta is the highest peak in these mountains and is located just a few kilometers from the epicenter.

Under contract from the California Coastal Commission, the Division of Mines and Geology and the U. S. Geological Survey have cooperatively prepared a comprehensive set of seven regional geologic maps which cover the entire California continental margin at a scale of 1:250,000. Map area 5, covering the Santa Cruz and Monterey Bay area, is scheduled to be published in mid-1990; see Cockerham and others (1990) and McCulloch and Greene (1990).

The new 1:750,000-scale State Fault Activity Map (Jennings, 1991, in preparation) will delineate active faults in California using a five color classification scheme for recency of faulting.

Metric units have been used throughout most of this volume, reflecting standard scientific practice worldwide. An exception is found in the article by Real and others; both photography and aviation use English units as standards. (One kilometer is equal to 0.62 miles, or conversely one mile equals 1.61 kilometers. One meter is equal to 39.4 inches, or one foot equals 0.30 meters).

The earthquake occurred on October 17, 1989 at 5:04 p.m. Pacific Daylight Time (PDT, local time). This has created some confusion because it occurred on October 18, 1989 at 00:04 Greenwich Mean Time (GMT; also called Universal Time Coordinated or UTC). Further, a local time change occurred on October 29, 1989. Up until October 29, GMT was equal to local time (PDT) plus 7 hours; after October 29, GMT was equal to local time (PST) plus 8 hours.

Additional copies of this publication and other maps and publications of DMG may be obtained by writing to the Publications and Information Office, Division of Mines and Geology, 660 Bercut Drive, Sacramento, CA 95814-0131.

REFERENCES

Bennett, J.H., and Sherburne, R.W., eds., 1983, The 1983 Coalinga, California Earthquakes: California Division of Mines and Geology, Special Publication 66, 335 p.

Bennett, J.H., and Sherburne, R.W., eds., 1984, The 1984 Morgan Hill, California, Earthquake: California Division of Mines and Geology, Special Publication 68, 271 p.

Cockerham, R. S., McCulloch, D. S., and Greene, H. G., 1990, Earthquake epicenters and selected fault-plane solutions of the central California Continental Margin: California Division of Mines and Geology, Geology of the California Continental Margin Geologic Map Series, Map 5-B, Sheet 2 of 4, scale 1:250,000.

Jennings, C. W., compiler, 1991 (in preparation), State Fault Activity Map: California Division of Mines and Geology, Geologic Data Series, Map No. 6, scale 1:750,000.

McCulloch, D. S., and Greene, H. G., 1990, Geologic map of the central California Continental Margin: California Division of Mines and Geology, Geology of the California Continental Margin Geologic Map Series, Map 5-A, Sheet 1 of 4, scale 1:250,000.

Oakeshott, G.B., ed., 1955, Earthquakes in Kern County California during 1952: California Division of Mines and Geology Bulletin 171, 283 p.

Plafker, G., and Galloway, J. P., eds., 1989, Lessons learned from the Loma Prieta, California, earthquake of October 17, 1989: U. S. Geological Survey Circular 1045, 48 p.

ACKNOWLEDGMENTS

The editors would like to thank all of the authors for their contributions and for cooperating with our rapid publication schedule. The DMG Publications group performed admirably throughout the preparation of this document In particular, we thank Robert Streitz, Jeff Tambert, Ross Martin, Carol Allen, Dinah Maldonado, Joy Sullivan and Margaret Walker for their efforts in drafting and production.

Finally, we thank all the reviewers and proofreaders. In addition to those persons listed at the end of each paper, we thank Michael Reichle, Anthony Shakal, James Davis, Joseph Ziony, Terry Lawler, and Alison Kenward.

SECTION I
The Earthquake

GEOLOGIC AND TECTONIC SETTING OF THE EPICENTRAL AREA OF THE LOMA PRIETA EARTHQUAKE, SANTA CRUZ MOUNTAINS, CENTRAL CALIFORNIA

by

David L. Wagner[1]

ABSTRACT

Movement along the San Andreas fault in the southern Santa Cruz Mountains caused the Loma Prieta earthquake of October 17, 1989. The San Andreas fault bisects the Santa Cruz Mountains in a northwesterly direction and is a boundary between two large crustal plates, the Pacific plate to the west and the North American plate to the east. Movement of the Pacific plate relative to the North American plate has juxtaposed geologically different basement terranes as well as sedimentary cover.

West of the San Andreas fault, continental granitic basement of the Salinian block is overlain by marine sedimentary and volcanic formations. East of the fault the basement is a heterogenous assemblage of oceanic rocks of the Franciscan Complex. Tertiary sedimentary and volcanic formations that overlie Franciscan basement superficially resemble those immediately across the fault but detailed studies show that they originated far apart.

Displacement along the San Andreas fault in central California has been variable over the past 30 million years. Changes in direction and rate of relative movement between the North American and Pacific plates are responsible for sedimentation patterns and tectonic events in the Santa Cruz Mountains. During periods of rapid plate movement that is oblique to the plate boundary, folding, reverse faulting, and uplift occur. When plate movement is slow, normal faulting occurs and sedimentary basins form. For about the past 3 million years the plate movement has been relatively rapid and there is a significant component of compression in a NE-SW direction, normal to the San Andreas fault. As a result, reverse faulting and uplift are occurring, typified by the 1989 Loma Prieta earthquake.

INTRODUCTION

The Loma Prieta earthquake of October 17, 1989 was the latest increment of displacement along the San Andreas fault that has been occurring over the last 30 million years. During this span of geologic time, distinctive rock types and geologic features have been offset 300 to 330 km along the San Andreas fault in central California (Nilsen and Clarke, 1975; Graham and others, 1989). The rocks, structure, and geomorphology of the Santa Cruz Mountains are a direct consequence of movement and associated deformation along the San Andreas fault.

The Santa Cruz Mountains are a sparsely populated, moderately rugged, heavily forested range that extends from the San Francisco peninsula southward to the Pajaro River east of Watsonville (Figure 1). Most of the uplift of the Santa Cruz Mountains occurred in the last few million years. In response to this rapid uplift, streams have vigorously cut through the fairly weak marine sedimentary rocks that underlie much of the range, forming deep steep-walled canyons. Slope failures are common, and as a result, thick unstable landslide deposits cover much of the range.

REGIONAL TECTONIC SETTING

The coast ranges of central California are a series of mountain ranges and valleys that trend northwest, parallel to the San Andreas fault. Geologically the region is a collage of fault-bounded tectonic blocks. All of the boundary faults between the blocks are part of the San Andreas fault system (Figure 1). The San Andreas fault system is a boundary between two major parts of the earth's crust, the North American plate and the Pacific plate. The Pacific plate has moved northwesterly relative to the North American plate at an average rate of about 40 mm/yr during late Cenozoic time (Stock and Molnar, 1988). This plate movement causes the displacement and the accompanying earthquakes along the San Andreas and related faults. Changes in the direction and rate of relative movement of the Pacific and North American plates have caused periods of folding, faulting, and uplift in the Santa Cruz Mountains as well as the rest of central California (Page and Engebretson, 1984).

[1]California Department of Conservation, Division of Mines and Geology, Geologic Information and Support Program

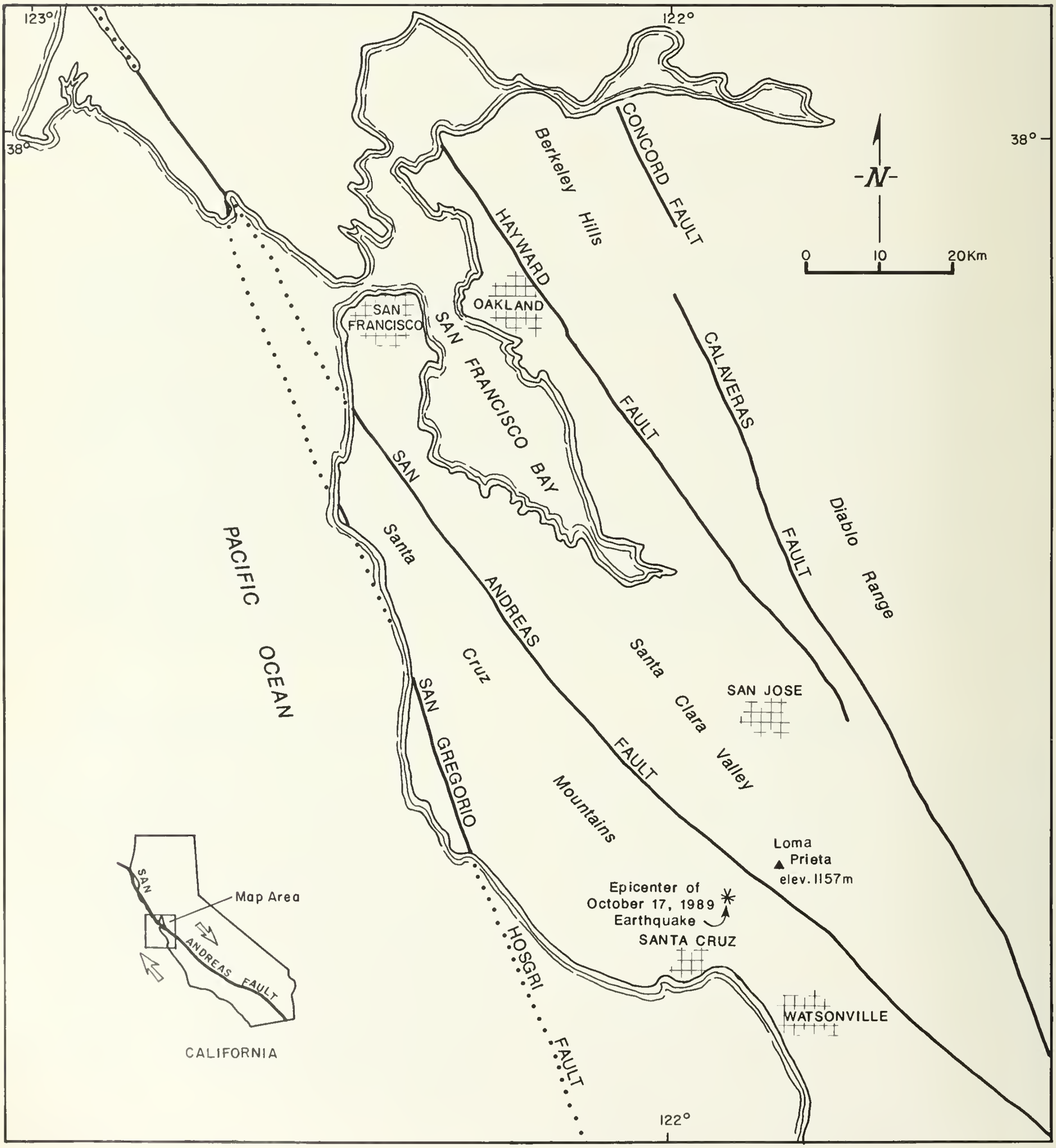


Figure 1. Map of the San Francisco Bay area showing faults that make up the San Andreas fault system.

GEOLOGY OF THE SANTA CRUZ MOUNTAINS

Movement along the San Andreas fault juxtaposes tectonic blocks of distinctly different basement lithologies in the central California coast ranges (Figure 2). Northeast of the fault Cenozoic sedimentary and volcanic rocks overlie a basement of heterogenous, highly deformed oceanic rocks of the Mesozoic Franciscan Complex. Southwest of the fault the basement is, for the most part, continental crust of granitic and metamorphic rocks known as the Salinian block (Figure 2). Although the San Andreas is the boundary between Franciscan rocks and the Salinian block, in places Franciscan rocks do occur west of the fault. The Pilarcitos block (Figure 3) is a sliver of basement rocks of the Franciscan Complex west of San Andreas. These rocks are thought to be evidence that Franciscan rocks underlie part of the central Santa Cruz Mountains (Stanley, 1985).

Rock Units Southwest of the San Andreas Fault. The part of the Salinian block that underlies the Santa Cruz Mountains was subdivided into subblocks by Stanley (1985) as shown on Figure 3. Two of these subblocks, the La Honda block and the Ben Lomond block, underlie the epicentral area of the Loma Prieta earthquake. The La Honda block is composed of the bulk of the Tertiary formations of the central Santa Cruz Mountains (Figures 3 and 4). These formations were deposited in the La Honda basin (Cummings and others, 1962). To the southwest, the La Honda basin was bounded by the Ben Lomond block, a granitic highland that provided sediment to the La Honda basin (Graham and others, 1989; Nilsen and Clarke, 1975).

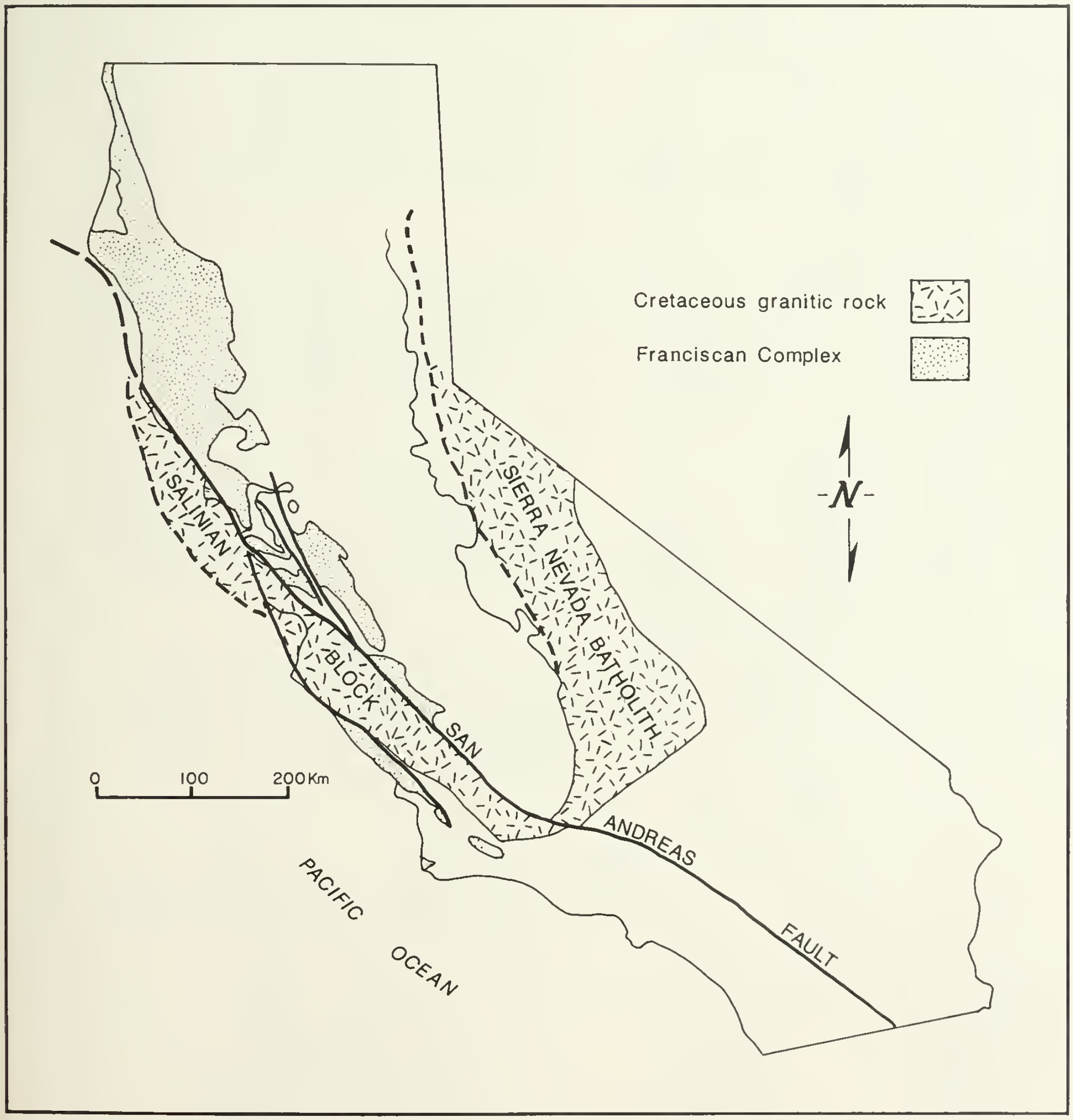


Figure 2. Map of California showing the distribution of contrasting basement rock types in parts of central and northern California. Movement along the San Andreas fault has juxtaposed the Salinian block composed of Cretaceous-age granitic rock with basement composed of rocks of the Franciscan Complex. Modified from Page (1981).

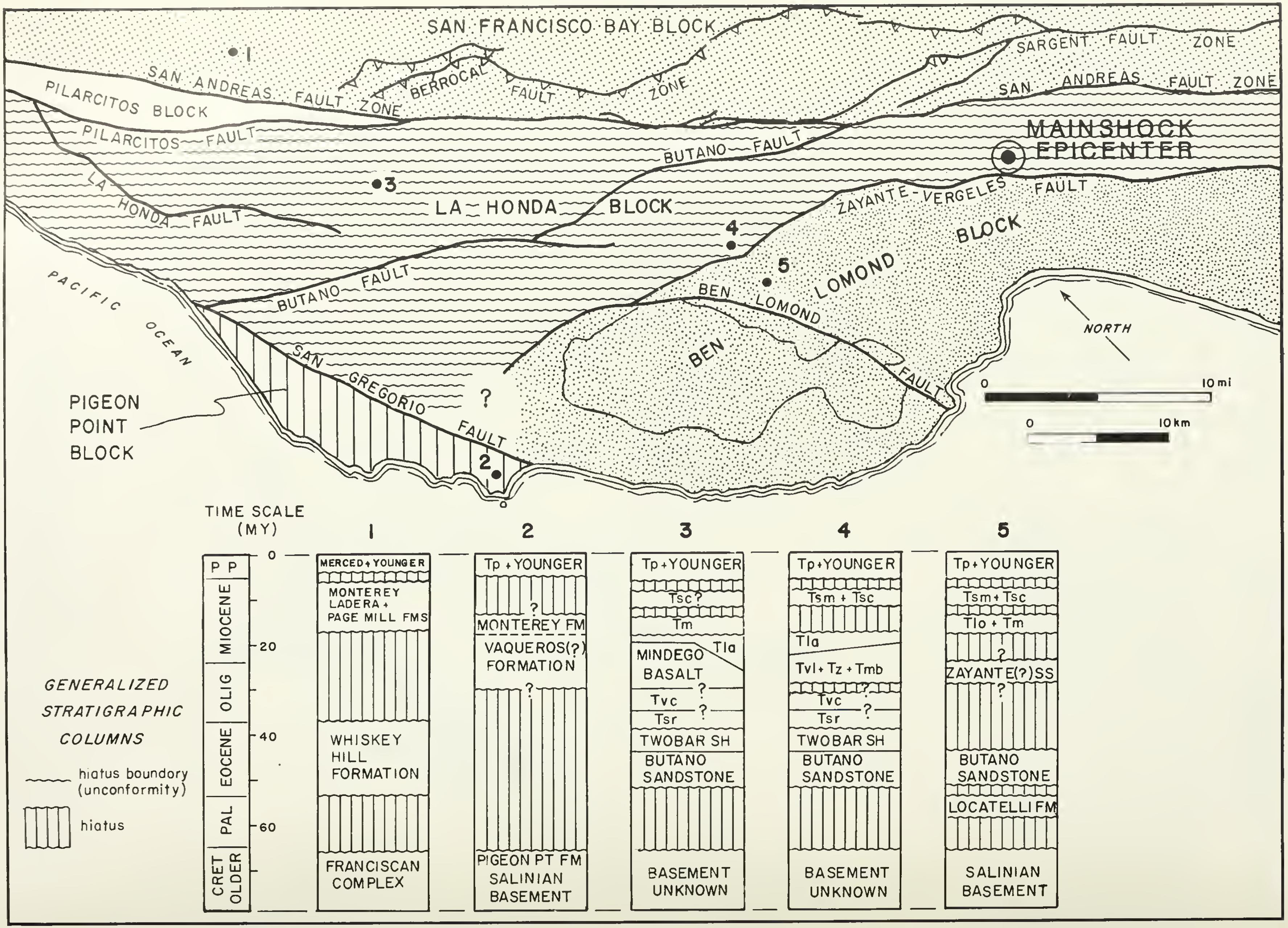


Figure 3. Map of fault-bounded blocks and representative stratigraphic columns in the Santa Cruz Mountains. Tp-Purisma Fm.; Tsc-Santa Cruz Mudstone; Tsm-Santa Margarita Fm.; Tm-Monterey Fm.; Tlo-Lompico Fm.; Tla-Lambert shale; Tmb-Mindego Basalt; Tvc, Tvl--Vaqueros Sandstone; Tsr-Rices Mudstone. Slightly modified from Stanley (1985).

CENTRAL SANTA CRUZ MOUNTAINS

BRABB, 1970, AND CLARK AND BRABB, 1978	
UPPER MIOCENE TO PLIOCENE SEQUENCE	PURISIMA FORMATION SANTA CRUZ MUDSTONE SANTA MARGARITA SANDSTONE
MIDDLE MIOCENE SEQUENCE	MONTEREY SHALE (OR MONTEREY FORMATION) LOMPICO SANDSTONE
EOCENE TO LOWER MIOCENE SEQUENCE	LAMBERT SHALE MINDEGO BASALT VAQUEROS SANDSTONE ZAYANTE SANDSTONE SAN LORENZO FORMATION --RICES MUDSTONE MEMBER --TWOBAR SHALE MEMBER BUTANO SANDSTONE
PALEOCENE SEQUENCE	LOCATELLI FORMATION
SALINIAN BASEMENT	

STANLEY, 1985	
PURISIMA FORMATION	UPPER MIOCENE TO PLIOCENE SEQUENCE
SANTA CRUZ MUDSTONE SANTA MARGARITA SANDSTONE	MIDDLE TO UPPER MIOCENE SEQUENCE
MONTEREY FORMATION LOMPICO SANDSTONE	LOWER TO MIDDLE MIOCENE SEQUENCE
LAMBERT SHALE MINDEGO BASALT ZAYANTE SANDSTONE VAQUEROS SANDSTONE OF THE WOODSIDE AREA VAQUEROS SANDSTONE: --LAUREL UNIT --CASTLE ROCK UNIT SAN LORENZO FORMATION --RICES MUDSTONE MEMBER ----BLOOMS CREEK SANDSTONE --TWOBAR SHALE MEMBER BUTANO SANDSTONE	EOCENE TO LOWER MIOCENE SEQUENCE
LOCATELLI FORMATION	PALEOCENE SEQUENCE
SALINIAN BASEMENT ON BEN LOMOND BLOCK: BASEMENT UNKNOWN ON LA HONDA BLOCK.	

SAN ANDREAS FAULT

EASTERN SANTA CRUZ MOUNTAINS

BEAULIEU, 1970	
SANTA CLARA FORMATION MERCED FORMATION	
MONTEREY FORMATION LADERA SANDSTONE PAGE MILL BASALT	LOWER TO MIDDLE MIOCENE
WHISKEY HILL FORMATION	EOCENE
FRANCISCAN BASEMENT	

Figure 4. Stratigraphic columns of the Santa Cruz Mountains. Stanley (1985) revised the stratigraphy of Brabb (1970) and Clark and Brabb (1978) and seperated an upper Miocene depositional sequence west of the San Andreas fault. Beaulieu (1970) concluded that the Butano Formation shown on older maps on both sides of the San Andreas fault (Dibblee, 1966) are different formations. The wavy lines are unconformities of regional extent.

Stanley (1985) modified the Tertiary formations described by previous authors (Cummings and others, 1962; Brabb, 1970; Clark, 1981) into five "depositional sequences" (Figures 3 and 4): (1) a Paleocene sequence, (2) an Eocene to lower Miocene sequence, (3) a lower to middle Miocene sequence, (4) a middle to upper Miocene sequence, and (5) an upper Miocene to Pliocene sequence. Boundaries between each of the five sequences are unconformities.

The Paleocene sequence consists of the Locatelli Formation. Patches of sandstone, mudstone, and conglomerate of the Locatelli Formation rest unconformably on granitic basement of the Ben Lomond block. The Locatelli Formation has not been positively identified on the La Honda block.

The Eocene to lower Miocene sequence consists of the Butano Sandstone, the San Lorenzo Formation, the Vaqueros Sandstone, the Zayante Sandstone, the Mindego Basalt, and the Lambert Shale. These units account for the bulk of the sedimentary fill of the La Honda basin.

The Eocene Butano Sandstone is the oldest formation of the Eocene to lower Miocene sequence. It overlies the granitic Ben Lomond block but its base has not been observed on the La Honda block. The Butano Sandstone is correlated with the Point of Rocks Sandstone of the Temblor Range (Clarke and Nilsen, 1973), 300 to 330 km to the southeast across the San Andreas fault. This indicates that the La Honda basin was continuous with the San Joaquin basin prior to the existence of the modern San Andreas fault (Stanley, 1985; Graham and others, 1989).

The San Lorenzo Formation, the Vaqueros Sandstone, and the Zayante Sandstone overlie the Butano Sandstone and are widespread on the La Honda block. These units are stratigraphically complex and are described in detail by Stanley (1985).

The Mindego Basalt was erupted into the La Honda basin from about 20 to 25 Ma (Stanley, 1985). Flows, tuffs, breccia, pillow lavas, and intrusive rocks were erupted from submarine vents, probably near the center of the La Honda basin. Overlying the Mindego Basalt is the Lambert Shale, a unit that is widespread on the La Honda block but not known on the Ben Lomond block.

The middle Miocene sequence of the Santa Cruz Mountains is represented by the Lompico Sandstone and the Monterey Formation. The Monterey Formation consists of siliceous and calcareous shale, mudstone, and sandstone. Patches of Monterey Formation are present throughout the Santa Cruz Mountains suggesting it was once much more extensive than it is today (Stanley, 1985).

An angular unconformity separates the lower Miocene sequence from the upper Miocene sequence. The upper Miocene sequence consists of the Santa Margarita Sandstone and the Santa Cruz Mudstone. The thickest part of the lower Santa Margarita Sandstone apparently was deposited in an 8- to 10-km-wide seaway that connected the San Joaquin basin to the Pacific Ocean (Phillips, 1983). Large cross beds in the sandstone were formed by strong tidal currents in the northeast-trending seaway that, eventually, was truncated by displacement along the San Andreas fault. The overlying Santa Cruz Mudstone was deposited in deepening water caused by marine transgression (Phillips, 1983).

The upper Miocene to upper Pliocene Purisima Formation is the youngest and most widespread Tertiary formation in the Santa Cruz Mountains. The Purisima is present throughout the Santa Cruz Mountains and is widespread offshore (Greene, 1977). Quaternary deposits including the Aromas Sand, marine and fluvial terrace deposits, and alluvium overlie the Purisima Formation.

Rock Units Northeast of the San Andreas Fault. Northeast of the San Andreas fault is the San Francisco Bay block (Figure 3). Heterogenous sedimentary, igneous, and metamorphic rocks of the Franciscan Complex form the basement of the San Francisco Bay block. Tertiary and Quaternary sedimentary rocks overlie the Franciscan basement.

Rocks of the Franciscan Complex include graywacke, shale, altered basaltic rock (greenstone), chert, limestone, conglomerate, and metamorphic rocks which are Late Jurassic through Late Cretaceous in age. Associated with the Franciscan Complex, is green to black serpentine, which has been incorporated into the Franciscan by complicated tectonic processes. Franciscan rocks have diverse geologic and geographic origins; they came together when the Farallon plate was subducted (underthrust) beneath the North American plate (Figure 6).

The Tertiary formations that overlie the Franciscan are superficially similar to those of the La Honda basin west of the San Andreas fault so the same stratigraphic nomenclature is common to both areas (Dibblee, 1966). However, Beaulieu (1970) compared the stratigraphic units on either side of the San Andreas and found significant differences in age and environment of deposition and renamed some of the formations (Figures 3 and 4). He concluded that the formations were deposited at sites far apart and were subsequently juxtaposed by movement along the San Andreas fault.

Landslides. Landslides are a common geologic feature of the Santa Cruz Mountains on both sides of the San Andreas fault. The mountain range has been uplifted rapidly over the last two to three million years, and as a result, the slopes are steep and prone to landsliding. Some coalescing landslides may cover entire slopes that are many square kilometers in extent (see Spittler and others, this volume).

FAULTING AND FOLDING IN THE SANTA CRUZ MOUNTAINS

Faults and folds in the Santa Cruz Mountains (Figure 5 and Brabb, 1989) are the result of wrench tectonics caused by interaction of the North American plate with the Pacific plate and the now subducted Farallon plate (Figure 6). Consequently most of the faults and folds trend northwest, parallel to the plate boundary.

San Andreas and Related Faults. Large-scale lateral displacement along the San Andreas fault was first recognized by Hill and Dibblee (1953) who documented 500 to 600 km of right-lateral displacement since the Late Cretaceous. They also presented data that suggested that displacement decreased with decreasing age of the offset geologic features. Thus, Hill and Dibblee treated the San Andreas as a continuous fault zone along which movement occurred at a consistent rate. Subsequent studies (Crowell, 1962, Nilsen and Clarke, 1975; Dickinson and Snyder, 1979) have shown that the San Andreas is a complex system of related faults. Evidence for episodic, not continuous, activity along the San Andreas fault is abundant (Sims, 1989).

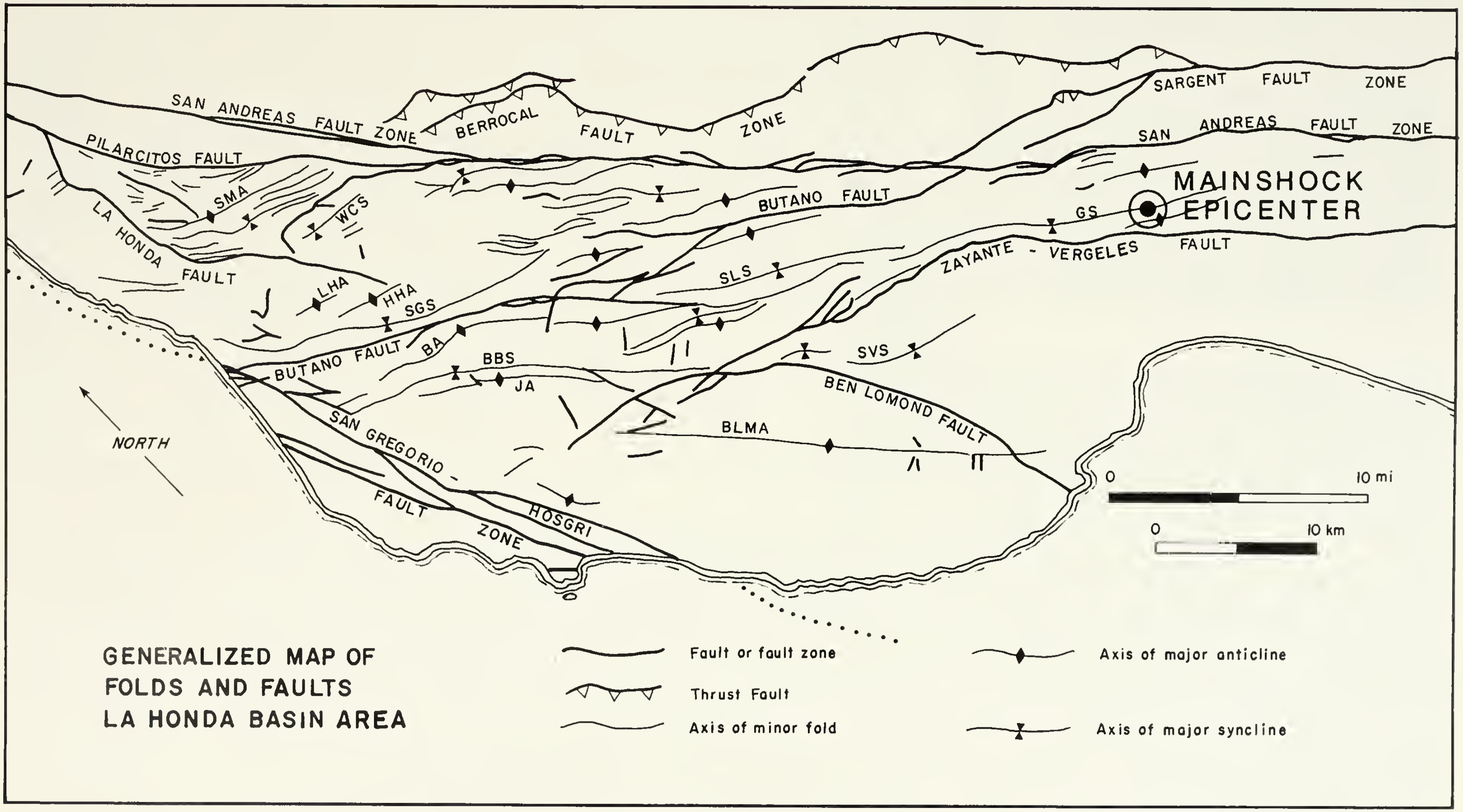


Figure 5. Generalized map of faults and folds southwest of the San Andreas fault modified from Stanley (1985). Berrocal and Sargent fault zones from McLaughlin (1974). Major folds are labeled as follows: BA-Butano anticline, BBS-Big Basin syncline, BLMA-Ben Lomond Mountain anticline, GS-Glenwood syncline, HHA-Haskin Hill anticline, JA-Johansen anticline, LHA-La Honda anticline, SGS-San Gregorio syncline, SLS-San Lorenzo syncline, SMA-San Morena anticline, SVS-Scotts Valley syncline, WCS-Weeks Creek syncline.

Atwater (1970) first applied plate tectonic theory to the San Andreas fault. She showed that San Andreas is a boundary between plates of the earth's crust and that movement along the fault system is a result of interaction between the plates. The plate tectonic model was later refined (Carlson, 1982) to show three stages of the San Andreas fault system since Late Cretaceous time (Figure 6). The first stage, prior to 42 Ma, was the subduction of the Farallon plate beneath the North American plate. Oblique convergence in this stage resulted in right- lateral displacement along an ancestral San Andreas fault. During this stage, the parts of the Salinian block that would eventually be the basement of the Ben Lomond and La Honda blocks were juxtaposed in what is now the Santa Cruz Mountains. During the second stage, 42 to 30 Ma, convergence between the Farallon plate and the North American plate was normal to the plate boundary so there was no right-lateral displacement between the two plates. By 30 Ma, the Farallon plate was entirely consumed by subduction, marking the birth of the San Andreas transform system (Atwater, 1970), and resumption of right-lateral displacement along the San Andreas fault in central California. Sims (1989) has provided evidence that the rate of movement along the San Andreas fault has varied. During the past five million years, the rate of slip along the San Andreas fault has averaged about 33 mm/yr according to Sims, greater than any time since its inception 30 million years ago.

At present, the Pacific plate continues to move rapidly past the North American plate at a rate of 48 mm/yr (DeMets and others, 1987). However, in the Santa Cruz Mountains, the San Andreas fault accounts for about 13 mm/yr of this movement (Minster and Jordan, 1987). Additional movement is accommodated by other faults in the San Andreas system, notably the San Gregorio - Hosgri as well as some deformation east of the Coast Ranges. Graham and Dickinson (1978) showed that geologic features have been offset 115 km along the San Gregorio - Hosgri fault since the Miocene. According to Minster and Jordan (1987), there is a significant component of compression, about 9 mm/yr, in a northeast-southwest direction across the San Andreas fault. This is consistent with the subsurface movement during the Loma Prieta earthquake. Movement was in a reverse oblique sense, along a fault plane that dips 70° to the southwest (Plafker and Galloway, 1989). Right-lateral displacement was calculated to be 1.6 ± 0.3 m (5.3 ft), reverse slip was 1.2 ± 0.3 m (3.9 ft), and Santa Cruz Mountains were uplifted about 36 cm (14 in) according to Lisowski and others (1990) and Plafker and Galloway (1989, p. 6).

Other Faults in the Santa Cruz Mountains. Between the San Andreas and the San Gregorio-Hosgri fault zones there are several predominantly dip-slip faults (Figure 5). These are the Zayante-Vergeles, Ben Lomond, Butano, La Honda, and Pilarcitos faults. East of the San Andreas fault is the Sargent- Berrocal fault zone.

The Zayante-Vergeles fault may have developed about the same time as the San Andreas and profoundly affected the sedimentary history of the Santa Cruz Mountains (Clark and Rietman, 1973). This fault is considered to be a normal fault by Clark and Rietman (1973), but it could be a strike-slip fault (Stanley, 1985). Fault-related features and the occurrence of small earthquakes may suggest that Zayante-Vergeles fault is an active branch of the modern San Andreas system (Coppersmith, 1979). The epicenter of the Loma Prieta earthquake coincides with the mapped surface trace of the Zayante-Vergeles fault, but the mainshock and the aftershock sequence do not coincide (Plafker and Galloway, 1989, p. 7).

The Ben Lomond, Butano, La Honda, and Pilarcitos faults are poorly exposed and little is known about them. The Ben Lomond fault is a curved fault and may have been active into Pleistocene time (Stanley and McCaffrey 1983). Little is known about the Butano and La Honda faults. The Pilarcitos fault could be an inactive abandoned trace of the San Andreas.

East of the San Andreas fault, faulting is dominated by reverse faults of the Sargent-Berrocal fault zone (McLaughlin, 1974). The Sargent fault is a reverse fault that dips steeply to the west (McLaugh-

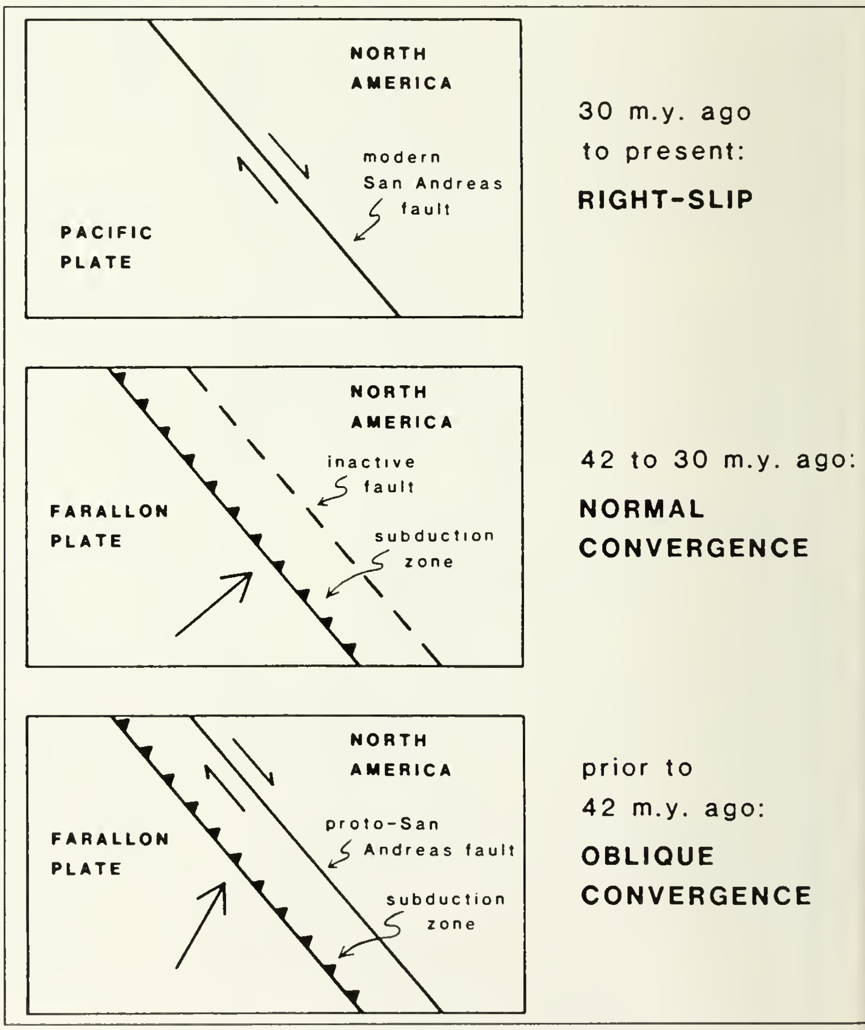


Figure 6. Schematic illustration of the three-stage history of plate interactions in the development of the San Andreas fault, modified from Carlson (1982) by Stanley (1985).

lin, 1974; McLaughlin and others, 1989). The Sargent fault is seismically active (McLaughlin, 1974) and shows evidence of surface movement during Holocene time (Bryant and others, 1981), but its relationship to the San Andreas fault is unknown. To the north is the Berrocal fault zone, a complex thrust fault that dips 5°-75° to the southwest beneath the Santa Cruz Mountains and is vertical in some places (McLaughlin, 1974). Franciscan rocks may be thrust as much as 2.3 km eastward over Cenozoic rocks along the Berrocal fault zone (McLaughlin, 1974).

Folds in the Santa Cruz Mountains. Northwest trending folding is a conspicuous feature of the Santa Cruz Mountains, particularly on the La Honda block (Figure 5). Folds on the La Honda block are isoclinal and overturned in contrast to the broad folds on the Ben Lomond block. Stanley (1985) attributes this to the proximity of the La Honda block to the San Andreas and the rigid granitic rock of the Salinian basement.

During Cenozoic time, episodes of folding and uplift have alternated with episodes of subsidence, basin formation, and marine transgression in Santa Cruz Mountains. These episodes have been related to changes in rates and direction of plate movement (Page and Engebretson, 1984). During periods of rapid plate movement that is oblique to the plate boundary, folding, reverse faulting, and uplift occur. During periods of slow plate movement, rifting causes sedimentary basins to form, and marine transgression occurs.

ACKNOWLEDGMENTS

Early versions of this paper were reviewed by John D. Sims, Charles W. Jennings, George J. Saucedo, and Robert H. Sydnor. Their comments are greatly appreciated. The figures were prepared by Dinah Maldonado, and Heidi Kruger typed the manuscript.

REFERENCES

Atwater, T., 1970, Implication of plate tectonics for the evolution of western North America: Geological Society of America Bulletin, v. 81, p. 3513-3536.

Beaulieu, J.D., 1970, Cenozoic stratigraphy of the Santa Cruz Mountains (Ph.D. thesis): Stanford University, 202 p.

Brabb, E.E., 1970, Preliminary geologic map of the central Santa Cruz Mountains, California: U.S. Geological Survey Open-File Map, scale 1:62,500.

Brabb, E.E., 1989, Geologic map of Santa Cruz County, California: U.S. Geological Survey Miscellaneous Investigations Series Map I-1905, scale 1:62,500.

Bryant, W.A., Smith, D.P., and Hart, E.W., 1981, The Sargent, San Andreas, and Calaveras fault zones: evidence for recency in Watsonville East, Chittenden, and San Felipe quadrangles, Monterey, San Benito, Santa Clara, and Santa Cruz counties, California: California Division of Mines and Geology Open-File Report 81-7.

Carlson, R.L., 1982, Cenozoic convergence along the California coast: a qualitative test of the hot-spot approximation: Geology, v. 10, p. 191-196.

Clark, J.C., 1981, Stratigraphy, paleontology, and geology of the central Santa Cruz Mountains, California Coast Ranges: U.S. Geological Survey Professional Paper 1168, 51 p.

Clark, J. C., and Brabb, E. E., 1978, Stratigraphic contrasts across the San Gregorio fault, Santa Cruz Mountains, west central California, *in* Silver, E. A., and Normark, W. R., eds., San Gregorio-Hosgri fault zone, California: California Division of Mines and Geology Special Report 137, p. 3-12.

Clark, J.C., and Rietman, J.D., 1973, Oligocene stratigraphy tectonics, and paleogeography southwest of the San Andreas fault, Santa Cruz Mountains and Gabilan Range, California Coast Ranges: U.S. Geological Survey Professional Paper 783, 18 p.

Clarke, S.H., Jr., and Nilsen, T.H., 1973, Displacement of Eocene strata and implications for the history of offset along the San Andreas fault, central and northern California, *in* Kovach, R.L., and Nur, A., eds., Proceedings of the conference on the tectonic problems of the San Andreas fault system: Stanford University Publications in Geological Sciences, v. 3, p. 368-367.

Coppersmith, K.J., 1979, Activity assessment of the Zayante-Vergeles fault, central San Andreas fault system, California (Ph.D. thesis): University of California, Santa Cruz, 333 p.

Crowell, J.C., 1962, Displacement along the San Andreas fault, California: Geological Society of America Special Paper 71, 61 p.

Cummings, J.C., Touring, R.M., Brabb, E.E., 1962, Geology of the northern Santa Cruz Mountains, California, *in* Bowen, O.E., Jr., ed., Geologic guide to the oil and gas fields of northern California: California Division of Mines and Geology Bulletin 181, p. 179-220.

DeMets, C., Gordon, R.G., Stein, S., and Argus, D.F., 1987, A revised estimate of Pacific-North American motion and implications for western North America plate boundary zone tectonics: Geophysical Research Letters, v. 14, p. 911-921.

Dibblee, T.W., Jr., 1966, Geologic map and sections of the Palo Alto 15-minute quadrangle, Santa Clara and San Mateo counties, California: California Division of Mines and Geology Map Sheet 8, scale 1:62,500.

Dickinson, W.R., and Snyder, W.S., 1979, Geometry of triple junctions related to San Andreas transform: Journal of Geophysical Research, v. 84, p. 561-571.

Graham, S.A. and Dickinson, W.R., 1978, Apparent offsets of on-land geologic features across the San Gregorio-Hosgri fault trend: California Division of Mines and Geology Special Report 137, p. 13-23.

Graham, S.A., Stanley, R.G., Bent, J.V., and Carter, J.B., 1989, Oligocene and Miocene paleogeography of central California and displacement along the San Andreas fault: Geological Society of America, v. 101, p. 711-730.

Greene, H.G., 1977, Geology of the Monterey Bay region: U.S. Geological Survey Open-File Report, 77-718, 314 p.

Hill, M.L., and Dibblee, T.W., Jr., 1953, San Andreas, Garlock, and Big Pine faults, California — a study of the character, history, and tectonic significance of their displacements: Geological Society of America Bulletin, v. 64, p. 443-458.

Lisowski, M., Prescott, W.H., Savage, J.C., and Svarc, J.L., 1990, A possible geodetic anomaly observed prior to the Loma Prieta, California, earthquake: Geophysical Research Letters, v. 17, p. 1211-1214.

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, p. 593-598.

McLaughlin, R.J., Clark, J.C., and Brabb, E.E., 1989, Geologic map and structure sections of the Loma Prieta 7.5-minute quadrangle, Santa Clara and Santa Cruz Counties, California: U.S. Geological Survey Open-File Report 88-752, scale 1:24,000.

Minster, J.B., and Jordan, T.H., 1987, Vector constraints on western U.S. deformation from space geodesy, neotectonics, and plate motions: Journal of Geophysical Research, v. 92, p. 4298-4304.

Nilsen, T.H., and Clarke, S.H., Jr., 1975, Sedimentation and tectonics in the early Tertiary continental borderland of central California: U.S. Geological Survey Professional Paper 925, 64 p.

Page, B.M., 1981, The Southern Coast Ranges, *in* Ernst, W.G., ed., The geotectonic development of California, Rubey Volume I: Prentice-Hall, Englewood Cliffs, New Jersey, p. 329-417.

Page, B.M., and Engebretson, D.C., 1984, Correlation between the geologic record and computed plate motions for central California: Tectonics, v. 3, p. 133-156.

Phillips, R.L., 1983, Late Miocene tidal shelf sedimentation, Santa Cruz Mountains, California, *in* Larue, D.K., and Steele, R.J., eds., Cenozoic marine sedimentation Pacific Margin, U.S.A.: Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 45-61.

Plafker, G. and Galloway, J.P., eds., 1989, Lessons learned from the Loma Prieta, California, Earthquake of October 17, 1989: U.S. Geological Survey Circular 1045, 48 p.

Sims, J.D., 1989, Chronology of displacement on the San Andreas fault in central California: Evidence from reversed positions of exotic rock bodies near Parkfield, California: U.S. Geological Survey Open-File Report 89-571, 43 p.

Spittler, T. E., Harp, E. L., Keefer, D. K., Wilson, R. C., and Sydnor, R. H., 1990, Landslide features and other coseismic fissures triggered by the Loma Prieta earthquake, central Santa Cruz Mountains, California: this volume, p. 59-66.

Stanley, R.G., and McCaffrey, R., 1983, Extent and offset history of the Ben Lomond fault, Santa Cruz County, California, *in* Anderson, D.W., and Rymer, M.J., eds., Tectonics and sedimentation along faults of the San Andreas system: Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 79-90.

Stanley, R.G., 1985, Middle Tertiary sedimentation and tectonics of the La Honda basin, central California: U.S. Geological Survey Open-File Report 85-596, 271 p.

Stock, J.M., and Molnar, P., 1988, Uncertainties and implications of the late Cretaceous and Tertiary position of North America relative to the Farallon, Kula, and Pacific plates: Tectonics, v. 7, p. 1339-1384.

SEISMOLOGICAL ASPECTS OF THE 17 OCTOBER 1989 EARTHQUAKE

by

Stephen R. McNutt[1] and Tousson R. Toppozada[1]

INTRODUCTION

On Tuesday, 17 October 1989, at 5:04:15.21 p.m. PDT, a magnitude 7.1 earthquake occurred on the San Andreas fault 16 km northeast of Santa Cruz (Figure 1). This was one of the largest earthquakes to occur in California since 1906. The event was responsible for 63 deaths and at least $5.9 billion of damage, making it the biggest dollar-loss natural disaster in United States history.

Just after the earthquake occurred, there was an extremely high demand for information about this earthquake and about earthquakes in the Bay area, in general. Since this was the first M>7 earthquake to occur within California in 38 years, there was also a demand for information about whether this earthquake was typical of what to expect in future events of the same size. With this in mind, the purposes of this article are: (1) to describe the seismological features of the earthquake; (2) to review the earthquake history of the Bay area; (3) to compare this earthquake with a similar 1865 event in the same area; and (4) to compare the event with earthquakes of similar size in other areas. This article has been prepared mainly as a summary paper, but we have gone into greater detail on several topics, so the article is also a source of information for the emergency response community, the media, and other researchers interested in hazards assessment. We have attempted to compile and summarize the best available information at the time of writing (15 March 1990), but anticipate that further research may refine or modify some of the conclusions presented here.

EARTHQUAKE HISTORY

Moderate and Large Earthquakes Statewide

Earthquakes of magnitude near that of the Loma Prieta event occur infrequently in California. Table 1 lists the 45 known events with M≥6.5 in California and within 50 km of its borders. The areas damaged by these earthquakes were outlined by Toppozada and others (1986). The occurrence of 45 events in 190 years suggests a statewide recurrence period of about 4 years, but the occurrence rate varies greatly with time and location. For example, the rate was high from 1892 through 1906 when 10 events occurred in 15 years (1.5 year recurrence). The record is probably incomplete before 1850 (Table 1).

Smaller earthquakes in urban areas can cause significant damage. A recent example is the 1987 Whittier Narrows earthquake of M_L 5.9 that occurred east of Los Angeles, causing $358 million damage (FEMA, 1987). The statewide rate of occurrence of damaging events (M≥5.5) is about eight times that of the M≥6.5 events, or on average about two events per year. As another example, an M_L 5.5 earthquake occurred on 28 February 1990 near Upland, 30 miles east of Los Angeles and caused at least $20 million damage (San Francisco Chronicle, 1990). The Earthquake Epicenter Map of California (Real and others, 1978) lists 452 events of M≥ 5 over a 75-year period, or an average of six events per year of M≥ 5.

Earthquakes of M> 5.5 within 60 km of San Francisco Bay

Thirty M> 5.5 events have occurred within 60 km of San Francisco Bay since 1850 (Figure 2). Before that time the record of M> 5.5 events is incomplete. However, two earthquakes of M~ 7 are known to have occurred in 1836 and 1838 on the Hayward and San Andreas faults, respectively. Before 1942, when U.C. Berkeley started determining magnitudes instrumentally, magnitudes were generally estimated from the size of the areas shaken at various levels of intensity (e.g., Toppozada, 1975).

Figure 2 shows that the occurrence rate in the Bay area was high until 1906, with 23 events occurring in 51 years. Since the largest known (M_S 8.3) Bay area event in 1906, only seven events with M> 5.5 have occurred. This suggests a period of stress buildup manifested by the high seismicity that culminated with the 1906 earthquake, and a period of recovery following this massive release of stress. Ellsworth and others (1981) proposed such an earthquake cycle that is controlled by the great 1906 event. The period of low seismicity and stress recovery may have ended in 1979, with the occurrence of five events of M> 5.5 from 1979 to 1989. This decade marks the end of a 68-year period (1911-1979) devoid of M> 5.5 activity that suggests a return to the higher pre-1906 seismicity. The historical record is less than one cycle long, however, so that this inference is not certain.

Smaller earthquakes (M≤ 5.5) have also occurred in the Bay area, but they are not shown in Figure 2 because their record is not complete before 1900 and because they represent only a minor part of the seismic energy released. One of these smaller earthquakes in 1957 caused more than $1 million damage in San Francisco (Oakeshott, 1959). Tocher (1959) and Jaumé and Sykes (1990) noted that the occurrence of M> 5.0 earthquakes in the Bay area increased after 1955.

The increased seismicity in recent years, including the M_S 7.1 event of 1989, should not be viewed as a "safety valve" against the occurrence of further destructive earthquakes. In the past, M 6.5 to

[1]California Department of Conservation, Division of Mines and Geology, Geologic Hazards Assessment Program

PARAMETERS OF THE LOMA PRIETA EARTHQUAKE

Origin time:	17 October 1989, 17hr 04min 15.21sec PDT
	18 October 1989, 00hr 04min 15.21sec UTC
Latitude:	37° 02.33' N ±1 km
Longitude:	121° 52.76' W±1 km
Depth:	17.6 km ± 1 km
Magnitudes:	M_S 7.1 average based on 21 observations
	m_b 6.5 average based on 88 observations
	M_L 7.0 U. C. Berkeley based on 1 observation
	M_W 6.9 average based on 9 observations
Fault plane:	Strike N50 ±10° W
	Dip 70 ±15° SW
	Rake 140 ±15°

See text for sources of information.

7 events have occurred in the Bay area in 1836 (Hayward fault), 1838 (San Andreas fault), 1865 (San Andreas fault), and 1868 (Hayward fault). These earthquakes, although destructive, were not followed by prolonged periods of low seismicity, as was the M_S 8.3 earthquake of 1906 (Figure 2).

The short historical record suggests that the continuing earthquake occurrence rate since 1979 might resemble the pre-1906 occurrence rate, which included several events of M≥6.5. This is consistent with the estimated probability of a M~7 event in the next 30 years in the Bay area of 50 percent (WGCEP, 1988).

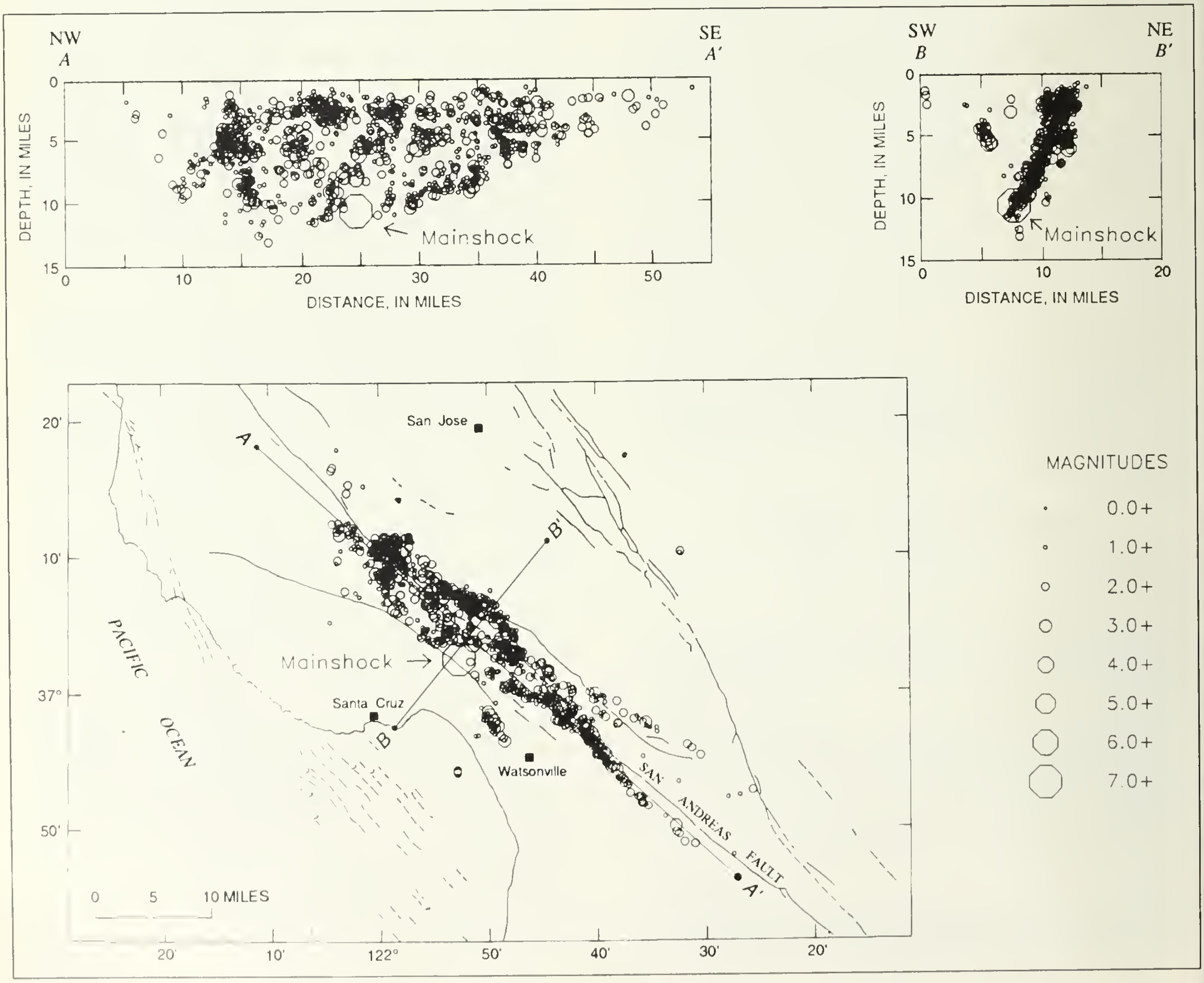


Figure 1. Spatial distribution of aftershocks of Loma Prieta earthquake in relation to San Andreas fault (bottom). Longitudinal cross section A-A' (top, right) and transverse cross section B-B' (top, left) display depth distribution of aftershocks. Faults are dashed where approximately located, dotted where inferred, and queried (offshore) where uncertain (source: Plafker and Galloway, 1989).

TABLE 1

CALIFORNIA EARTHQUAKES OF M≥ 6.5

Date	I[1]	Magnitude	Source[2]	Region
1800/11/22	VII	~6.5	T	San Diego-San Juan Capistrano
1812/12/08	VII	~7	T[3]	Los Angeles and Orange Counties
1812/12/21	VII	~7	T	Santa Barbara and Ventura Counties
1836/06/10	VIII	~7	T	Hayward fault, east San Francisco Bay
1838/06	VIII	~7	T	San Andreas fault, San Francisco Bay
1852/11/29	IX	~6.5	T	Fort Yuma, Colorado River delta
1857/01/09	IX+	~8	T	Fort Tejon, Central San Andreas fault
1860/03/15	VI+	6.6	T	North of Carson City, Nevada
1865/10/08	IX	6.6	T	Santa Cruz Mountains
1868/10/21	IX+	7.1	T	Hayward fault, east San Francisco Bay
1872/03/26	IX+	~8	T	Owens Valley, eastern Sierra Nevada
1872/03/26	V	~6.5	T	Owens Valley, eastern Sierra Nevada
1872/04/11	IX	6.9	T	Round Valley, eastern Sierra Nevada
1873/11/22	VIII	7.0	T	North California and South Oregon coast
1885/04/11	VII	6.5	T[4]	San Benito-Fresno County border
1887/06/03	VIII	6.6	T	Carson City, Nevada
1890/02/09	VI+	6.6	T	San Diego-Imperial Counties area
1892/02/23	IX	7.0	T	California-Mexico border area
1892/04/19	IX	6.7	T	Vacaville, western Sacramento Valley
1892/04/21	IX	6.5	T	Winters, western Sacramento Valley
1892/05/28	VI	6.6	T	San Diego-Imperial Counties area
1897/06/20	VIII	6.5	T	Gilroy, Santa Clara County
1898/03/30	IX	6.5	T	Mare Island, Solano and Sonoma Counties
1898/04/14	IX	6.7	T	Coastal Mendocino County
1899/07/21	VIII	6.8	T	Southwestern San Bernardino County
1899/12/25	IX	6.9	T	San Jacinto fault, Riverside County
1901/03/03	VII	6.5	TT	Parkfield, central San Andreas fault
1906/04/18	IX+	8.3	R	San Francisco, northern San Andreas fault
1908/11/04	VII?	6.5?	R	Panamint Range, Inyo County
1911/07/01	VII	6.6	R	Coyote, Santa Clara County
1918/04/21	IX	6.8	R	San Jacinto fault, Riverside County
1923/01/22	VIII	7.2	R	Off Cape Mendocino
1927/11/04	VIII	7.5	R	Off west coast of Santa Barbara County
1940/05/18	IX	7.1	R	Imperial fault
1942/10/21	VI+	6.5	C	Borrego Valley, San Diego-Imperial Counties
1948/12/04	VII	6.5	C	Desert Hot Springs, Riverside County
1952/07/21	XI	7.7	R	Arvin-Tehachapi area, Kern County
1954/12/21	VII	6.5	B	Humboldt County
1968/04/09	VII	6.4 (M_S 6.8)	C	Borrego Mountain, San Diego-Imperial Counties
1971/02/09	XI	6.4 (M_S 6.5)	C	San Fernando
1979/10/15	IX	6.4 (M_S 6.9)	C	Imperial fault
1980/05/25	VII	6.6 (M_S 5.8)	C	Mammoth Lakes, Mono County
1980/11/08	VII	6.9 (M_S 7.2)	B	Off Humboldt County coast
1983/05/02	VIII	6.5 (M_S 6.5)	BC	Coalinga, western San Joaquin Valley
1989/10/17	IX	7.0 (M_S 7.1)	B	Loma Prieta, Santa Cruz Mountains

[1]Maximum reported Modified Mercalli intensity.

[2]M Source: T - - Toppozada and others (1981), intensity magnitude; +0.3 M correction applied (Ellsworth, 1990).
R - - Richter (1958), M_S
B - - U. C. Berkeley, M_L
C - - California Institute of Technology, M_L
TT- - Toppozada (1990), intensity magnitude
BC- - Mean of Berkeley M 6.7 and Caltech M 6.3

[3]Jacoby and others (1988) proposed a location on the San Andreas fault near Wrightwood.

[4]Revised Location (Toppozada and others, 1990).

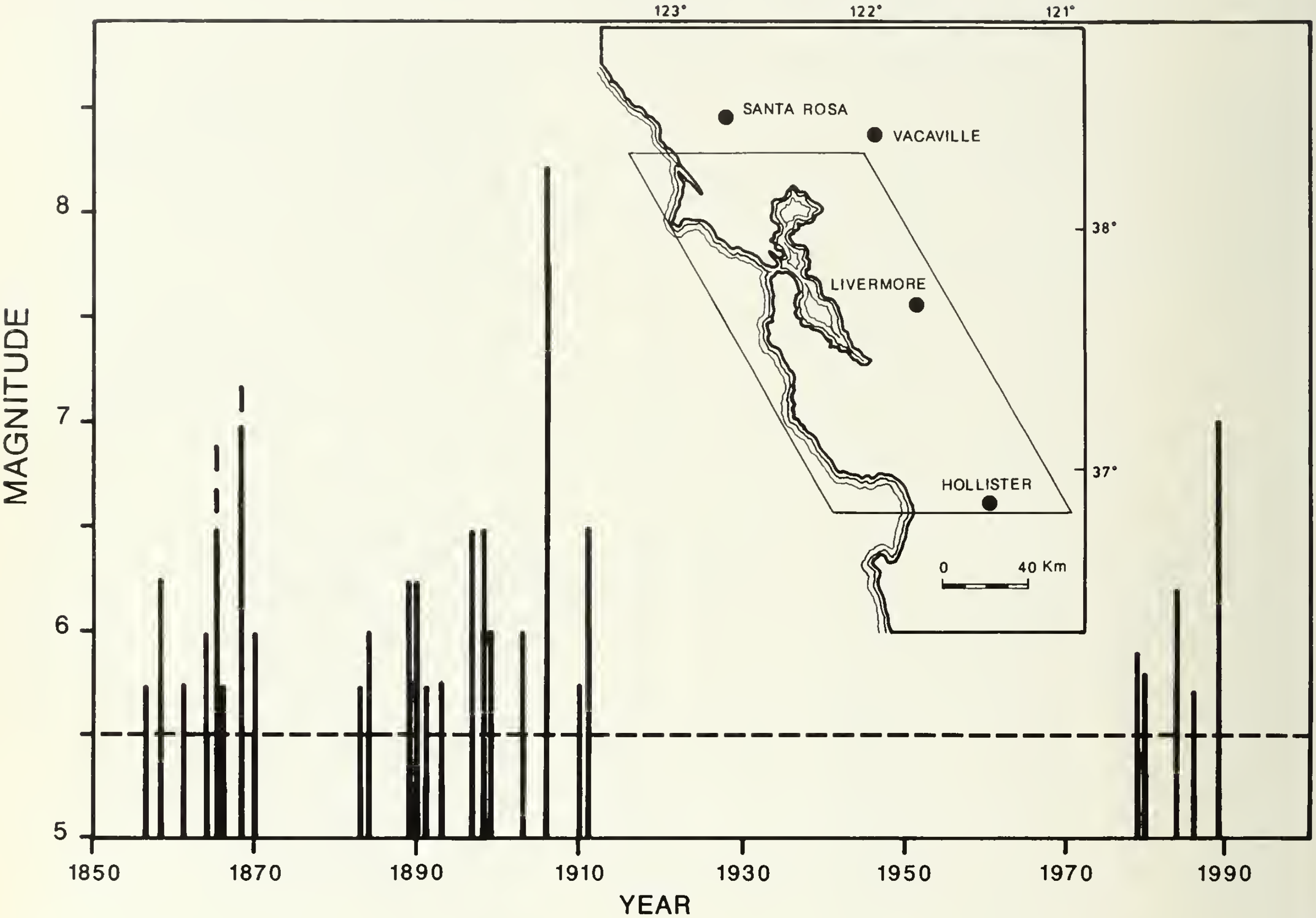


Figure 2. Earthquakes with M> 5.5 (dotted line) within 60 km of San Francisco Bay from 1849 to 1990. The index map shows the area for which data are displayed. Height of bar is proportional to earthquake magnitude.

The Rupture Vicinity of the 1989 Earthquake

The section of the San Andreas fault that ruptured in 1989 may have ruptured in 1838 (Louderback, 1947), 1865 (this paper, below) and 1906. The fault makes an 8-10° bend near both ends of this section (Jennings, 1975), resulting in increased horizontal compression in the Loma Prieta segment. This change in geometry and stress may tend to control the size of events in this section, and may partially explain the fact that the through-going 1906 surface fault offset decreased abruptly in this segment relative to the adjacent section to the north (WGCEP, 1988; Lawson, 1908).

The microseismicity of the Loma Prieta area prior to 17 October 1989 had a persistent but low level of M< 3 activity (Olson, 1990; Olson and Lindh, 1990). Events in this area were slightly deeper than those in adjacent sections of the fault and formed a U-shaped pattern when viewed in cross section (USGS Staff, 1990).

Two events (Lake Elsman events) of M 5.0 and 5.2 occurred near Loma Prieta on June 27, 1988 and August 8, 1989, respectively. At depth these events were located 4 km northeast of the west-dipping plane defined by the Loma Prieta aftershocks (Figure 1), and may have occurred on a different fault. Their fault plane solutions indicate equal components of right-lateral and reverse slip on a northeast-dipping plane with a strike of N 60° W (Olson and Lindh, 1990). These events were widely felt and caused minor damage. These events have been called preshocks, but are not considered to be foreshocks in the usual sense of the word.

CHARACTERISTICS OF THE MAINSHOCK

The 17 October 1989 earthquake occurred in the Santa Cruz Mountains at latitude 37°02.33' N, longitude 121° 52.76' W, at a depth of 17.6 km (Dietz and Ellsworth, 1990). The location of the mainshock is shown in Figure 1 as the largest octagon.

The surface wave magnitude (M_S) of the earthquake is 7.1, as determined from readings at 21 world-wide stations (NEIC, 1990). The individual station values ranged from M_S 6.6 to M_S 7.4. The body wave magnitude (m_b) for the event is 6.5 (NEIC, 1990), and the moment magnitude (M_W) is 6.9 (Kanamori and Helmberger, 1990).

STRONG GROUND SHAKING FROM THE LOMA PRIETA EARTHQUAKE OF 17 OCTOBER 1989, AND ITS RELATION TO NEAR SURFACE GEOLOGY IN THE OAKLAND AREA

modified from:

A PRELIMINARY REPORT TO:

GOVERNOR'S BOARD OF INQUIRY ON THE 1989 LOMA PRIETA EARTHQUAKE

by

Anthony F. Shakal[1], Mark J. DeLisle[1], Michael S. Reichle[1], and Robert B. Darragh[1]

DESCRIPTION OF THE EARTHQUAKE

The Loma Prieta earthquake occurred on the San Andreas fault approximately 16 km east of Santa Cruz and 33 km southwest of San Jose. The map in Figure 1A shows the San Andreas fault, the earthquake epicenter and cities of central coastal California. The stippled line on the San Andreas fault between San Juan Bautista and Lexington Dam indicates the approximate extent of the aftershock zone and, by inference, the extent of fault rupture during the mainshock. The locations of Strong Motion Instrumentation Program (SMIP) stations that recorded the strong shaking during the earthquake are shown by solid symbols, and the peak horizontal acceleration recorded at each station is given near the symbol. Stations in the Oakland/San Francisco area are repeated in Figure 1B.

The earthquake hypocenter, where the fault rupture initiated, is at 37° 02'N, 121°52'W at a depth of 18 km. This depth is greater than the 12-15 km maximum depth typical for hypocenters on the San Andreas fault. Fault rupture did not reach the surface, which is unusual for an event of this magnitude on the San Andreas; this fact may be related to the greater depth of the hypocenter or the local tectonic regime.

The local, or Richter, magnitude of the event is 7.0 (U.C. Berkeley). The surface wave (long-period) magnitude is 7.1 (NEIC, 1989).

The source mechanism of the event was a combination of strike-slip faulting, common on the San Andreas, and thrust faulting, which is more unusual. The coastal block on the west side of the San Andreas moved to the north and upward relative to the east side of the San Andreas. Estimates by the USGS (Lisowski and others, 1990) are that the coastal block moved approximately 1.6 ± 0.3 m to the north and 1.2 ± 0.3 m upward.

OBSERVED STRONG GROUND MOTION

Recorded peak horizontal acceleration values from SMIP stations for the Loma Prieta earthquake are plotted on the map in Figure 1A. The maximum horizontal acceleration recorded at each station is given near each station. Stations in the epicentral area have accelerations as high as 0.64 g. The most distant station triggered in Santa Rosa (175 km) recorded about 0.05 g. Peak values at stations in the San Francisco/Oakland area (95 km) are shown on a map with an expanded scale in Figure 1B. The lowest values, near 0.06 g, were recorded at stations sited on rock in San Francisco, on Yerba Buena Island and in Berkeley. The highest values were recorded at the San Francisco airport and other soil sites in the Bay Area.

The peak horizontal acceleration values are plotted against distance in Figure 2. A curve of the predicted ground motion using a standard relationship (Joyner and Boore, 1981) is also shown for reference. It is obvious that most of the data are above the median curve, and in fact much of the data are above the +1 sigma curve for an event of this magnitude. In general, peak horizontal acceleration values at distant stations are higher than would be expected; several stations, including stations in Oakland, had accelerations between two and three standard deviations above the median value.

Selected accelerograms of particular interest are shown in Figure 3. Figure 3A includes two records from the epicentral area. One record is from a station (Corralitos) very close to the San Andreas fault; the other record (Capitola) is from the coastal area extending from Santa Cruz to Watsonville in which damage was extensive. Figure 3B shows records from a rock/soil pair near San Francisco. Yerba Buena Island is a rock outcrop in the middle of the San Francisco Bay, and Treasure Island is a nearby manmade island. These records are presented to illustrate the levels of shaking on rock and soil in the San Francisco-Oakland area, about 95 km from the epicenter.

[1] California Department of Conservation, Division of Mines and Geology, Strong Motion Instrumentation Program

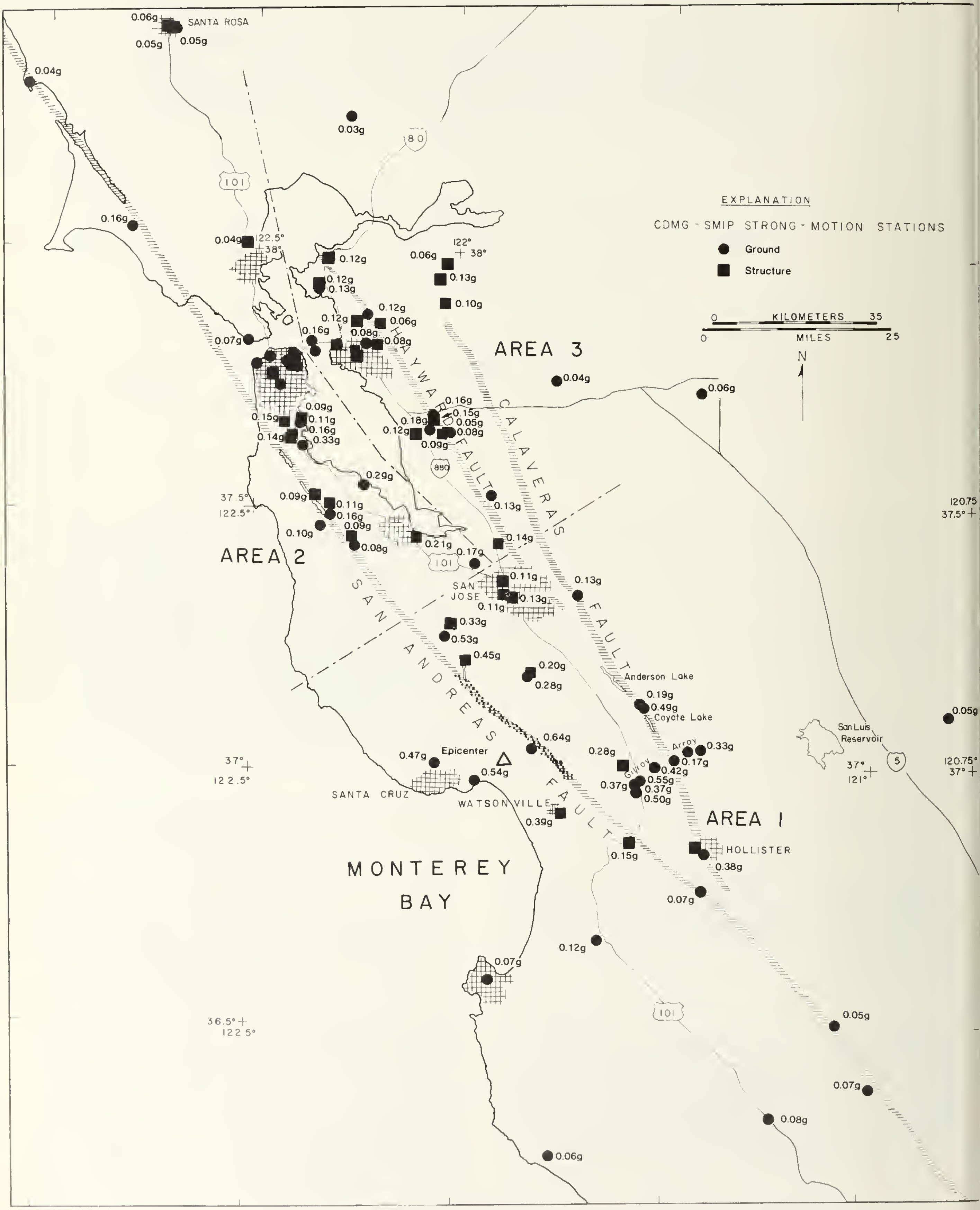


Figure 1A. Map of central coastal California showing the San Andreas fault, the epicenter and aftershock zone of the Loma Prieta earthquake, and the locations of SMIP stations that recorded the strong shaking. Peak horizontal accelerations recorded at each station appear next to the station. The San Francisco/Oakland area is repeated in Figure 1B at larger scale.

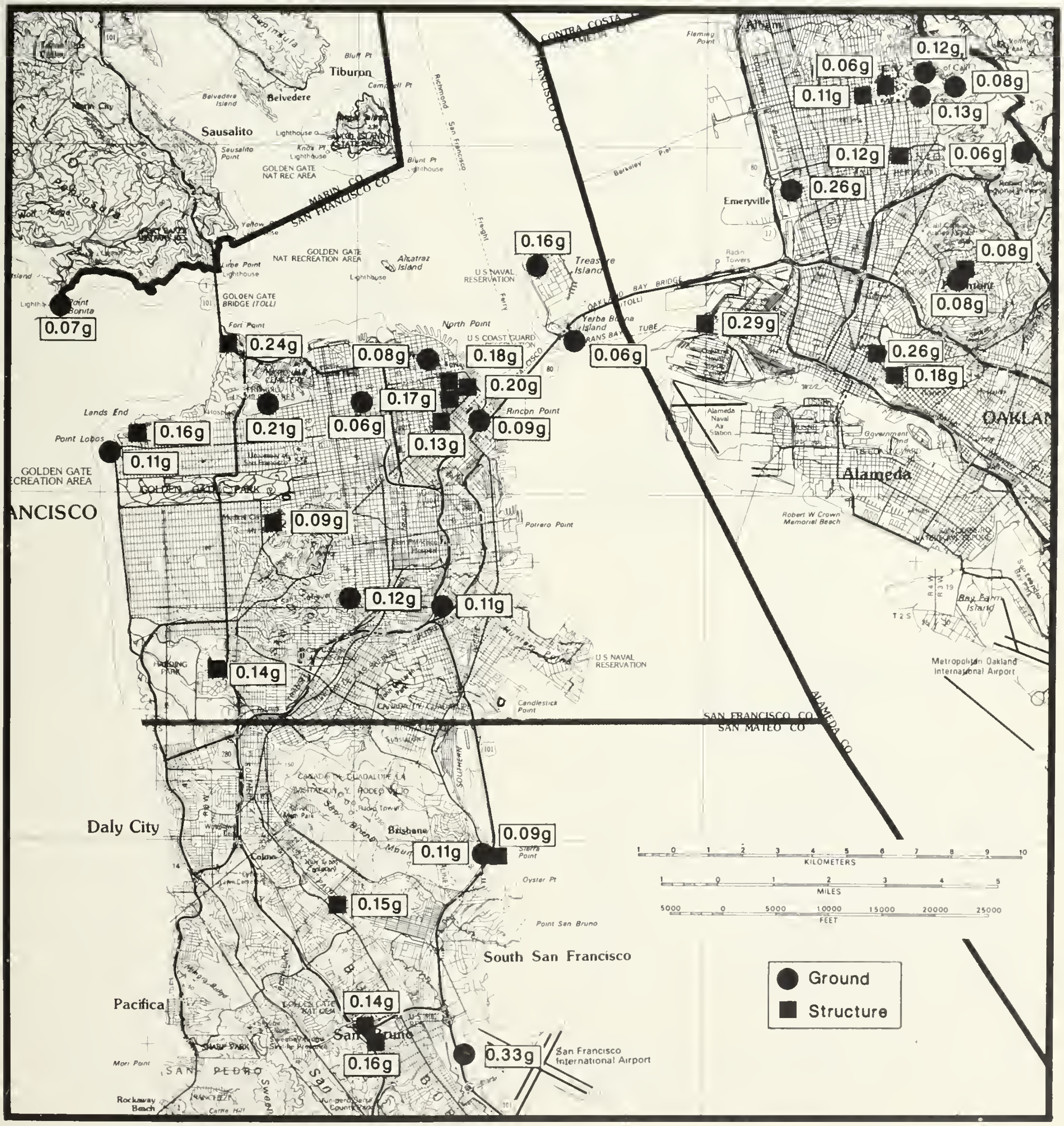


Figure 1B. San Francisco/Oakland area showing strong motion stations that recorded the Loma Prieta earthquake and the peak acceleration values recorded at SMIP (Shakal and others, 1989) and USGS (Maley and others, 1989) stations.

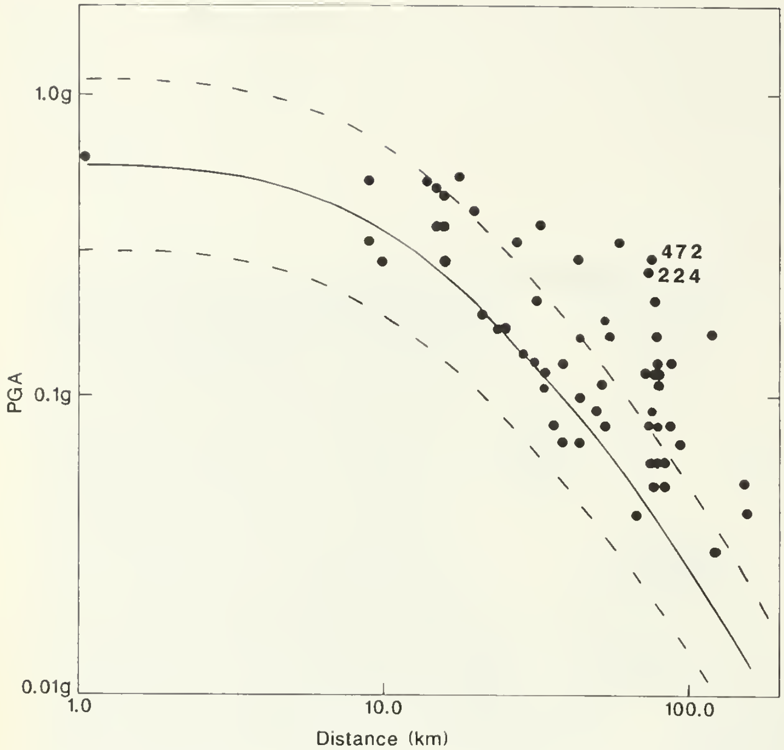


Figure 2. Peak horizontal acceleration values (PGA) versus distance (to the surface trace of the fault over the aftershock zone) for strong motion data from SMIP stations for the Loma Prieta earthquake. The solid and dashed curves are the median and one standard deviation curves, respectively, from the Joyner-Boore attenuation relationship (EERI, 1989). The numbered symbols are for Oakland stations discussed in the text.

Surficial Geology in the Vicinity of the Cypress Structure, Oakland

The geology of the San Francisco Bay area has been well studied. Figure 4 is an illustration from a study of San Francisco Bay geology (Helley and others, 1979) which focused on bay mud and other flatland deposits in the Bay area. The map in Figure 4 shows that the bay mud (shaded area) is widespread in the coastal areas. The thickness of the bay mud is highly variable, however. Contours of the thickness of the bay mud are shown in Figure 5 (from Goldman, 1969). The maximum thickness of the bay mud is about 120 feet. The thickness near Treasure Island is about 20 feet and at the eastern approach to the Bay Bridge in Oakland the thickness is about 40 feet. Farther east, toward the Cypress Street Structure (Interstate 880), the bay mud decreases in thickness.

In addition to bay mud, other geologic units are important in the Oakland area. As shown on the map in Figure 6 (from Radbruch, 1957), they include artificial fill, Merritt Sand and the Temescal Formation. The Temescal Formation grades laterally into the Merritt Sand Formation. The Merritt Sand is a well-sorted fine-grained sand to clayey sand with lenses of sandy, silty clay. The Temescal Formation consists of poorly-sorted, irregular interbedded clay, silt, sand and gravel.

Although no strong motion stations recorded the motion on or near the Cypress Structure during the Loma Prieta earthquake, the motion was recorded at stations about 2 km to the west, east and north. The horizontal components of the records from these three stations are shown in Figure 7. The peak horizontal accelerations at the three stations are very similar (0.26 to 0.29 g). The station at the Oakland wharf (SMIP Station 472) recorded a maximum acceleration of 0.29 g. Figure 6 indicates that the wharf is located in an area of bay mud. However, the soil profile in Figure 7 shows that the total depth of the fill and bay mud is only about 12 feet, and that Merritt Sand lies below the bay mud. The station in Emeryville (USGS Station 1662) lies about 2 km north of the structure. This station is on about 10 feet of fill. The underlying formation at this station is the Temescal formation. The third station in the set (SMIP Station 224) is in Oakland about 2 km east of the Cypress structure. The soil profile shows that there is no bay mud but a few feet of fill at the site. The fill overlies the same formation as at the wharf station (Merritt Sand).

The soil profile at locations along the Cypress Structure is shown in the profile in Figure 8, which was developed from borings performed by the California Department of Transportation (Caltrans) preparatory to construction. These borings show that the bay mud at the Cypress Structure, where present, is less than 20 feet thick. The pile-tip depths (from Caltrans) are also shown in Figure 8. In the section where the bay mud is 20 feet thick, the piles extend to a depth of about 60 feet. The formation under the northern part of the structure (Temescal Formation) is similar to that underlying the Emeryville station.

The records from the stations at the wharf, at Emeryville and near Lake Merritt (Figure 7) are all quite similar in peak values and predominant frequency despite the differences in the near-surface geologic conditions and depths of fill and bay mud. This suggests that the specific near-surface geology at the Cypress Structure did not cause significantly different motion than that shown by the records in Figure 7.

As another example, Treasure Island was created in 1936-1937 by placing up to 35 feet of hydraulic fill over sand and bay mud deposits near Yerba Buena Island (Lee,1969). The record from a station on Treasure Island is similar in frequency content, though somewhat lower in amplitude (0.16 g, Figure 3B) than the Oakland area records.

The strong motion data from the Oakland area does indicate that amplified levels of motion occurred at the Cypress Structure. However, the amplification effect occurs throughout the flat-lying portions of Oakland, not just in a localized zone near the Cypress Structure. To observe the amplification at the Oakland stations, compare the peak motion at the Oakland stations discussed above to the motion at Berkeley or Piedmont (0.08 - 0.13 g; Figure 1B), or at Yerba Buena Island (0.06 g; Figure 3B). The amplification in the flat-lying areas is also apparent in Figure 2 - the data points for the Oakland area (designated 472 and 224) are well above the predicted values, and in fact are the farthest above the median curve. Whatever factor is causing increased shaking levels in Oakland appears to extend throughout the flat-lying areas, and is not limited to areas of bay mud.

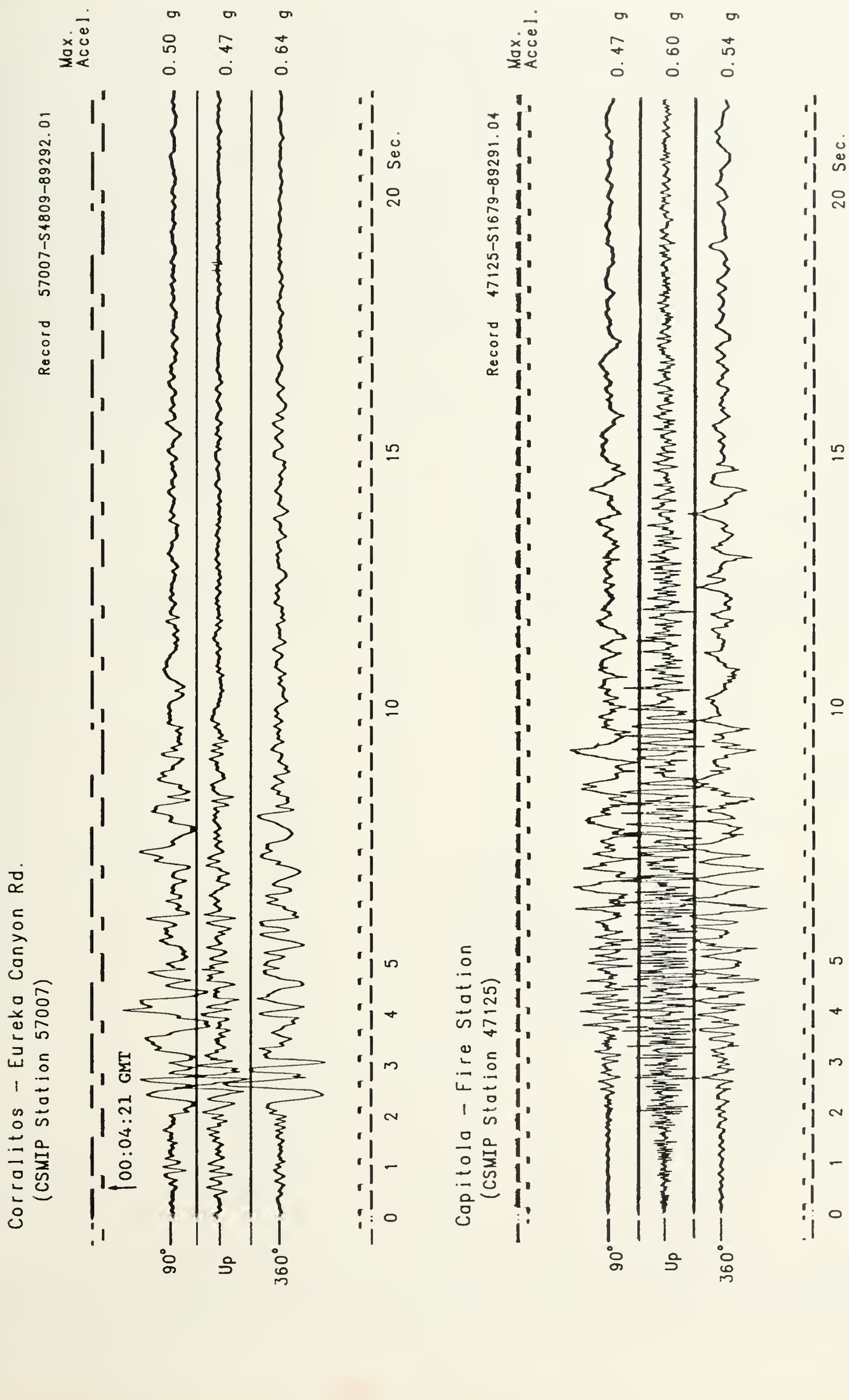


Figure 3a. Selected strong motion records from the Loma Prieta epicentral area.

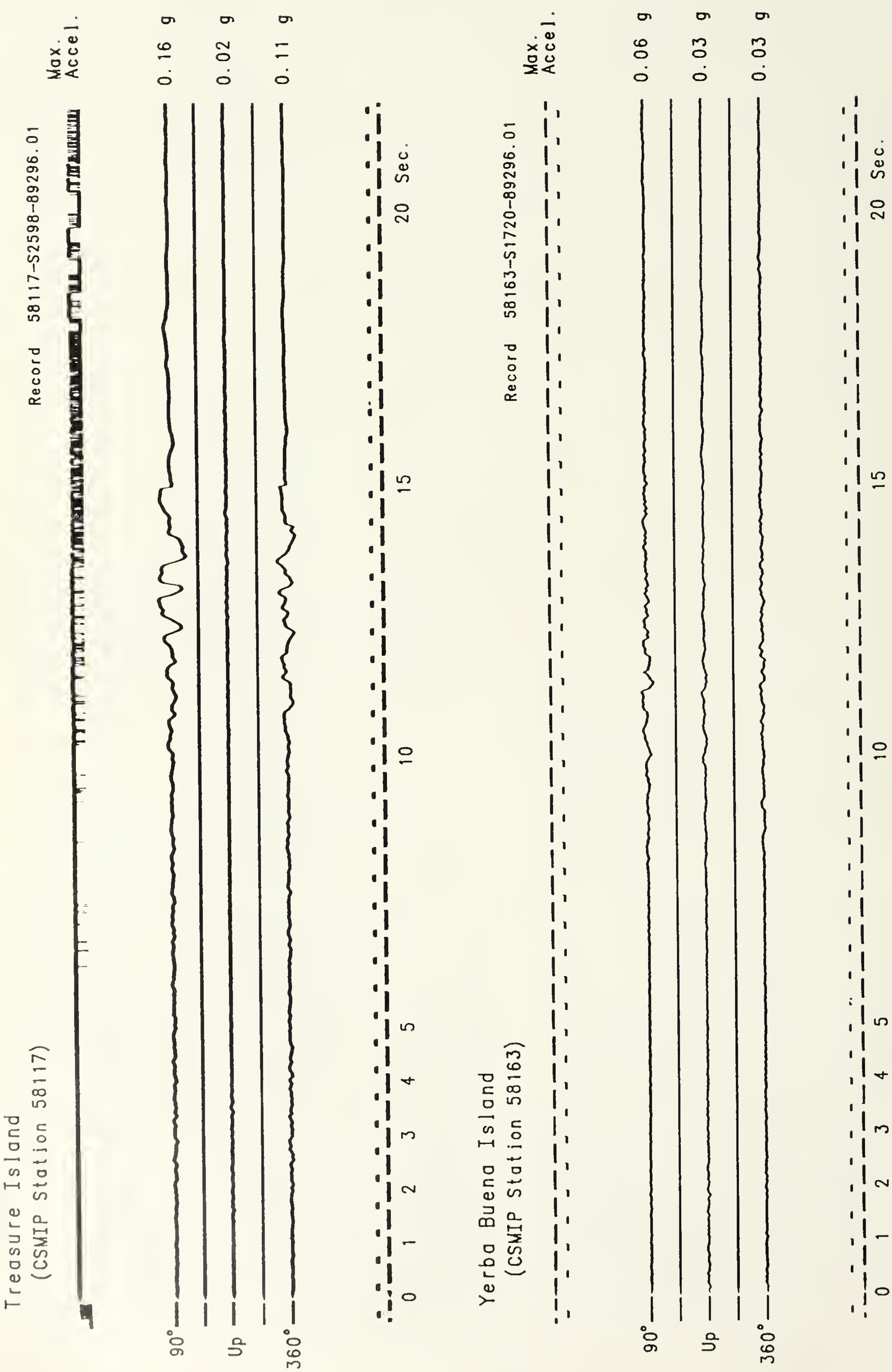


Figure 3b. Selected strong-motion records from a soil (upper) and rock (lower) station in the San Francisco/Oakland area.

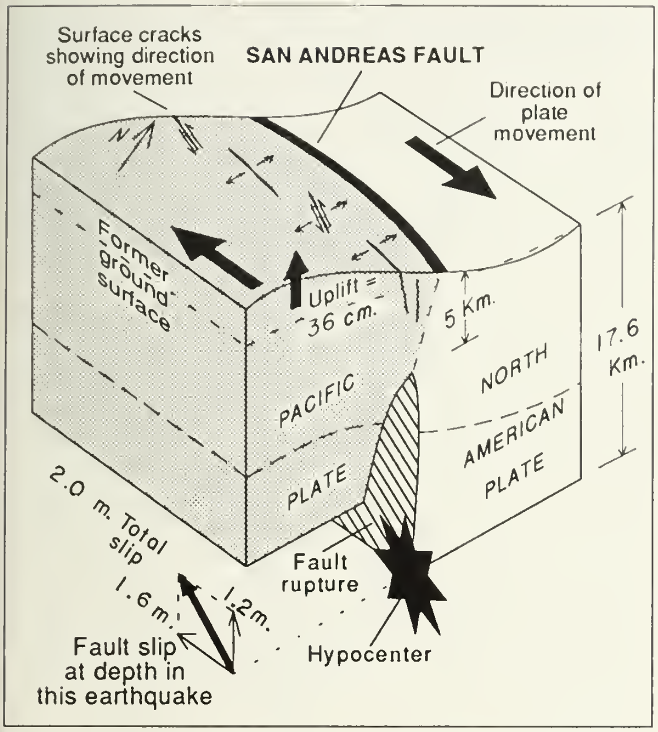


Figure 3. Schematic diagram showing inferred motion on the San Andreas fault during the Loma Prieta earthquake. Vertical and horizontal slip on the buried fault and vertical surface deformation were determined from geodetic data (source: Plafker and Galloway, 1989).

Local magnitude (M_L) estimates were 6.7 (CIT) and 7.0 (UCB). The local magnitude scale (M_L) developed by Richter begins to saturate in the range of 6.5 to 7 (e.g., Kanamori, 1983). Thus, for earthquakes of this size and larger, the surface wave magnitude (M_S) or moment magnitude (M_W) usually is a better estimate of size than local magnitude (M_L). Standard errors in magnitude determinations are typically about 0.2 units for both M_S and M_L (Bonilla and others, 1984; Darragh and Bolt, 1987).

Figure 3 shows a block diagram of the motion on the San Andreas fault during the earthquake. These motions were calculated from geodetic measurements made in the region the day after the earthquake occurred and include data measured by Geodolite, H-P 3808, the Global Positioning System, and the Very Long Base Line array (Prescott and others, 1990). The slip during the event was inferred to be 1.6 ± 0.3 m of right-lateral strike slip and 1.2 ± 0.3 m of reverse dip slip on the fault surface between depths of 5 and 18 km (Lisowski and others, 1990). These values decrease rapidly through the volume of crust adjacent to the fault so that only 36 cm of uplift was observed at the earth's surface (Plafker and Galloway, 1989; USGS Staff, 1990).

The fault plane solution for the mainshock, based on 267 P-wave first motion readings at epicentral distances ranging from 1.6 to 562 km, is shown in Figure 4 A (Oppenheimer, 1990). The mechanism is oblique right-lateral strike-slip with about equal parts strike-slip and thrust motion. The preferred mechanism has a strike of N 50° ± 10°W, a dip of 70°± 15° SW, and a rake of 140°± 15°. The strike agrees well with the surface trace of the San Andreas fault in the vicinity of the epicenter.

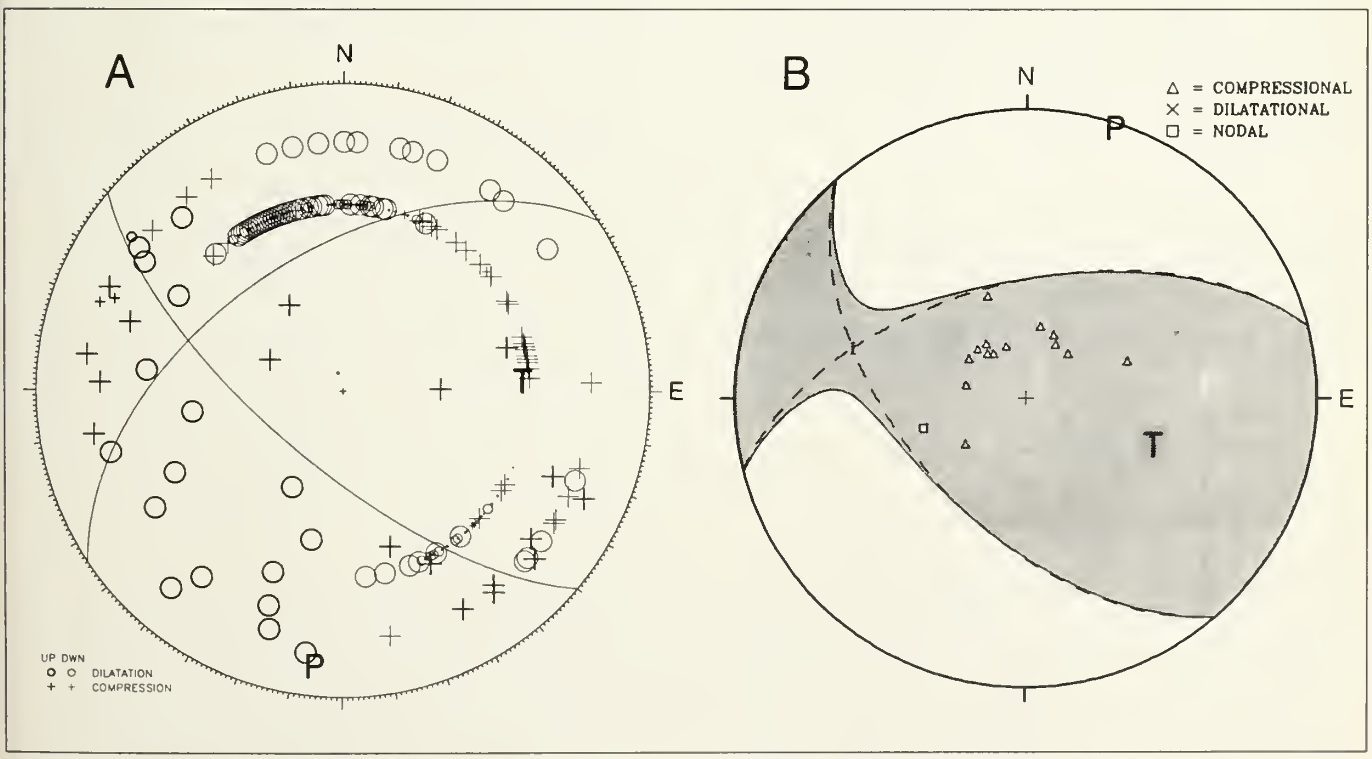


Figure 4. A. Lower hemisphere plot of fault-plane solution for the Loma Prieta main shock, based on data from 267 local and regional stations and the velocity model of Dietz and Ellsworth (1990). Circles and pluses indicate dilatational and compressional first motions, respectively. "T" is tension axis and "P" is pressure axis (source: Oppenheimer, 1990). B. Lower hemisphere nodal plane and nodal surface solutions for the main shock based on decomposition of the moment-tensor solution. Data from 15 worldwide stations were modelled to obtain the moment tensor. "T" is tension axis and "P" is pressure axis (source: S. Sipkin, NEIC, 1990).

In addition to obtaining the standard fault plane solution, other attempts were made in near real-time to determine the earthquake mechanism and moment tensor from analyses of longer period waves recorded at regional and teleseismic distances (see discussion by McNally and others, 1989). Most results are in good agreement with the mechanism shown in Figure 4 A. For example, the NEIC (1990) moment tensor solution is shown in Figure 4 B. The moment tensor gives a better characterization of the entire fault rupture, as opposed to the fault plane solution of Figure 4 A that characterizes only the rupture initiation.

Several broadband estimates of the source mechanisms, as well as the geometry of the aftershock zone with respect to the mainshock hypocenter (Figure 1), indicate that rupture during the event was bilateral. The rupture initiated at the hypocenter and propagated along the fault to the southeast and northwest and upward. Using the rupture time of 10 seconds (see below) and a rupture extent of 20 km in each direction (Plafker and Galloway, 1989) yields a rough estimate for the average rupture velocity of 2 km/sec.

Preliminary estimates of the seismic moment range from 1.9 to 11 x 10^{26} dyne-cm. We computed a stress drop of 33 bars using the value of 3.0 x 10^{26} dyne-cm (which corresponds to the M_W of 6.9), rigidity = 3 x 10^{11} dyne-cm, w = 12 km, and L = 40 km in the relation of Kanamori and Anderson (1975, p. 1091) for strike-slip faults. The stress drop is about average for strike-slip faults. Estimates of centroid depths (center of moment release) range from 8-15 km. Estimates of the source-time function fall into two groups: 10 seconds or less (Choy and others, 1990; Nábělek, 1990; Romanowicz and others, 1990; Wallace and Lay, 1990; Woods and others, 1990; Salzberg and others, 1990; USGS Staff, 1990), and 20 seconds or longer (Widmer and Masters, 1990; Romanowicz and others, 1990; Choy and others, 1990; NEIC, 1989). Two or three distinct bursts of energy, or sub-events, have been used in preliminary models of the shorter source time functions, with the last of these sub-events the largest (Choy and others, 1990; Nábělek, 1990; Wallace and Lay, 1990).

Based on the above preliminary results, the earthquake appears to have been relatively rich in short-period and long-period (mantle) energy, but relatively deficient in the intermediate periods. The enriched long-period energy of the earthquake and the discrepency in displacement directions for crustal and mantle components of the easternmost Pacific plate lead Furlong and others (1990) to suggest possible decoupling of the crust and mantle at depth.

THE AFTERSHOCK SEQUENCE

Numerous smaller earthquakes - aftershocks - occur after every moderate or large earthquake. These are of special concern for hazards assessment because they may cause deaths, injuries, or further damage to structures already damaged by the mainshock. For example, people were killed during aftershocks of the Kern County earthquake of 21 July 1952 (Oakeshott, 1955). Also, there have been instances where people died from heart attacks during aftershocks (e.g., 1980 Campania, Italy earthquake; NEIS, 1980).

For the Loma Prieta earthquake, there were two aftershocks of M 5.0 and larger, and 48 of M 4.0 and larger as of March 1, 1990 using combined data from all sources. The number of M≥ 4 shocks varies somewhat with reporting source as follows: UCB (43), USGS (32), and NEIC (28). Table 2 lists the M≥ 4.0 aftershocks. USGS locations are listed where available because of the greater USGS station density in the vicinity of the epicenters and hence better location control. U.C. Berkeley magnitude values are preferred because Berkeley operates Wood-Anderson torsion seismographs, similar to the instruments used by Richter in developing the magnitude scale. Figure 5 shows the number of aftershocks per day from 17 October 1989 to 10 February 1990, clearly showing the characteristic decay proportional to one divided by time.

The sequence was statistically consistent with the "generic California" sequence of Reasenberg and Jones (1989; see also Reasenberg and Matthews, 1990), with the exception that either the b-value was low or the a-value was low. (The b-value reflects the ratio of large to small events, the a-value reflects the productivity, and the p-value reflects the rate of activity.) Preliminary parameters for the sequence are p=1.19, a=-1.67, and b=0.75, so that all are within one standard deviation of the respective generic values (Reasenberg and Jones, 1990). The remaining variable, c, is held constant at 0.05 days (Reasenberg and Jones, 1989). Based on the generic sequence, but updating the parameters with preliminary results from monitoring the first 4 days of Loma Prieta aftershocks, it was estimated that there was a 12 percent chance of an aftershock of M≥ 6 in the two months following October 21, 1989.

The main part of the aftershock zone for the 17 October earthquake was 53 km long after the first four days (USGS written communication, 1989; Figure 1 of McNutt, 1990) and 66 km long by 31 October (Figure 1; USGS Staff, 1990). It is commonly observed that aftershock zones tend to grow larger with time. For example, the aftershock zone of the M_S 6.8 Borrego Mountain earthquake of 1968 grew from 42 km in the first 22 hours to 64 km one year later (Allen and Nordquist, 1972).

Figure 1 also shows cross-sectional views of the aftershock zone. The aftershocks define a plane dipping about 70° southwest, consistent with the fault plane solutions of Figure 4. The San Andreas fault in this region is not vertical, as previously supposed, but dips at a steep angle. This is the reason that the epicenter does not plot on the surface trace of the fault. The earthquake hypocenter occurred at a depth of 17.6 km on the southwest-dipping San Andreas, and thus is located to the southwest of the surface expression of the fault. Also, note in Figure 1 that there is a cluster of events off the main fault to the southwest; one of the M 5 aftershocks occurred in this off-fault cluster. Such clusters are common in aftershock zones, and are explained by an increase in shear stress resulting from the fault slip (Das and Scholz, 1981; Stein and Lisowski, 1983), or an increase in pore pressure (Li and others, 1987). Clearly, however, most of the aftershocks are located within about 2 km of the main fault.

There is considerable variety in the fault plane solutions of the aftershocks, including thrust, normal, right-lateral, left-lateral, and oblique mechanisms (Branch of Seismology, USGS, 1990; Oppenheimer, 1990). The diversity of aftershock mechanisms suggests that the majority of the aftershocks occurred off the main fault plane, and that the stresses in the aftershock zone underwent a major reorganization. Also, the aftershock zone is about 3 km wide, much larger than the relative horizontal location errors of about 0.3 km (Dietz and Ellsworth, 1990), giving additional support to this interpretation. It appears that the mainshock involved almost complete stress drop on

TABLE 2
LOMA PRIETA AFTERSHOCKS OF M≥4.0

Month	Day	Time (UTC)	Latitude[1] Deg	Latitude[1] Min	Longitude[1] Deg	Longitude[1] Min	Depth[1] (km)	BRK M_L	MAGNITUDE USGS[2] M	MAGNITUDE NEIC[3] m_b	MAGNITUDE NEIC[3] M_L
10	18	00:04:15	37	02	121	53	18	7.0	$7.1 M_S$	6.6	
10	18	00:07:15	37	13	121	57	12	4.7	4.6		
10	18	00:07:43	36	57	121	48	18	4.7	4.9		
10	18	00:08:20[4]	37	02	121	52	00	4.4			
10	18	00:08:54	36	57	121	46	13	4.3	4.1		
10	18	00:09:55	37	01	121	46	08	4.0	4.0		
10	18	00:11:45	37	09	122	01	06	4.2	4.0		
10	18	00:12:02[4]	37	02	121	52	00	4.5			
10	18	00:12:42	37	07	122	01	04	4.6	4.5		
10	18	00:13:08	37	10	122	03	11		4.1		
10	18	00:15:10[4]	37	02	121	52	00	4.4			
10	18	00:16:54	37	05	121	56	04	4.1	4.1		
10	18	00:17:26[4]	37	02	121	52	00	4.0			
10	18	00:19:17	37	09	122	00	10	4.0	4.0		
10	18	00:23:37	37	01	121	47	03		4.0		
10	18	00:25:04	37	01	121	48	07	4.8	4.8	5.0	
10	18	00:30:40	37	05	122	00	01	4.2	4.2		
10	18	00:38:28	37	10	122	01	08	4.3	4.3		
10	18	00:41:24	37	10	122	03	11	5.1	5.2	4.8	
10	18	00:45:37	36	55	121	43	01	4.0	4.0		
10	18	02:15:49	37	04	121	44	16	4.5	4.5	4.4	
10	18	02:26:03	37	01	121	46	01	4.2	4.2	4.1	
10	18	03:23:57[5]	37	10	122	00	22	4.0			
10	18	04:16:32	37	03	121	54	10	4.1	4.1		
10	18	04:50:26	37	08	122	03	06	4.3	4.3	4.6	
10	18	05:18:34	37	01	121	51	13	4.2	4.2	4.5	
10	18	06:39:10[5]	36	56	121	43	12	4.3			
10	18	10:22:04	36	59	121	51	08	4.4	4.5	4.3	
10	19	03:55:00[5]	36	59	121	49	19	4.0			
10	19	08:45:49	36	57	121	51	06	4.0	4.3		3.7
10	19	09:53:50	36	55	121	41	06	4.5	4.5	4.3	
10	19	10:14:34	36	57	121	50	07	4.6	5.0	4.6	4.3
10	19	12:25:33	36	55	121	41	04		4.0		3.8
10	20	00:18:20[6]	37	06	121	57	12	4.3[7]			3.9
10	20	08:12:54[5]	37	11	122	05	16	4.0			
10	21	00:49:42	37	01	121	53	09	4.6	4.3	4.5	
10	21	22:14:56	37	03	121	53	11	4.9	4.6	4.5	
10	22	14:24:37[5]	36	59	121	48	15	4.1			
10	25	01:27:26	37	05	121	56	09	4.7	4.5	4.6	
10	25	13:00:42	36	53	121	39	09	4.0			
10	25	22:01:49	36	59	121	47	14	4.0			
10	26	09:01:29[6]	37	03	121	54	14	4.0[7]			
10	30	11:17:13	37	04	121	49	13	4.0			3.7
11	02	05:50:10	37	03	121	48	09	4.7	4.3	4.6	
11	05	01:30:42	37	05	121	56	15	4.0			
11	05	13:37:34	37	03	121	53	10	4.2	4.0		
11	07	23:42:37	37	13	122	02	08	4.2	4.2	4.4	
12	02	20:02:00[6]	37	12	122	03	11	4.0[7]			
02	07	14:12:14	36	56	121	42	03	4.0	4.2		

[1]USGS preliminary locations, except where noted (F. W. Lester, written communication, 1990).

[2]Duration magnitudes from low-gain instruments (J. P. Eaton, personal communication).

[3]National Earthquake Information Center, Preliminary Determination of Epicenters, Weekly.

[4]U. C. Berkeley locations assigned to be the same as the mainshock location; depth not assigned.

[5]U. C. Berkeley preliminary locations (R. A. Uhrhammer, written communication, 1990).

[6]NEIC preliminary locations.

[7]BRK magnitude given in NEIC (Preliminary Determination of Epicenters, Weekly).

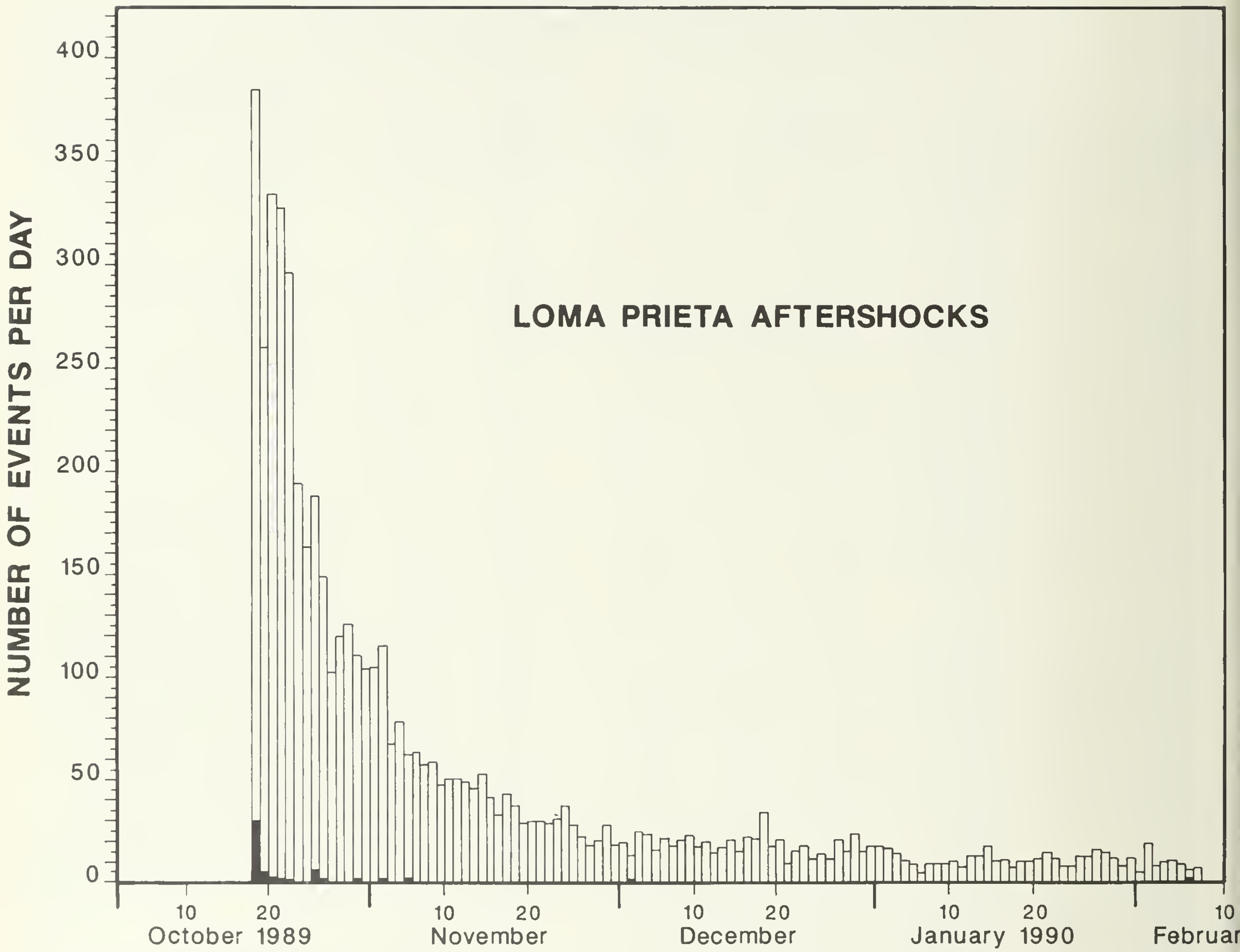


Figure 5. Preliminary histogram of the number of aftershocks per day. Earthquakes had locations determined using at least 5-phase readings and had RMS time residuals of 0.35 sec or less. Solid part of bars indicates aftershocks with M≥4.0 (source: modified from figure provided by F. W. Lester, USGS).

the main fault plane so that most of the aftershocks represent redistributed stresses off the fault (Oppenheimer, 1990). In contrast, the mechanisms of aftershocks of many moderate strike-slip events, such as the 1979 M_L 5.9 Coyote Lake earthquake (Reasenberg and Ellsworth, 1982) agree more closely with the mechanism of the mainshock.

INTENSITY PATTERN

Damage from the Loma Prieta earthquake was fairly widespread. A number of lifelines were affected, notably Interstate 880 (Nimitz Freeway), the San Francisco - Oakland Bay Bridge, and Highway 480 (Embarcadero Freeway) (see Figure 1 of McNutt and Sydnor, this volume). Numerous other bridges and roads were damaged.

Most of San Francisco fared well during the earthquake whose epicenter was about 90 km away, although damage to the various highways and to structures in the Marina district was extensive. Most damage was located in isolated pockets and was severe only in old structures. In Santa Cruz, Watsonville, and Los Gatos, by comparison, a much higher percentage of structures were affected; these cities were located within 23 km of the epicenter.

Intensities from the earthquake reached VIII on the Modified Mercalli intensity (MM) scale (see Montgomery, this volume) throughout much of the epicentral area (Figure 6 A; Stover and others, 1990). Isolated instances of MM IX are assigned to the collapse of the elevated section of the Interstate 880 (Nimitz Freeway) in Oakland, to the damaged Highway 480 (Embarcadero Freeway) in San Francisco, and to the Marina district of San Francisco. Some areas of San Francisco underlain by thick deposits of Quaternary bay mud and eolian sand dunes show intensity levels one to two MM units higher than the central part of the city underlain by rock (Figure 6A; Stover and others, 1990).

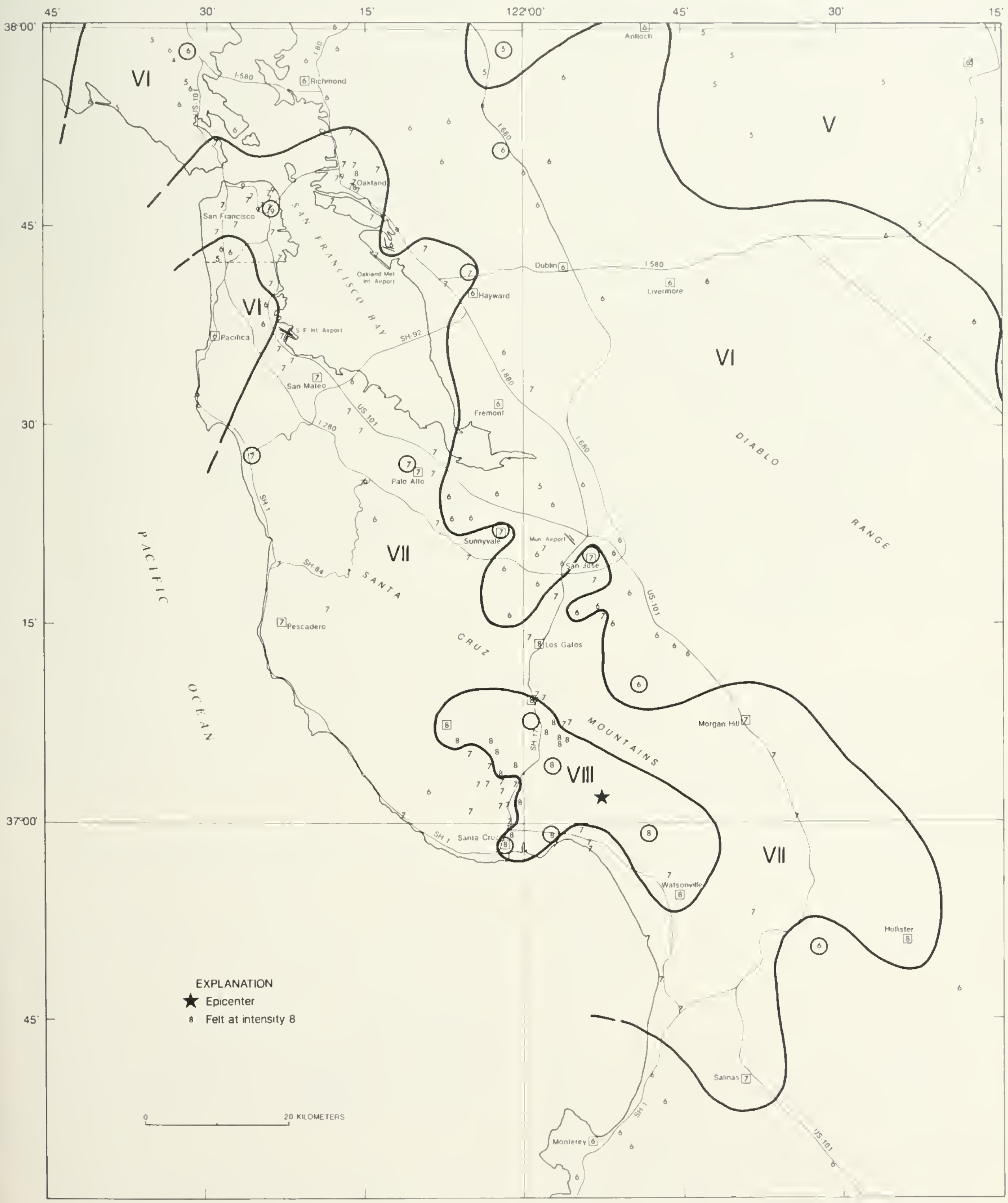


Figure 6. A. Isoseismal map for the San Francisco Bay region for the Loma Prieta earthquake of 17 October 1989. Locations that also reported the 1865 earthquake are circled, and are listed in Table 3 (source: Stover and others, 1990).

Figure 6. B. Isoseismal map for the surrounding region for the Loma Prieta earthquake. Locations that also reported the 1865 earthquake are circled, and are listed in Table 3 (source: Stover and others, 1990).

The area shaken at intensity VII or greater, which can cause significant damage to structures, was 4,300 km^2 on land (Figure 6 A). This compares well to the intensity VII or greater area of 4,100 km^2 on land of the 1865 event discussed below. By comparison, the area shaken at MM VII or greater in the 1906 San Francisco earthquake was 48,000 km^2 on land (Toppozada and Parke, 1982).

One of the most surprising features of the earthquake was the lack of primary surface rupture representing the faulting motion (Hart and others, this volume). The impressive cracks shown in the news media were mostly superficial features secondary to the faulting at depth. Numerous ground failures occurred over an area 100 km long by 40 km wide, stretching from San Gregorio to Hollister, with additional coastal bluff landslides occurring in a narrow strip along the coast all the way up to Marin County (Plant and Griggs, 1990; Sydnor and others, this volume). Ground failures included landslides, debris slides, rockfalls, and bedrock slides (Spittler and others, this volume). Liquefaction phenomena were widespread, occurring from Oakland to Salinas, and produced numerous sand boils and mud volcanoes (Figure 1 of McNutt and Sydnor, this volume).

STRONG SHAKING

Most people in the vicinity of the earthquake felt about 10 to 15 seconds of strong ground shaking. The P wave was felt first, then the strong shaking was associated with the S waves and surface waves. In addition to being felt by millions of people, the earthquake was recorded by 93 strong motion accelerographs operated by the Division of Mines and Geology Strong Motion Instrumentation Program (Shakal and others, 1989; Shakal and others, this volume; and Reichle and others, this volume). Data from these instruments show about 10-15 seconds of shaking stronger than 0.1 g. This corresponds to the duration of shaking that was felt by most people. The strongest shaking recorded in the near field at a ground-response site (a site not located in or near a building or bridge) was 0.64 g horizontal. It was noted by field observers that damage near this particular site (Corralitos) was relatively minor, whereas damage nearby, particularly on ridges, was extensive. This may suggest that shaking on the ridges and throughout much of the epicentral area was stronger than 0.64 g (Spittler and Sydnor, 1990).

COMPARISON TO THE 1865 EARTHQUAKE

On 8 October 1865 an earthquake caused structural damage from Watsonville to San Francisco and major damage in the Santa Cruz Mountains. The isoseismal map of Toppozada and others (1981) shows the epicenter at 37.2°N, 121.9°W on the northern flank of the Santa Cruz Mountains. Stover and others (1990) compared the intensity of the Loma Prieta event to that reported by Toppozada and others (1981) for the 1865 earthquake at 13 places that reported both events. We have reviewed and revised the comparison at these 13 places and compared 15 additional places that reported both events. Places that reported both the 1865 and 1989 events are circled in Figures 6A and 6B.

Table 3 shows the comparison at the 28 sites that reported both earthquakes. The table is arranged by increasing distance from the Loma Prieta epicenter and, hence, generally by decreasing intensity. San Francisco had anomalously high intensities in both events. MM IX damage in San Francisco in 1989 was to freeways and to the sandy fill areas of the Marina District, neither of which existed in 1865. Note that in the comparison in Table 3, we had no 1989 reports for three localities that reported the 1865 event, so we compared them to intensities from neighboring localities. There is good agreement at all places that reported both earthquakes, with differences of a whole intensity unit at only five places (footnote 4 in Table 3). This remarkable agreement in the effects of both earthquakes spans the entire range of intensities reported, from MM I (not felt) to MM VIII, and from distances of 8 to 390 km. Further, Townley and Allen's (1939) descriptions of the 1865 earthquake as being felt for 10 to 15 seconds in San Francisco, being most severe at Santa Cruz and near Watsonville, and causing people to feel nausea in Sacramento, are analogous to the effects of the 1989 event.

There is a suggestion from the pattern of intensity distribution that the 1865 event was located somewhat northward of the 1989 event because it had higher intensities at New Almaden and had lower values at Corralitos and Soquel (Table 3). This is marginally significant, however, because in the same general north-south trend, San Francisco, San Leandro, and Watsonville do not show systematic differences between the two earthquakes. No significant intensity differences are apparent from Table 3 and Figure 6, indicating that the difference in location between the 1865 and 1989 events is less than 25 km.

We infer that the magnitudes of the two earthquakes are also very similar. Toppozada and others (1981) originally estimated M 6.3 for the 1865 event using Toppozada's 1975 equations relating isoseismal areas to magnitude. These equations were found by Ellsworth (1990) to underestimate M by 0.3 unit, which changes the magnitude from 6.3 to 6.6. The similarity over all intensities of the 1865 and Loma Prieta events suggests a magnitude for the 1865 earthquake even closer to Loma Prieta's M 7.1.

When Toppozada's (1975) relation is applied to the intensity VI areas in 1865 (21,000 km^2) and in 1989 (22,000 km^2), the results are M 6.25 and M 6.3, respectively. When the relation is applied to the intensity VII areas in 1865 (4,100 km^2) and in 1989 (4,300 km^2) the results are M 6.6 and M 6.65, respectively. This confirms that the 1865 and 1989 events had similar magnitudes, and it also indicates that the 1975 relations may underestimate M by about 1/2 unit in the Bay area. This is because the relations are based on earthquakes located primarily *outside* the Bay area. The 1989 event is the first earthquake located in the Bay area or vicinity having an instrumentally determined magnitude in the M 7 range. A magnitude of about 7 for the 1865 earthquake estimated by comparing it to the 1989 event is better than that derived from relations based on earthquakes located outside the Bay area where crustal conditions are different.

In summary, intensity comparisons indicate that the 1989 earthquake is almost a duplicate of the 1865 event. The epicentral locations are less than 25 km apart and the magnitudes are within 0.1 to 0.5 unit. If the 1865 event occurred on the San Andreas, this suggests that the 1865 and 1989 events may be characteristic earthquakes for this segment of the fault. It is possible, however, that the 1865 earthquake occurred on a neighboring fault, as did the M 5.0 and M 5.2 events of June 1988 and August 1989 about 10 km north of the Loma Prieta epicenter. In either case, the region has generated four earthquakes of M~ 7 or greater (1838, 1865, 1906, and 1989), more than almost any other area in California in the short historical record.

TABLE 3

MM INTENSITIES FOR LOCALITIES REPORTING BOTH THE OCTOBER 8, 1865 AND OCTOBER 17, 1989, CALIFORNIA EARTHQUAKES

Distance[1]	Locality	1865[2]	1989[3]
8-WNW	Santa Cruz Gap Rd.	VIII	VIII
9-SE	Corralitos[4]	VII	VIII
10-SW	Soquel[4]	VII	VIII
13-NW	Mountain Charlie's[5]	VIII?	VIII?
15-WSW	Santa Cruz	VII-VIII	VIII
16-NNE	New Almaden[4]	VII-VIII	VI+
18-SE	Watsonville	VII-VIII	VIII
33-N	San Jose	VII-VIII	VII
38-SE	San Juan Bautista	VI?	VI
40-NNW	Santa Clara	VII	VII at Sunnyvale, 8 km W of Santa Clara
55-WNW	Redwood City	VI-VII	VI
70-NW	Half Moon Bay	VI+	VII
77-NNW	San Leandro	VI	VI-VII
83-NNW	Alamo	VI	VI
90-NW	San Francisco	VII	VII-IX
99-NNW	Pacheco	VI	V-VI at Concord, 3 km E of Pacheco
104-NNW	Martinez	VI	VI
105-NE	Stockton	V-VI	V
113-NW	San Rafael	V-VI	VI
137-NNW	Napa	VI	VI
143-NW	Petaluma	V-VI	V
165-NNE	Sacramento	IV-V	V
166-NW	Santa Rosa	V-VI?	V
200-NE	Placerville[4]	II	I (Not Felt)
226-NNE	Marysville	II-III	III
246-ESE	Visalia	I (Not Felt)	No Report
248-NNE	Nevada City[4]	II	I (Not Felt)
390-NNW	Shasta	II-III	III at Redding, 8 km E of Shasta

[1]Distance in km and azimuth from Loma Prieta epicenter.

[2]MM intensities revised from Toppozada and others (1981).

[3]MM intensities from Stover and others (1990), and from Carl Stover (personal communication).

[4]Locations reporting intensities differing by a unit MM between the two earthquakes.

[5]Mountain Charlie's near Highway 17 and Summit Road had conspicuous ground cracks in 1865 and also in 1989. (See Cotton and others [this volume] for description of co-seismic surface fissures.)

COMPARISON TO OTHER M 7 EARTHQUAKES

Earthquakes of M~7 occur infrequently in California. Conse-uently it is instructive to examine earthquakes of this size that ccurred elsewhere. The purpose of this section is to learn if the 1989 arthquake is typical of other events of this size and to obtain some amiliarity with expected features of large earthquakes. We empha-ize the size and distribution in space and time of aftershocks since iese are of great concern to the emergency response community. In articular, the largest aftershocks are the ones most likely to cause urther damage.

Parameters of eight earthquakes including the Loma Prieta event re shown in Table 4. The events were selected mainly on the basis f magnitude and data quality, and because they occurred on land. ive of these events are within 0.2 magnitude units of the Loma Prieta vent, and the other two are included because they are well known: rmenia (1988) and Kern County (1952). The tabulated parameters iclude several that are not routinely reported: aftershock zone ength, magnitude difference between the mainshock and largest ftershock, time to largest aftershock, distance to largest aftershock, nd number of M≥4.0 aftershocks. When compared to the other vents, the Loma Prieta earthquake has a roughly median aftershock one length, a larger than average magnitude difference between the iainshock and largest aftershock, a median time from the mainshock the largest aftershock, a roughly median distance to the largest af-rshock, and a slightly higher than average number of M≥4 after-iocks (although there were fewer large aftershocks). The Loma rieta earthquake is similar to the 1980 Campania, Italy earthquake ot only in most of the listed parameters but in its rupture extent, epth, and geometry as well (Deschamps and King, 1983).

If suitable measurements were made on the mainshock and data on ther similar events were readily available, then it might be possible predict spatial and temporal features of the aftershock sequence. easenberg and Jones (1989) considered mainshock magnitude and ased temporal probability estimates for large aftershocks on evalu-tion of a 'generic California' sequence, updated with preliminary ieasurements of the sequence in progress. Such estimates were used y the emergency response community and by field geologists fol-owing the Loma Prieta earthquake. In general, however, this ap-roach is limited by the fact that stochastic or random variability far utweighs measurement errors in terms of quantifying earthquake arameters. Especially for large earthquakes, therefore, it may be rudent to base short-term aftershock hazard assessments on upper anges of parameters, rather than on average values.

The process which gives rise to aftershocks is not uniform from lace to place nor even necessarily uniform at the same place at ifferent times. Rather, many random processes in the earth, about hich we know relatively little, act to modify aftershock sequences. There is probably about an order of magnitude variability in some of the parameters listed in Table 4 which would be more apparent if many more events were added to the sample. Bonilla and others (1984), for example, found this range of variability when comparing earthquake magnitude to rupture length for strike-slip faults (preliminary data show that rupture length is about two-thirds of aftershock zone length). Singh and Suarez (1988) showed that the number of M≥5 aftershocks (compared to our number of M≥4) of M≥7 subduction zone events varied by a factor of 40 (!), but included systematic regional variation. Doser (1990) found that the timing of the largest aftershock was less than 24 hours 60 percent of the time for M≥5.5 earthquakes within the western Cordillera, but nearly one-third occurred more than one week after their mainshocks (similar to Table 4). Each of these studies tried to minimize measurement errors by judicious selection of data and measurement techniques, yet stochastic variability still dominates any simple trends.

Based on the selected parameters of the sample above, the Loma Prieta earthquake appears to be fairly typical of events of its size. However, the duration of the main rupture was less than usual because rupture was bilateral rather than unilateral. The size of the fault surface that ruptured may have been somewhat smaller than usual, although the aftershock zone length in Table 4 does not appear to be anomalous. Most earthquakes of the same size tend to have more large aftershocks. Large ranges in parameters are to be expected, in general, since stochastic variability is greater than measurement error. This indicates the need for caution when using the Loma Prieta earthquake or any other single earthquake as a model for future M 7 events in California.

PROBABILITIES

The Loma Prieta earthquake occurred on a fault segment that had been identified in several studies as having a relatively high probability for an earthquake of M 6.5 to 7 (WGCEP, 1988; Lindh, 1983; Sykes and Nishenko, 1984). In the 1988 study, the probability was estimated at 30 percent over the 30-year period from 1988 to 2018. The Loma Prieta earthquake occurred in the correct area and within the forecast size range. The segment of the San Andreas fault immediately to the north of the Loma Prieta segment was identified in the same study as having a 20 percent probability of producing an event of M 7 in the next 30 years. Two segments of the Hayward fault in the East Bay also were identified as each having a 20 percent chance of producing an M 7 event in the next 30 years (WGCEP, 1988).

An earthquake of M~ 7 similar to the Loma Prieta event located closer to San Francisco and Oakland, would be much more destructive than the Loma Prieta event. A major earthquake (M 7.0-7.5) in the East Bay could be as destructive to the whole Bay area as a larger (M_S 8.3) earthquake on the San Andreas fault (Steinbrugge and others, 1987).

TABLE 4
SELECTED EARTHQUAKES OF M_S 6.8 - 7.7 AND THEIR AFTERSHOCKS

Name, Place and Date	Lat., Long. and Depth	Aftershock Zone Length (time)	Mainshock Magnitude	Largest Aftershock Magnitude	Mag. Diff.	Time of Largest Aftershock[1]	Distance to Largest Aftershock[2]	No. of $M\geq4$ Aftershocks (1st month)	References
Imperial Valley California 1940.05.18	32° 44' N 115° 30' W —[3]	>63 km (surf.rupt.)	M_S 7.1 M_L 6.7	M_L 5.5	1.2	19 min.	4 km[4]	21	Hileman and others, 1973; Richter, 1958
Kern County California 1952.07.21	34° 59' N 119° 02' W —[3]	90 km (1.5 yr)	M_S 7.7 M_L 7.2	M_S 6.4	1.3	13 min.	3 km	162	Richter, 1958; Oakeshott, 1955; Ishida and Kanamori, 1980; Hileman and others, 1973
Ghaenat Iran 1979.11.27	34° 08' N 59° 52' E 10 km[5]	111 km	M_S 7.2 m_b 6.1	M_S 6.0	1.2	10 days	9 km	25 (most M>4.4)	Haghipour and Amidi 1980; NEIS, 1979 (monthly)
El Asnam Algeria 1980.10.10	36° 10' N 01° 22' E 6 km	54 km	M_S 7.3 m_b 6.5	M_S 6.1 m_b 6.2	1.2	3 hours	23 km	36	Burford and others, 1981; NEIS, 1980 (monthly); Yielding and others, 1981
Humboldt County offshore Calif. 1980.11.08	41° 07' N 124° 15' W 19 km	153 km (57 days)	M_S 7.2 M_L 6.9 m_b 6.2	M_S 4.3 M_L 5.4 m_b 5.0	1.5	18 hours	98 km	20	J. Eaton, writ. comm., 1983; NEIS, 1980 (monthly)
Campania Italy 1980.11.23	40° 46' N 15° 18' E 16 km	92 km	M_S 6.9 m_b 6.0	M_S 5.3 m_b 4.9	1.6	2 days	22 km	43	Deschamps and King, 1983; NEIS, 1980 (monthly); Del Pezzo and others, 1983
Armenia S.S.R. 1988.12.07	41° 00' N 44° 12' E 10 km[5]	45 km (28 days)	M_S 6.8 m_b 6.3	m_b 5.9	0.4	4 min.	~1 km[4]	>18	Simpson and others, 1989; Borcherdt, 1989; NEIC, 1988 (monthly)
Loma Prieta California 1989.10.17	37° 02' N 121° 53' W 17.6 km	68 km (1 month)	M_S 7.1 M_L 7.0 m_b 6.5	M_L 5.1 m_b 4.8	1.9	37 min.	23 km	46	Plafker and Galloway, 1989; NEIC, 1989 (weekly); Dietz and Ellsworth, 1990

[1]Time from mainshock to largest aftershock.
[2]Distance from mainshock to largest aftershock.
[3]Depths are not known for these events because of sparse station coverage at the time.
[4]Estimated.
[5][illegible]

SUMMARY

This article has highlighted some of the seismological features of the Loma Prieta earthquake of 17 October 1989. The earthquake had surface wave magnitude 7.1 and originated at 18 km depth in the Santa Cruz Mountains. The aftershock zone was about 66 km long and included 48 events of M≥ 4.0. While no primary surface fault rupture occurred, numerous ground fissures and hundreds of landslides were seismically induced. Strong shaking from the earthquake was felt for 10-15 seconds over a wide area, resulting in high levels of damage near the epicenter and isolated pockets of damage at distances of up to 100 km. The earthquake was very similar to the earthquake of 1865 in both size and location. It was also similar in many of its parameters to other events of comparable size located elsewhere.

For most residents of the Bay area, the Loma Prieta earthquake was the strongest earthquake they have ever experienced. Several other segments of faults in California have significant probabilities for producing earthquakes of comparable size over the next several decades. Several of these segments in the Bay area are located closer than the Loma Prieta event to the centers of population of San Francisco and Oakland, and thus pose a greater hazard. Such destructive Bay area earthquakes have occurred twice in the 1830's and twice in the 1860's.

ACKNOWLEDGMENTS

We thank Bob Darragh, Chris Cramer, and Robert Sydnor for reviewing the manuscript. Carl Stover, Rick Lester, Dave Oppenheimer, Bob Uhrhammer, Janet Crampton, Jean Olson, Lynn Dietz, Hiroo Kanamori, George Plafker, Claudia Hallstrom, and Jerry Eaton generously provided data and advice. Terry Lawler and Virginia Williams assisted with preparation of the manuscript and tables.

Note added in proof:

On April 18, 1990, six additional aftershocks with M≥4.0 occurred at or beyond the southeastern end of the Loma Prieta aftershock zone near Chittenden. The M=5.4 event at 13:53 UTC (06:53 PDT) was the largest aftershock to date.

Month	Day	Time(UTC)	Latitude Deg	Latitude Min	Longitude Deg	Longitude Min	Depth (km)	Magnitude USGS M
04	18	13:37:57	36	56	121	38	5	4.7
04	18	13:41:39	36	56	121	39	5	4.4
04	18	13:53:51	36	56	121	39	5	5.4
04	18	14:52:24	36	55	121	39	5	4.0
04	18	14:28:16	36	56	121	41	6	4.0
04	18	15:46:03	36	58	121	40	5	5.0

See Table 2 (page 17) for further explanation.

(Source: F. W. Lester, USGS, written communication, 1990)

REFERENCES

Allen, C.R., and Nordquist, J.M., 1972, Foreshock, main shock,and larger aftershocks of the Borrego Mountain earthquake: U.S. Geological Survey Professional Paper 787, p. 16-23.

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., ed., 1989, Results and data from seismologic and geologic studies following earthquakes of December 7, 1988, near Spitak, Armenia S.S.R.: U.S. Geological Survey Open-File Report 89-163A, 188 p.

Branch of Seismology, USGS, 1990, Seismogenic structure and seismicity of the 1989 Loma Prieta, California sequence: EOS, Transactions of the American Geophysical Union, v. 71, no. 8, p. 291, (abstract).

Burford, R.O., Harsh, P.W., and Espinosa, A.F., 1981, Last October [1980] 7.3 quake in Algeria reviewed: Geotimes, v. 26, no. 5, p. 18-20.

Choy, G.L., Boatwright, J., Lavonne, C.K., Needham,R.E., and Zirbes, M., 1990, Source characteristics of the Loma Prieta Earthquake of October 17, 1989 from broadband seismograms: EOS, Transactions of the American Geophysical Union, v. 71, no. 8, p. 287, (abstract).

Darragh, R.B., and Bolt, B.A., 1987, A comment on the statistical regression relation between earthquake magnitude and fault rupture length: Bulletin of the Seismological Society of America, v. 77, no. 4, p. 1479-1484.

Das, S., and Scholz, C.H., 1981, Off-fault aftershock clusters caused by shear stress increase?: Bulletin of the Seismological Society of America, v. 71, no. 5, p. 1669-1675.

Del Pezzo, E., Iannaccone, G., Martini, M., and Scarpa, R., 1983, The 23 November 1980 Southern Italy earthquake: Bulletin of the Seismological Society of America, v. 73, no. 1, p. 187-200.

Deschamps, A., and King, G.C.P., 1983, The Campania-Luciana (southern Italy) earthquake of 23 November 1980: Earth and Planetary Science Letters, v. 62, p. 296-304.

Dietz, L.D., and Ellsworth, W.L., 1990, The October 17, 1989 Loma Prieta, California, earthquake and its aftershocks: geometry of the sequence from high-resolution locations: Geophysical Research Letters, v. 17, p. 1417-1420.

Doser, D.I., 1990, Foreshocks and aftershocks of large (M > 5.5) earthquakes within the western Cordillera of the United States: Bulletin of the Seismological Society of America, v. 80, no. 1, p. 110-128.

Ellsworth, W.L., 1990, (in press), Earthquake history 1769-1989: *in* Wallace, R.E., ed., The San Andreas fault system: U.S. Geological Survey Professional Paper 1515.

Ellsworth, W.L., Lindh, A.G., Prescott, W.H., and Herd, D.G., 1981, The 1906 San Francisco earthquake and the seismic cycle, *in* Simpson, D.W., and Richards, P.G., eds., Earthquake Prediction - An International Review: American Geophysical Union, Washington, D.C., p. 126-140.

FEMA (Federal Emergency Management Agency), 1987, The Los Angeles-Whittier Narrows earthquake of October 1, 1987: Federal/State hazard mitigation survey team report, Publication no. FEMA-799-DR-CA.

Furlong, K.P., Langston, C.A., Ammon, C.J., Clouser, R.H., Vogfjord, K.S., and Wagner, G.S., 1990, Seismic rupturing in the lower crust along the San Andreas?: lessons from Loma Prieta: EOS, Transactions of the American Geophysical Union, v. 71, no. 8, p. 288, (abstract).

Haghipour, A., and Amidi, M., 1980, The November 14 to December 25, 1979 Ghaenat earthquakes of northeast Iran and their tectonic implications: Bulletin of the Seismological Society of America, v. 70, no. 5, p. 1751-1757.

Hart, E.W., Bryant, W.A., Wills, C.J., and Treiman, J.A., 1990, The search for fault rupture and significance of ridgetop fissures, Santa Cruz Mountains, California: this volume, p. 83-94.

Hileman, J.A., Allen, C.R., and Nordquist, J.M., 1973, Seismicity of the southern California region 1 January 1932 to 31 December 1972: Seismological Laboratory, California Institute of Technology, 488 p.

Ishida, M., and Kanamori, H., 1980, Temporal variation of seismicity and spectrum of small earthquakes preceding the 1952 Kern County, California, earthquake: Bulletin of the Seismological Society of America, v. 70, no. 2, p. 509-527.

Jacoby, G.C., Jr., Sheppard, P.R., and Sieh, K.E., 1988, Irregular recurrence of large earthquakes along the San Andreas fault: Evidence from trees: Science, v. 241, p. 196-199.

Jaumé, S.C., and Sykes, L.R., 1990, Seismicity changes in the San Francisco Bay region before the Loma Prieta earthquake of 1989: EOS, Transactions of the American Geophysical Union, v. 71, no. 8, p. 288, (abstract).

Jennings, C.W., 1975, Fault map of California: California Division of Mines and Geology, Geologic Data Map no. 1, scale 1:750,000.

Kanamori, H., 1983, Mechanism of the 1983 Coalinga earthquake determined from long-period surface waves: California Division of Mines and Geology Special Publication 66, p. 233-240.

Kanamori, H., and Anderson, D.L., 1975, Theoretical basis of some empirical relations in seismology: Bulletin of the Seismological Society of America, v. 65, no. 5, p. 1073-1095.

Kanamori, H., and Helmberger, D.V., 1990, Semi-realtime study of the 1989 Loma Prieta Earthquake using teleseismic and regional data: EOS, Transactions of the American Geophysical Union, v. 71, no. 8, p. 291, (abstract).

Lawson, A.C., ed., 1908, The California Earthquake of April 18, 1906: Report of the State Earthquake Investigation Commission, Carnegie Institution of Washington, Publication 87, v. 1, 451 p.

Li, V.C., Seale, S.H., and Cao, T., 1987, Postseismic stress and pore pressure readjustment and aftershock distributions: Tectonophysics, v. 144, p. 37-54.

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, 15 p.

Lisowski, M., Prescott, W.H., Savage, J.C., and Svarc, J.L., 1990, A possible geodetic anomaly observed prior to the Loma Prieta, California, earthquake: Geophysical Research Letters, v. 17, p. 1211-1214.

Louderback, G.D., 1947, Central California earthquakes of the 1830's: Bulletin of the Seismological Society of America, v. 37, p. 33-74.

McNally, K.C., Lay, T., Protti-Quesada, M., Valenise, G., Orange, D., and Anderson, R.S., 1989, Santa Cruz Mountains (Loma Prieta) earthquake: EOS, Transactions of the American Geophysical Union, v. 70, no. 45, p. 1463-1467.

McNutt, S.R., 1990, Loma Prieta Earthquake, October 17, 1989, Santa Cruz County, California: California Geology, v. 43, p. 3-7.

McNutt, S.R., and Sydnor, R.H., 1990, Introduction: this volume, p.v-viii.

Montgomery, D.R., Representative damage photographs from the Loma Prieta earthquake: this volume, p. 113-120.

Nábělek, J., 1990, Broadband teleseismic body wave analysis of the October 18, 1989 Loma Prieta earthquake: EOS, Transactions of the American Geophysical Union, v. 71, no. 8, p. 289, (abstract).

NEIC (National Earthquake Information Center), 1988, Preliminary Determination of Epicenters, U.S. Geological Survey.

NEIC (National Earthquake Information Center), 1989, Preliminary Determination of Epicenters, U.S. Geological Survey.

NEIC (National Earthquake Information Center), 1990, Preliminary Determination of Epicenters, U.S. Geological Survey.

NEIS (National Earthquake Information Service), 1979, Preliminary Determination of Epicenters, U.S. Geological Survey.

NEIS (National Earthquake Information Service), 1980, Preliminary Determination of Epicenters, U.S. Geological Survey.

Oakeshott, G.B., ed., 1955, Earthquakes in Kern County California during 1952: California Division of Mines Bulletin 171, 283 p.

Oakeshott, G. B., ed., 1959, San Francisco earthquakes of March 1957: California Division of Mines Special Report 57, 127 p.

Olson, J., and Lindh, A., 1990, Seismicity preceding the Loma Prieta Earthquake: EOS, Transactions of the American Geophysical Union, v. 71, no. 8, p. 289, (abstract).

Oppenheimer, D.H., 1990, Aftershock slip behavior of the 1989 Loma Prieta, California earthquake: Geophysical Research Letters, v. 17, p. 1199-2002.

Plafker, G., and Galloway, J.P., eds., 1989, Lessons learned from the Loma Prieta, California, earthquake of October 17, 1989: U.S. Geological Survey Circular 1045, 48 p.

Plant, N., and Griggs, G.B., 1990, Coastal landslides caused by the October 17, 1989 earthquake, Santa Cruz County, California: California Geology, v. 43. no. 4, p. 75-84.

Prescott, W.H., Lisowski, M., Johnston, M.J.S., Schulz, S.S., Savage, J.C., and Clark, T.A., 1990, Deformation before, during and after the Loma Prieta earthquake of October 1989: EOS Transactions of the American Geophysical Union, v. 71, no. 8, p. 291, (abstract).

Real, C.R., Toppozada, T.R., and Parke, D.L., 1978, Earthquake epicenter map of California: California Division of Mines and Geology, Map Sheet 39.

Reasenberg, P.A., and Ellsworth, W.L., 1982, Aftershocks of the Coyote Lake, California, earthquake of August 6, 1979: A detailed study: Journal of Geophysical Research, v. 87, p. 10,637-10,655.

Reasenberg, P.A., and Jones, L.M., 1989, Earthquake hazard after a mainshock in California: Science, v. 243, p. 1173-1176.

Reasenberg, P.A., and Jones, L.M., 1990, California aftershock hazard forecasts: Science, v. 247, p. 345-346.

Reasenberg, P.A., and Matthews, M.V., 1990, California aftershock model uncertainties; Response: Science, v. 247, p. 343-345.

Reichle, M.S., Darragh, R.B., Huang, M., Cao, T., Vetter, U. R., and Shakal, A.F., 1990, Preliminary analysis of processed strong-motion data from the Loma Prieta earthquake: this volume, p. 47-57.

Richter, C.F., 1958, Elementary seismology: W.H. Freeman and Company, San Francisco, California, 768 p.

Romanowicz, B., Caen, H.L., and Deschamps, A., 1990, The Loma Prieta Earthquake of October 18, 1989: preliminary results using teletransmitted data from the Geoscope Network: EOS, Transactions of the American Geophysical Union, v. 71, no. 8, p. 290, (abstract).

Salzberg, D.H., Carabajal, C.C., Barker, J.S., and Wu, F.T., 1990, Preliminary source characteristics of the October 18, 1989 Loma Prieta mainshock based on teleseismic P and S waveforms: EOS, Transactions of the American Geophysical Union, v. 71, no. 8, p. 290, (abstract).

San Francisco Chronicle, 1990, L.A. Quake Damage Estimates Rise: San Francisco Chronicle, San Francisco, California, March 2, 1990, p. A-1, A-26.

Shakal, A.F., DeLisle, M., Reichle, M.S., and Darragh, R., 1990, Strong ground shaking from the Loma Prieta earthquake of 17 October 1989, and its relation to near surface geology in the Oakland area: this volume, p. 29-46.

Shakal, A.F., Huang, M. J., Reichle, M.S., Ventura, C., Cao, T., Sherburne, R.W., Savage, M., Darragh, R., and Petersen, C., 1989, CSMIP strong-motion records from the Santa Cruz Mountains (Loma Prieta), California earthquake of 17 October 1989: California Division of Mines and Geology, Report No. OSMS 89-06, 196 p.

Simpson, D., Cranswick, E., Andrews, M., and Glassmoyer, G., 1989, Preliminary aftershock locations (December 21, 1988 - January 4, 1989): U.S. Geological Survey Open-File Report 89-163A, p. 75-85.

Singh, S.K., and Suarez, G., 1988, Regional variation in the number of aftershocks ($m_b \geq 5$) of large, subduction-zone earthquakes ($M_w \geq 7.0$): Bulletin of the Seismological Society of America, v. 78, no. 1, p. 230-242.

Spittler, T.E., Harp, E.L., Keefer, D.K., Wilson, R.C., and Sydnor, R.H., 1990, Landslide features and coseismic fissures triggered by the Loma Prieta earthquake, central Santa Cruz Mountains, California: this volume, p. 59-65.

Spittler, T.E., and Sydnor, R.H., 1990, Landslides and ridge-top failures associated with the epicentral area of the Loma Prieta earthquake of October 17, 1989, Santa Cruz County, California: EOS Transactions of the American Geophysical Union, v. 71, no. 8, p. 290, (abstract).

Stein, R.S., and Lisowski, M., 1983, The 1979 Homestead Valley earthquake sequence, California: Control of aftershocks and postseismic deformation: Journal of Geophysical Research, v. 88, no. B8, p. 6477-6490.

Steinbrugge, K.V., Bennett, J.H., Lagorio, H.J., Davis, J.F., Borchardt, G., and Toppozada, T.R., 1987, Earthquake planning scenario for a magnitude 7.5 earthquake on the Hayward Fault in the San Francisco Bay area: California Division of Mines and Geology, Special Publication 78, 243 p.

Stover, C.W., Reagor, B.G., Baldwin, F.W., and Brewer, L.R., 1990, Preliminary isoseismal map for the Santa Cruz (Loma Prieta), California, earthquake of October 18, 1989 UTC: U.S. Geological Survey Open-File Report 90-18, 24 p.

Sydnor, R.H., Griggs, G. B., Weber, G. E., McCarthy, R. J., and Plant, N., 1990, Coastal bluff landslides in Santa Cruz County resulting from the Loma Prieta earthquake of 17 October 1989: this volume, p. 67-82.

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.

Tocher, D., 1959, Seismic history of the San Francisco region: *in* Oakeshott, G.B., ed., 1959, San Francisco earthquakes of March 1957: California Division of Mines Special Report 57, p. 39-48.

Toppozada, T.R., 1975, Earthquake magnitude as a function of intensity data in California and western Nevada: Bulletin of the Seismological Society of America, v. 65, no. 5, p. 1223-1238.

Toppozada, T.R., 1990, Earthquake history and hazards in central California, within 100 km of Parkfield: California Division of Mines and Geology, (manuscript in review), 120 p.

Toppozada, T.R., Hallstrom, C., and Ransom, D., 1990, M> 5.5 Earthquakes within 100 km of Parkfield, CA: Seismological Research Letters, v. 61, no. 1, p. 42, (abstract).

Toppozada, T.R., and Parke, D.L., 1982, Areas damaged by California earthquakes, 1900-1949: California Division of Mines and Geology Open-File Report 82-17 SAC, 65 p.

Toppozada, T.R., Real, C.R., and Parke, D.L., 1981, Preparation of isoseismal maps and summaries of reported effects for pre-1900 California earthquakes: California Division of Mines and Geology Open-File Report 81-11 SAC, 182 p.

Toppozada, T.R., Real, C.R., and Parke, D.L., 1986, Earthquake history of California: California Geology, v. 39, no. 2, p. 27-33.

Townley, M.D., and Allen, M.W., 1939, Descriptive catalog of earthquakes of the Pacific coast of the United States, 1769 to 1928: Bulletin of the Seismological Society of America, v. 29, p. 1-297.

U.S. Geological Survey Staff, 1990, The Loma Prieta, California, earthquake: an anticipated event: Science, v. 247, p. 286-293.

Wallace, T.C., and Lay, T., 1990, Preliminary analysis of the broadband P waves from the 1989 Loma Prieta earthquake: EOS, Transactions of the American Geophysical Union, v. 71, no. 8, p. 290, (abstract).

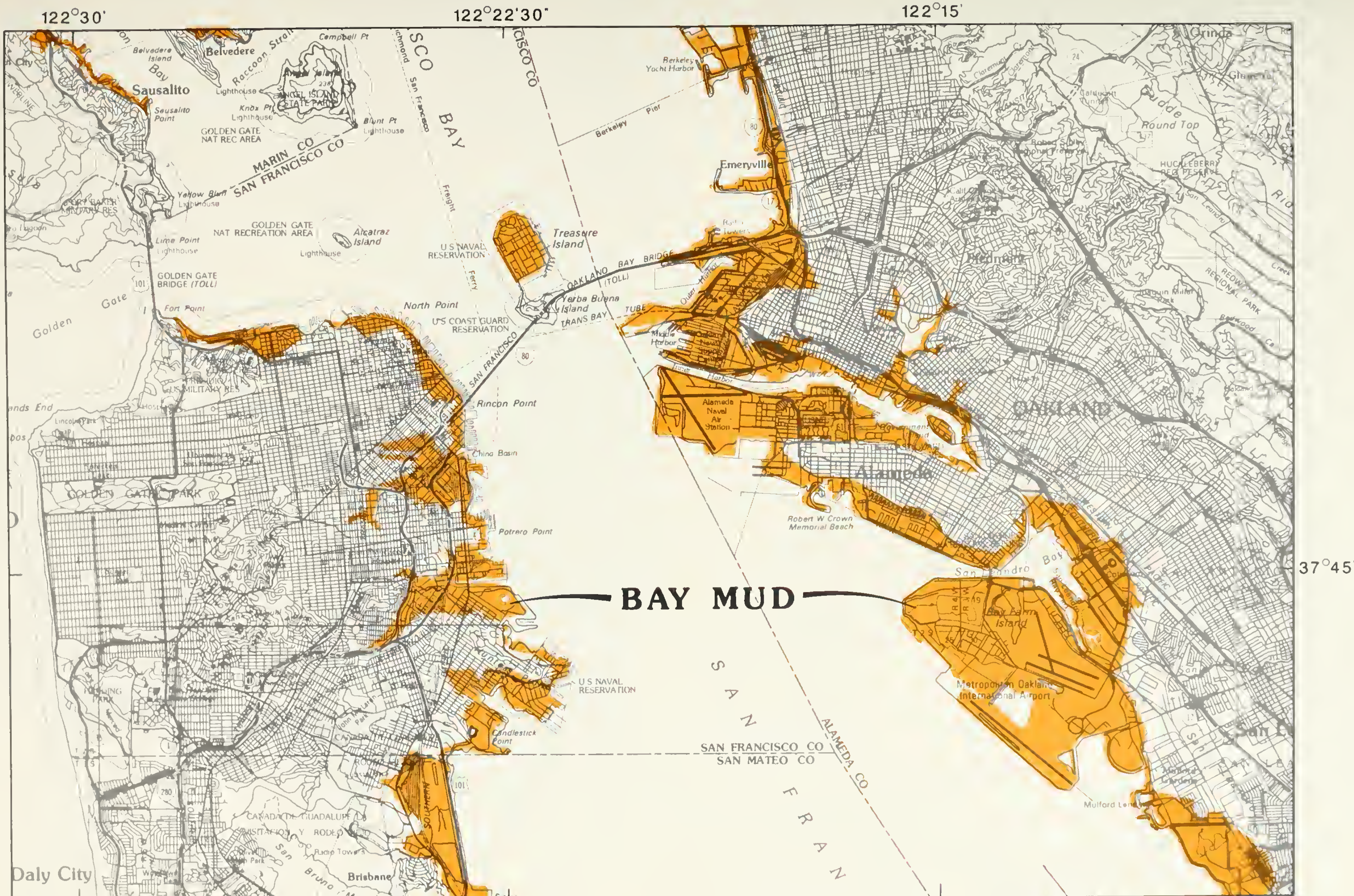
WGCEP (Working Group on California Earthquake Probabilities), 1988, Probabilities of large earthquakes occurring in California on the San Andreas fault: U.S. Geological Survey Open-File Report 88-398, 62 p.

Widmer, F., and Masters, G., 1990, The long-period moment tensor of the Loma Prieta earthquake from IRIS/IDA data: EOS, Transactions of the American Geophysical Union, v. 71, no. 8, p. 290, (abstract).

Woods, B.B., Satake, K., Zhao, L.S., Jones, L.E., Kanamori, H., and Helmberger, D.V., 1990, Notes on the Loma Prieta earthquake: EOS, Transactions of the American Geophysical Union, v. 71, no. 8, p. 290, (abstract).

Yielding, G., Jackson, J.A., King, G.C.P., Sinvhal, H., Vita-Finzi, C., and Wood, R.M., 1981, Relations between surface deformation, fault geometry, seismicity, and rupture characteristics during the El Asnam (Algeria) earthquake of 10 October, 1980: Earth and Planetary Science Letters, v. 56, p. 287-304.

SECTION II
Earthquake Effects



Base map by USGS.

Figure 4. Generalized Quaternary geology of the San Francisco - Oakland area (from Helley, and others, 1979). Areas of bay mud are denoted by color.

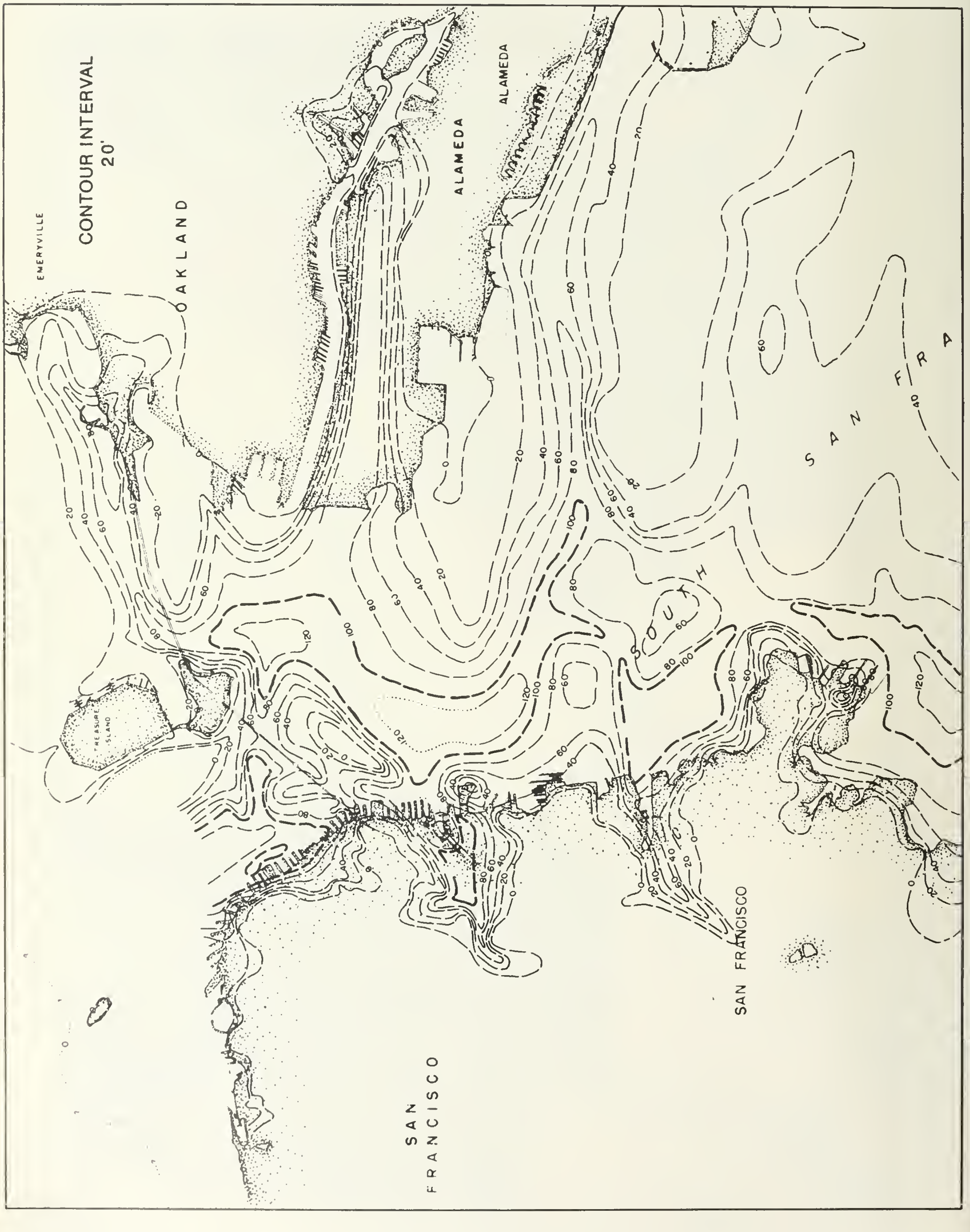
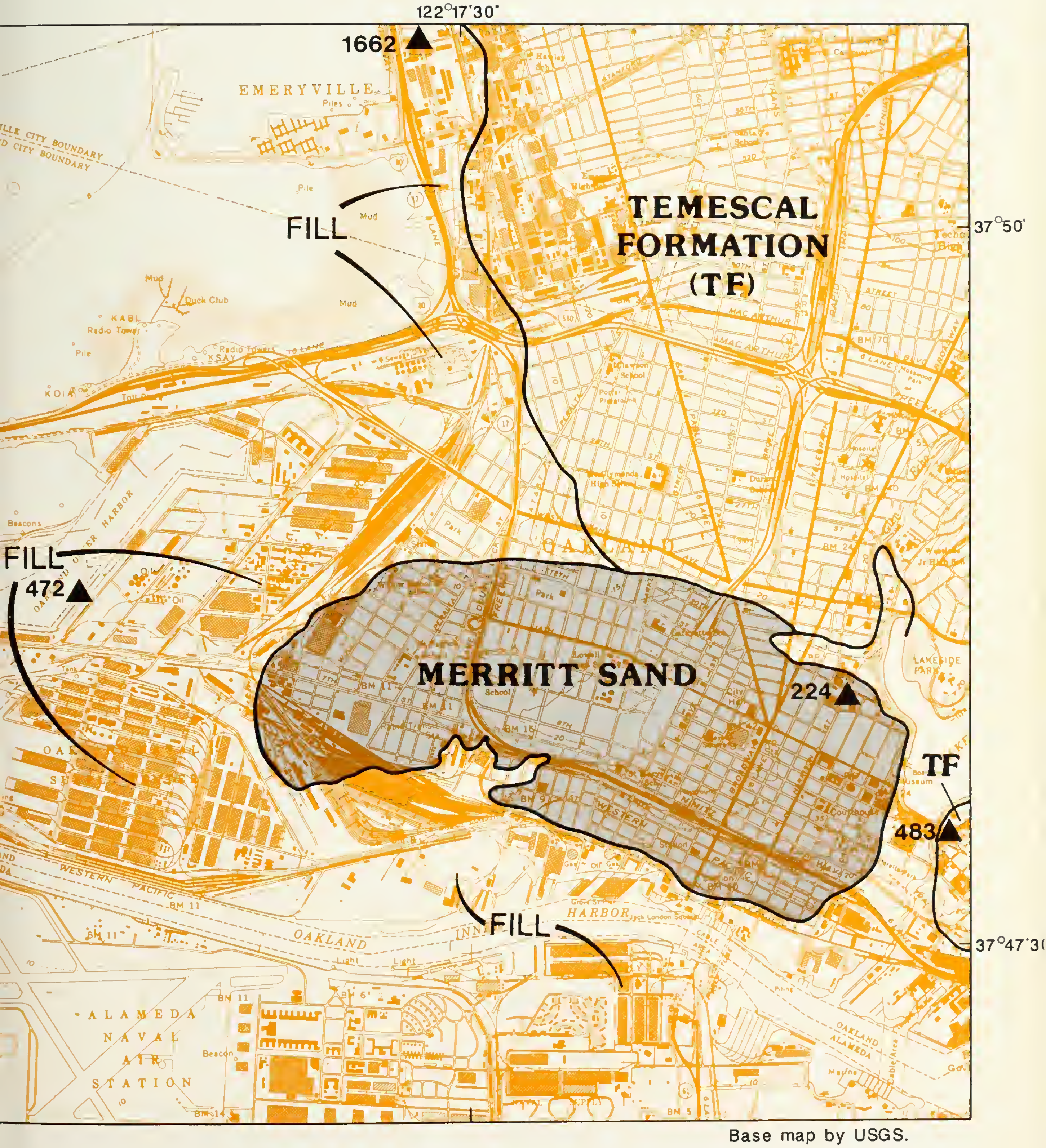


Figure 5. Thickness of bay mud (after Goldman, 1969).



...ure 6. Surficial geology in Oakland area (from Radbruch, 1957). Triangles indicate locations of nearby SMIP (472, 224) and USGS (1662) strong motion stations. ...ation 483 is an 18-story building, so the basement record is not used here since it may be affected by soil-structure interaction.)

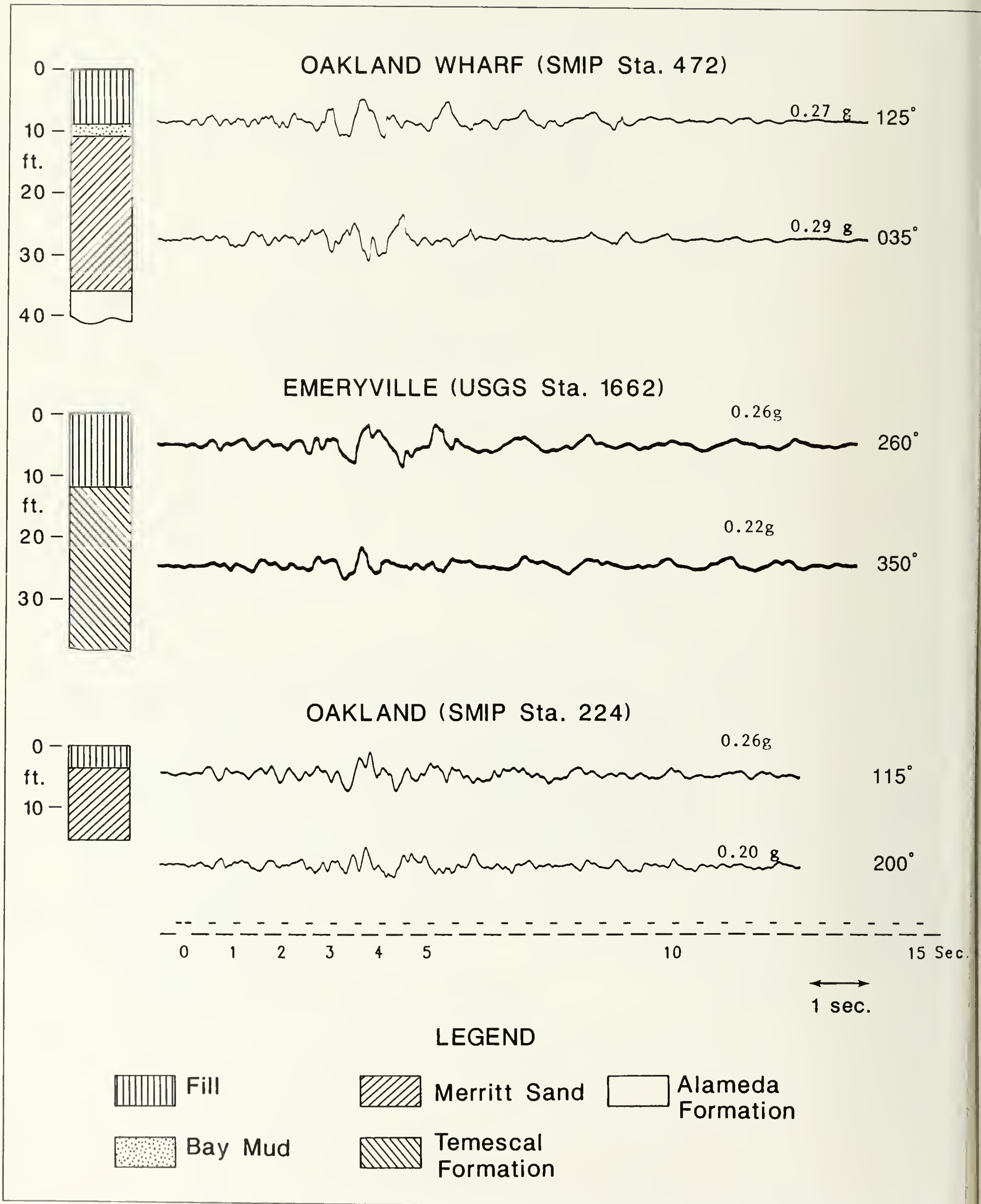
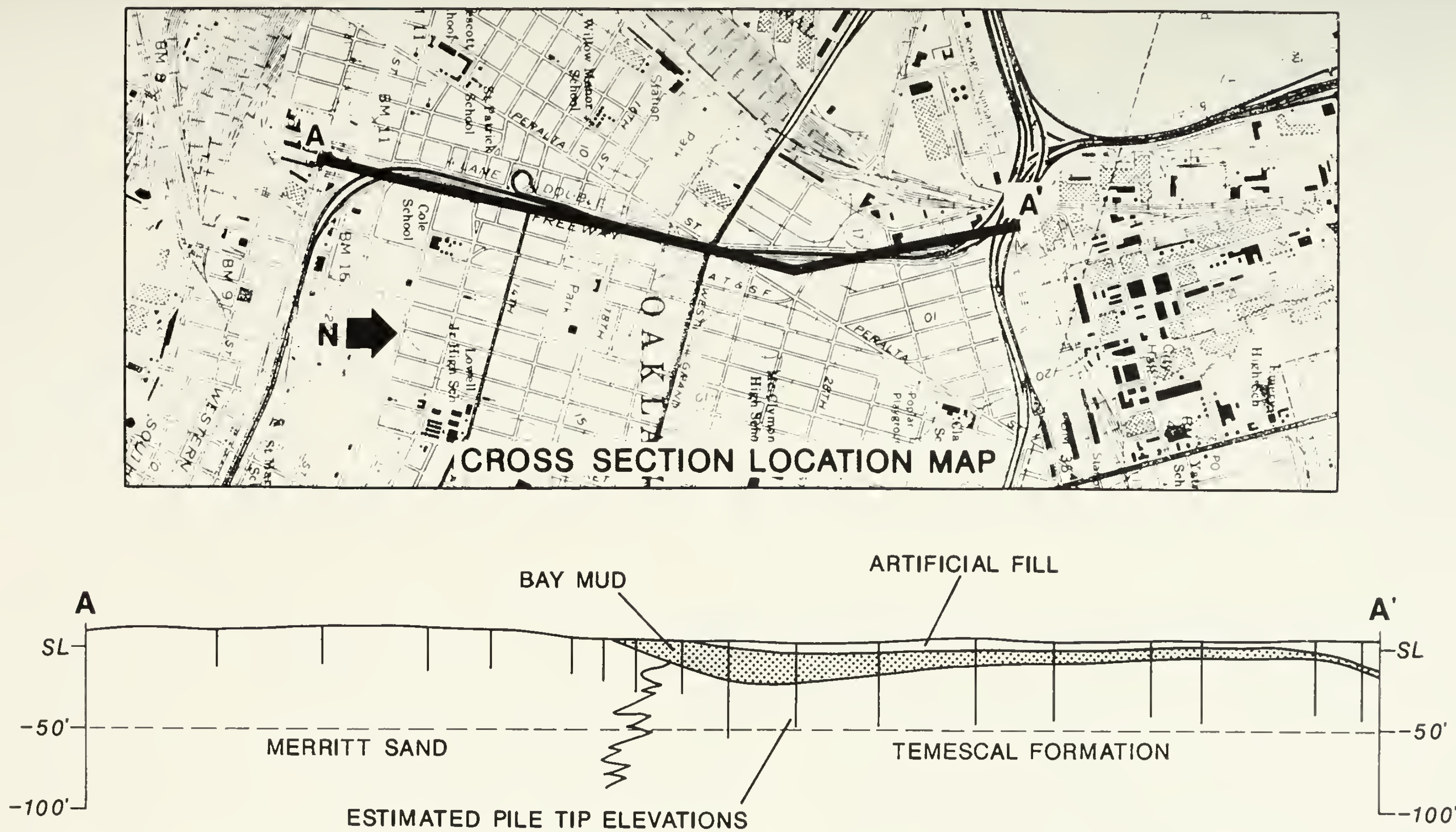


Figure 7. Horizontal components of the accelerograms from three stations in the Oakland area, each 2 km from the Cypress Structure. The shallow soil profile near each station is also shown.



EXPLANATION

Artificial Fill – Refuse, bay mud, dredged sand

Bay Mud – Unconsolidated dark plastic carbonaceous clay and silty clay

Merritt Sand – Loose to very dense brown – to reddish brown sand with lenses of silty, sandy clay and clay

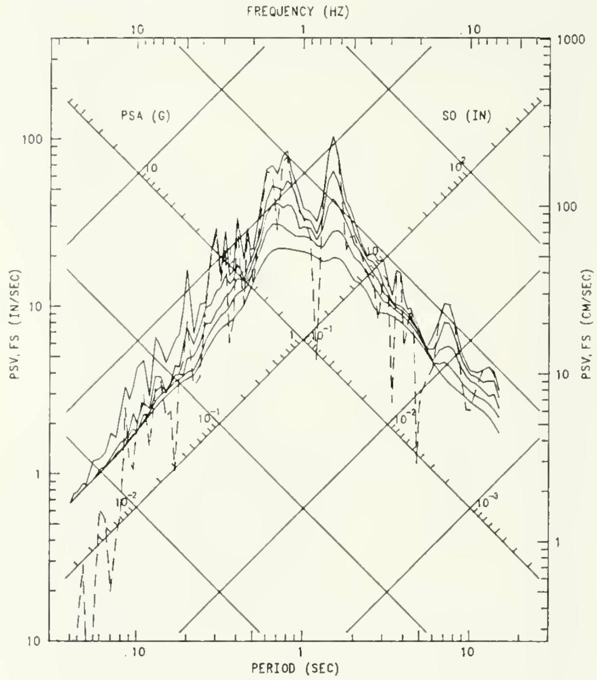
Temescal Formation – Irregularly interbedded clay, silty, sand and gravel

0' 1000'
SCALE

Figure 8. Near-surface geology along the Cypress Structure (section A-A').

LOMA PRIETA (SANTA CRUZ MOUNTAINS) EARTHQUAKE 17 OCTOBER 1989 17:04 PDT
OAKLAND - OUTER HARBOR WHARF
CHN 1: 305 DEG (TERMINAL AREA, NEAR CENTER)
ACCELEROGRAM BANDPASS-FILTERED WITH RAMPS AT .05-.07 TO 23.0-25.0 Hz
58472-C0221-89293.05 112189.0106-OL89A472A

—— RESPONSE SPECTRA: PSV, PSA & SD – – – FOURIER AMPLITUDE SPECTRUM: FS
DAMPING VALUES: 0, 2, 5, 10, 20%



LOMA PRIETA (SANTA CRUZ MOUNTAINS) EARTHQUAKE 17 OCTOBER 1989 17:04 PDT
OAKLAND - 2-STORY OFFICE BLDG.
CHN 2: 290 DEG (GROUND FLOOR, AT NE CORNER)
ACCELEROGRAM BANDPASS-FILTERED WITH RAMPS AT .05-.07 TO 23.0-25.0 Hz
58224-C0120-89293.02 112089.2140-OL89A224A

—— RESPONSE SPECTRA: PSV, PSA & SD – – – FOURIER AMPLITUDE SPECTRUM: FS
DAMPING VALUES: 0, 2, 5, 10, 20%

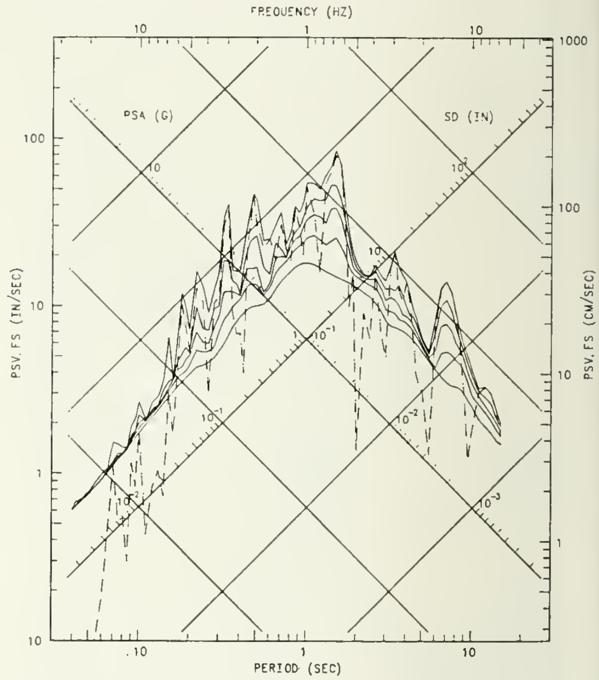
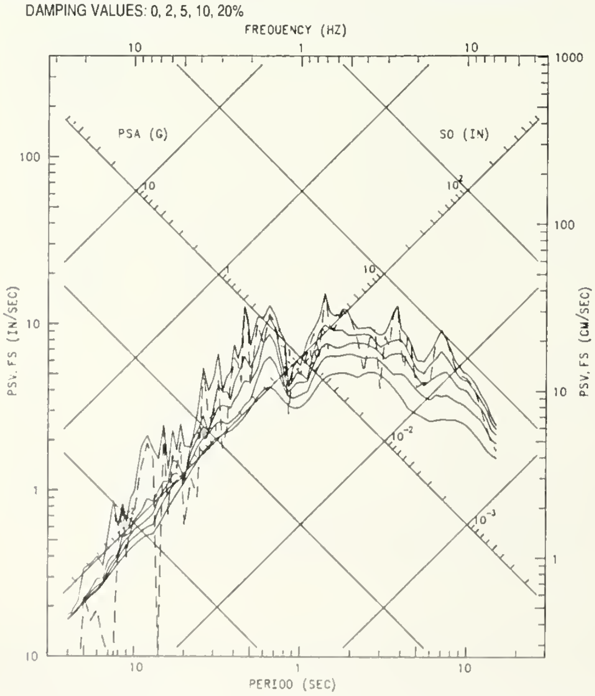


Figure 9A. Response spectra for the (approximately) east-west components of the records from the Oakland wharf (left) and a two-story office building near Lake Merritt (right) in Oakland.

LOMA PRIETA (SANTA CRUZ MOUNTAINS) EARTHQUAKE 17 OCTOBER 1989 17:04 PDT
YERBA BUENA ISLAND
CHN 1: 90 DEG
ACCELEROGRAM BANDPASS-FILTERED WITH RAMPS AT .05-.07 TO 23.0-25.0 Hz
58163-S1720-89296.01 112189.1718-OL89A163

—— RESPONSE SPECTRA: PSV, PSA & SD – – – FOURIER AMPLITUDE SPECTRUM: FS
DAMPING VALUES: 0, 2, 5, 10, 20%



LOMA PRIETA (SANTA CRUZ MOUNTAINS) EARTHQUAKE 17 OCTOBER 1989 17:04 PDT
TREASURE ISLAND
CHN 1: 90 DEG
ACCELEROGRAM BANDPASS-FILTERED WITH RAMPS AT .05-.07 TO 23.0-25.0 Hz
58117-S2598-89296.01 111789.2114-OL89A117

—— RESPONSE SPECTRA: PSV, PSA & SD – – – FOURIER AMPLITUDE SPECTRUM: FS
DAMPING VALUES: 0, 2, 5, 10, 20%

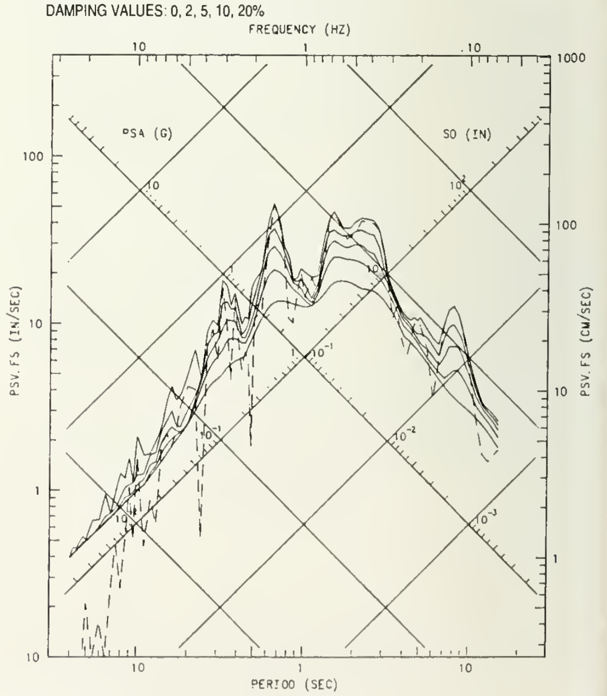


Figure 9B. Response spectra for the east-west components of the records from Yerba Buena Island (left) and Treasure Island (right).

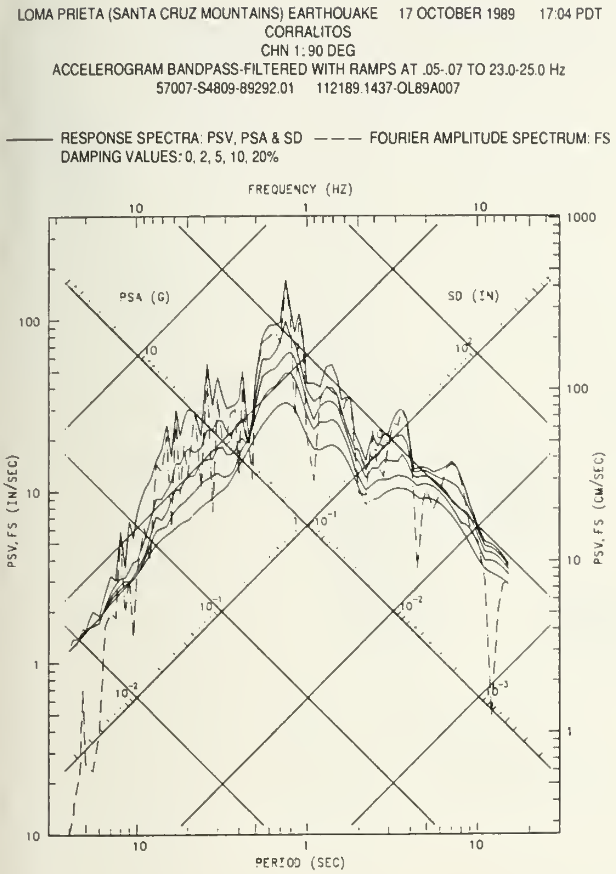


Figure 9C. Response spectra for the east-west component of the record from Corralitos, a station in the epicentral area and within 1 km of the San Andreas fault.

Processed Accelerograms from Stations near the Cypress Structure

The records shown in Figure 7 from the Oakland wharf and the office building near Lake Merritt have been digitized and processed to obtain spectra and velocity and displacement time histories. The spectra for these two stations, for the east-west component, are shown in Figure 9A. The spectra have a peak at a period of about .5 seconds. The wharf spectrum shows another peak at about 0.8 seconds period. (The data for both the wharf and the Lake Merritt building are ground or reference channels, not structure channels.) The spectra from the Treasure Island and Yerba Buena Island records are shown in Figure 9B. The spectrum at Treasure Island looks similar to that at the wharf, but has lower peak values in the spectrum. The spectrum at Yerba Buena Island, near Treasure Island but on rock, is only about one-third that of the Treasure Island spectrum. For reference, Figure 9C shows the response spectrum for the Corralitos station in the epicentral area.

The preliminary displacement time histories computed from the Treasure Island record are shown in Figure 10. They show a peak displacement of over 9 cm in the east-west direction and nearly 4.5 cm north-south. In other words, the displacement in the east-west direction was approximately double that in the north-south direction. The Cypress Structure is nearly north-south, so the larger east-west displacement occurred nearly transverse to the structure. The peak displacement at the wharf and the Lake Merritt stations is also about) cm.

Anticipated Strong Shaking in the Bay Area for a Future Magnitude 7 Earthquake on the San Andreas Fault near San Francisco

For the Loma Prieta earthquake, a zone within about 20 km of the fault experienced the strongest shaking. This region, where the peak acceleration was generally 40% g or greater, is indicated in Figure 11. The region includes the heavily damaged coastal area from Santa Cruz to Watsonville, where the strong shaking lasted for 10 seconds or more. (Note that the Oakland/San Francisco area is approximately 90 km from the fault rupture.)

To gain some understanding of what shaking levels should be anticipated if the same event were to happen farther north on the San Andreas next to San Francisco, for example from Daly City northward, the zone of strongest shaking from Figure 11 is overlain on the San Andreas fault in Figure 12. The figure shows that all of the northern San Francisco peninsula would be included in the zone of strong shaking. Consideration of accelerations at distances beyond 20 km in Figure 11 suggests that, for the Daly City event being considered, rock accelerations in Oakland would be near 20-30% g, in contrast to near 10% g in the Loma Prieta event. If the same amplification occurs that occurred in the Loma Prieta event, the motion in much of the flat-lying portion of Oakland is expected to be 40-60% g.

Anticipated Strong Shaking in the Bay Area for a Future Magnitude 7 Earthquake on the Hayward Fault

To gain some understanding of what shaking levels should be anticipated if an event like the Loma Prieta earthquake were to occur on the Hayward fault, the zone of strongest shaking from Figure 11 is overlain on the northern section of the Hayward fault in Figure 13. The strongly-shaken area would cover almost all of the East Bay if this occurred. The long duration shaking that occurred in the Capitola - Watsonville area (see Figure 3A, for example) could be expected through much of the East Bay. The San Francisco peninsula would also be strongly shaken, with values of 20% g occurring at rock sites, and significantly higher levels in soil areas. In this case, accelerations in the flat-lying portions of Oakland would exceed the 0.64 g at Corralitos, but nonlinear and nearfield effects preclude even a rough numerical estimate.

ACKNOWLEDGMENTS

The California Strong Motion Instrumentation Program (CSMIP) extends its appreciation to the individuals and organizations which have permitted and cooperated in the installation of seismic strong-motion equipment on their property. The authors would like to recognize the CSMIP technicians for their diligence and care in installing and maintaining the stations and in recovering records.

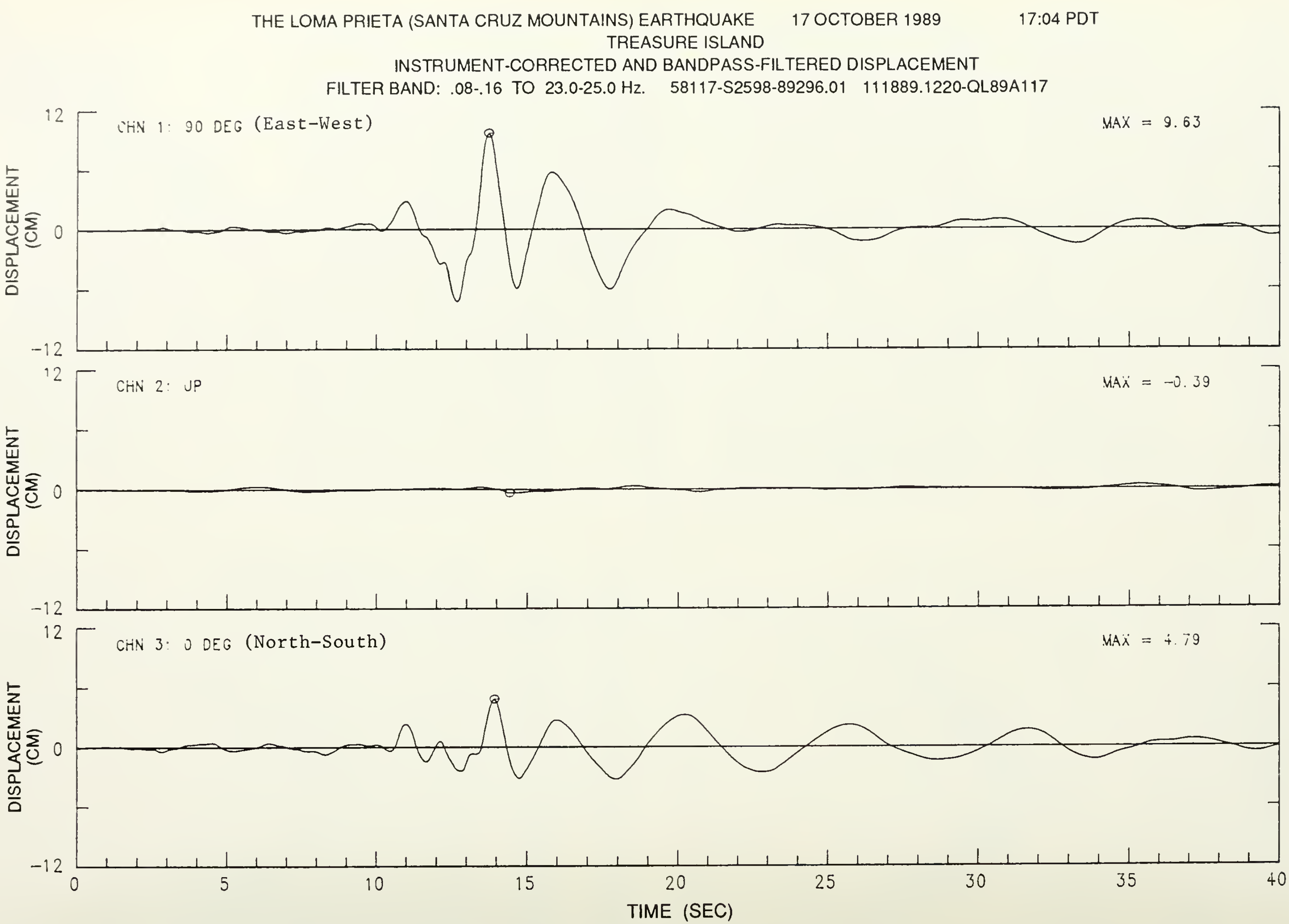
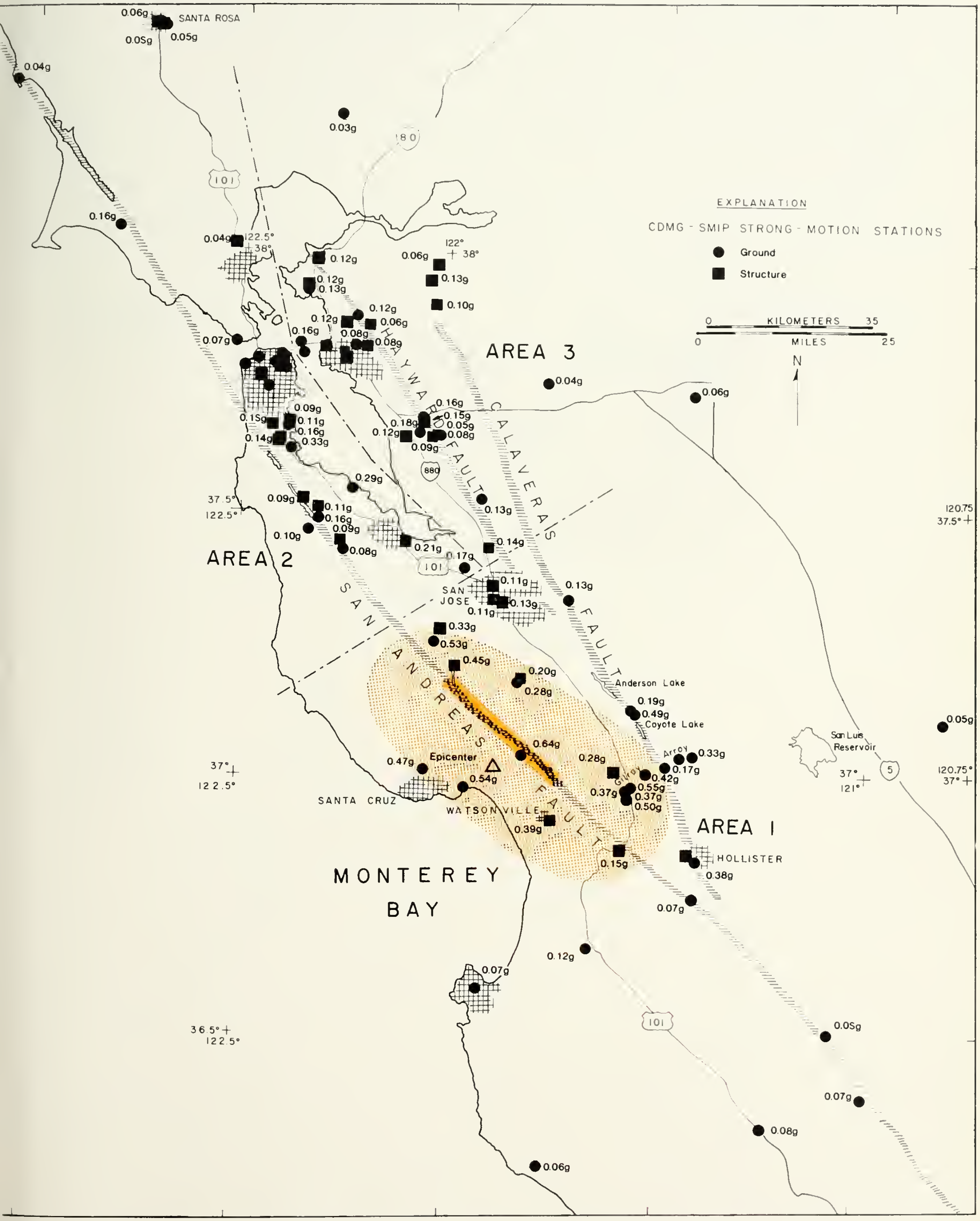


Figure 10. Computed displacement time-history for three components of the record from the Treasure Island station.



igure 11. Strongly shaken zone (stippled area) for the 17 October 1989, Loma Prieta earthquake (peak acceleration generally 0.4 g or greater).

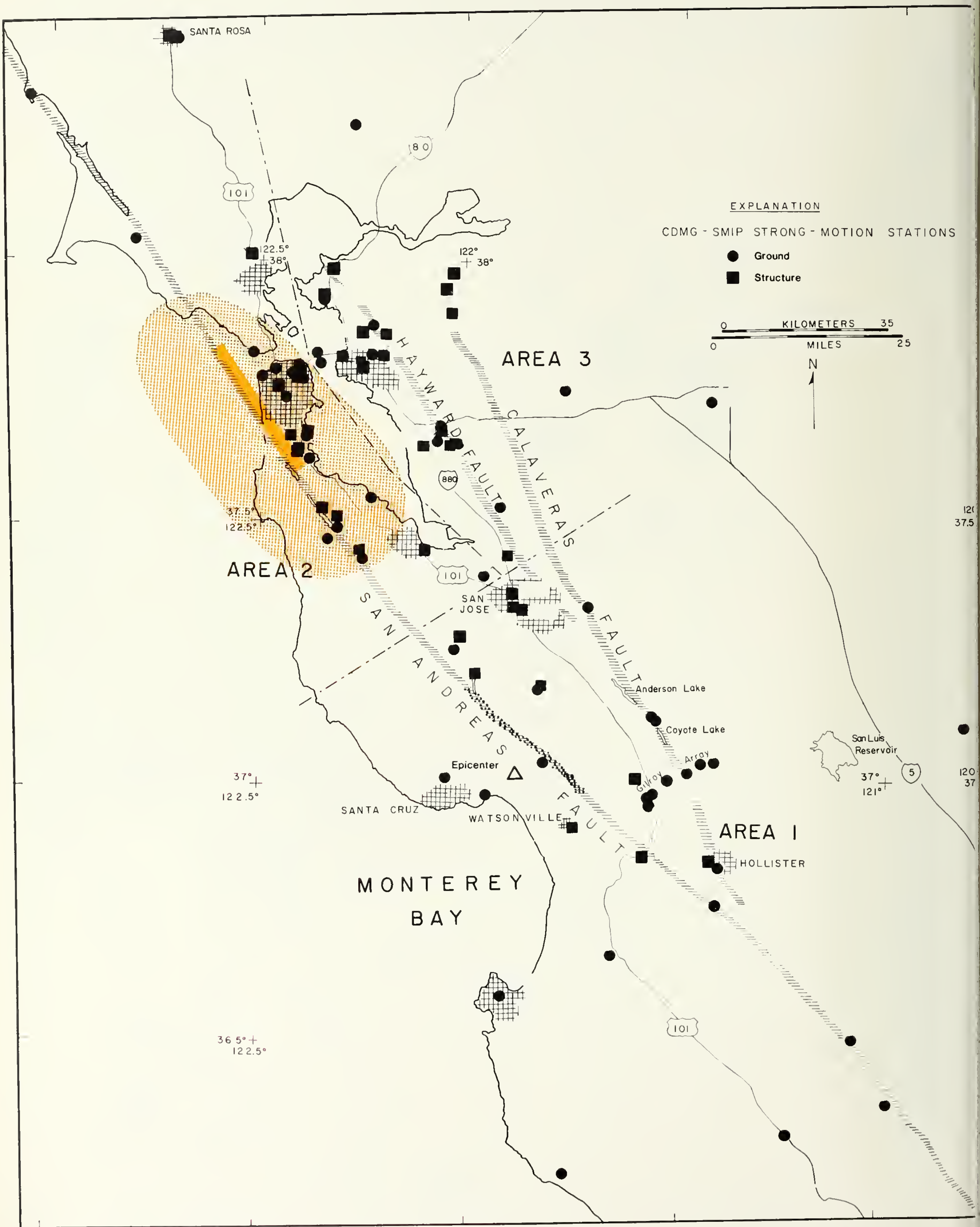
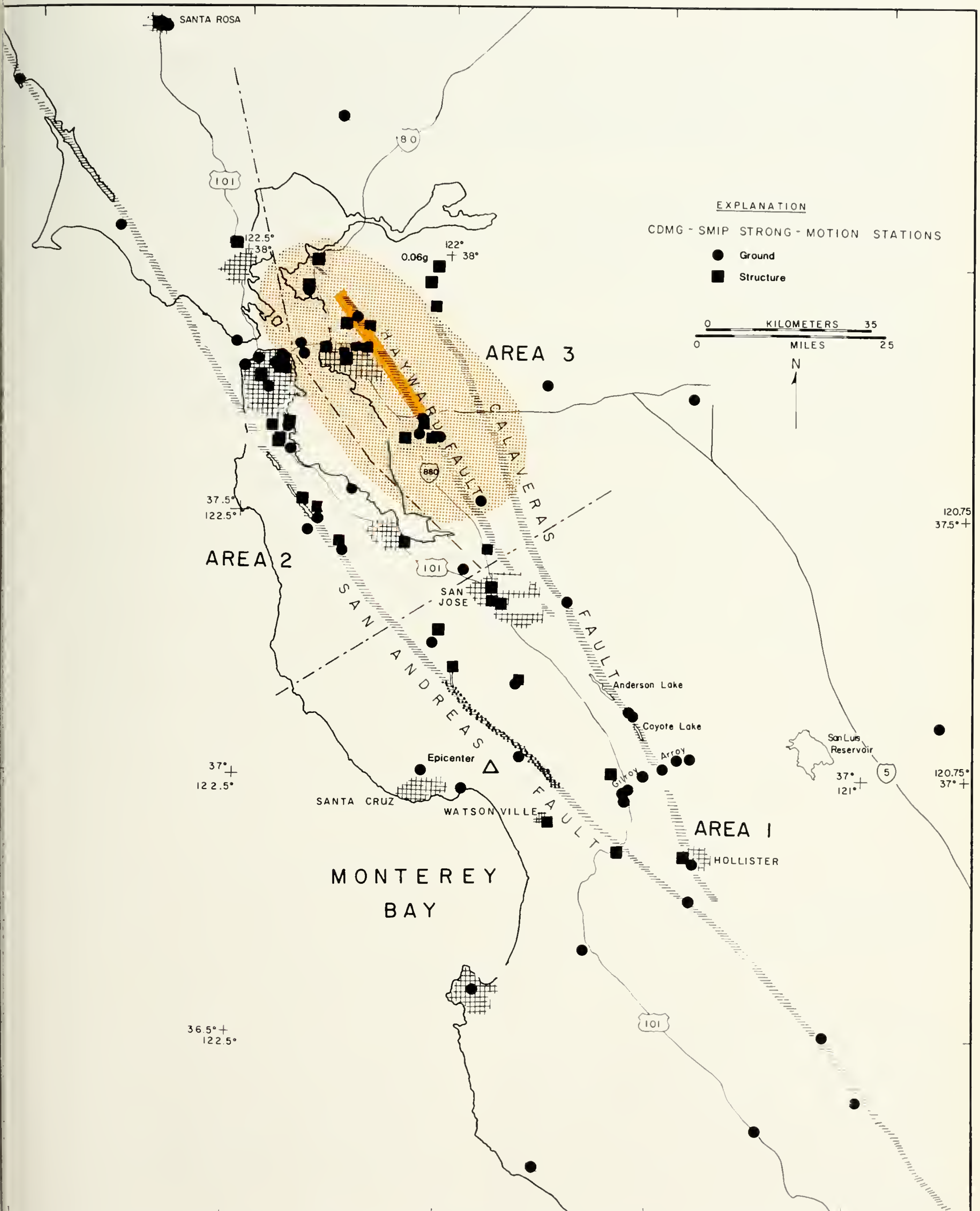


Figure 12. Strongly shaken zone anticipated from a magnitude 7 earthquake like the Loma Prieta event on the San Andreas Fault near San Francisco.



F re 13. Strongly shaken zone anticipated from a magnitude 7 earthquake like the Loma Prieta event on the Hayward Fault near Oakland.

REFERENCES

EERI (Earthquake Engineering Research Institute) Geoscience Reconnaissance Team, 1989, Geoscience Investigations of the Earthquake of 17 October 1989, near the Summit of Loma Prieta in the Southern Santa Cruz Mountains: Borcherdt, J., and Donovan, N., (Coordinators), and Bolt, B., Boore, D., Celebi, M., Eberhart-Phillips, D., Hall, T., Hough, S., Shakal, A., and Sharp, R.

Goldman, H.B., 1969, Geology of San Francisco Bay *in* Geologic and engineering aspects of San Francisco Bay fill: California Department of Conservation, Division of Mines and Geology, Special Report 97.

Helley, E., Lajoie, K., Spangle, W., and Blair, M., 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.

Joyner, W.B., and Boore, D.M., 1981. Peak horizontal acceleration and velocity from strong-motion records including records from the 1979 Imperial Valley, California, earthquake: Bulletin of the Seismological Society of America, v. 71, p. 2011-2038.

Lee, C. H., 1969, Treasure Island fill, *in* Goldman, H. B., ed., Geologic and engineering aspects of San Francisco Bay fill: California Division of Mines and Geology, Special Report 97, p. 69-72.

Lisowski, M., Prescott, W.H., Savage, J.C., and Svarc, J.L., 1990, A possible geodetic anomaly observed prior to the Loma Prieta, California, earthquake: Geophysical Research Letters, v. 17, p. 1211-1214.

Maley, R., Costa, A., Ellis, F., Etheredge, E., Foote, L., Johnson, D., Porcella, R., Salsman, M., and Switzer, J., 1989, U.S. Geological Survey strong-motion records from the Northern California (Loma Prieta) earthquake of October 17, 1989: U.S. Geological Survey, Open File Repo 89-568.

NEIC (National Earthquake Information Center) ,1989, Preliminary determination of epicenters: No. 42-89, U.S. Geological Survey.

Radbruch, D.H. (1957) Areal and engineering geology of the Oakland west quadrangle, California: U.S. Geological Survey, Miscellaneous Geologic Investigations Map I-239.

Shakal, A., Huang, M., Reichle, M., Ventura, C., Cao, T., Sherburne, R., Savage, M., Darragh, R., and Petersen, C., 1989, CSMIP strong-motion records from the Santa Cruz Mountains (Loma Prieta), California earthquake of 17 October 1989: California Department of Conservation, Division of Mines and Geology, Report OSMS 89-06, 196 p.

PRELIMINARY ANALYSIS OF PROCESSED STRONG MOTION DATA FROM THE LOMA PRIETA EARTHQUAKE

By

Michael S. Reichle[1], Robert B. Darragh[1], Moh-Jiann Huang[1], Tianqing Cao[1], Ute R. Vetter[1], and Anthony F. Shakal[1]

INTRODUCTION

An extensive strong-motion data set from a magnitude 7 earth-ıake is unprecedented worldwide. The strong-motion data gener-ed by the Loma Prieta earthquake will be the basis for the first :tensive analyses of source mechanism, attenuation of strong motion, fects of local site geology and response of structures for an earth-ıake of this magnitude. This paper discusses observed variations peak ground motion with distance and possible factors contribut-g to those variations. We use the analog accelerograms (Shakal and hers, 1989; Maley and others, 1989) and the initial 26 digitized and ocessed ground-response records (CSMIP, 1989; Huang and oth-s, 1990) in this discussion. Obviously, these are complicated topics ıd many of our initial observations may be modified as more :celerograms are digitized and incorporated into the analyses.

PEAK GROUND ACCELERATION

Of the 93 CSMIP stations and 38 U.S. Geological Survey stations iggered by the Loma Prieta earthquake (see Shakal and others,)89; Shakal and others, this volume; and Maley and others, 1989), ⁷ are from ground response (free field) stations or stations located buildings with two stories or less. Peak ground acceleration data om these 77 stations (listed in the referenced reports) are plotted in gure 1 as a function of distance from the aftershock zone. Only ations within 100 km are plotted. As one would expect, there is ınsiderable scatter in the peak acceleration data. Also shown in the gure are the expected median, median -1 standard deviation, and edian +1, +2 and +3 standard deviation peak acceleration curves for moment magnitude 6.9 earthquake using the relationships obtained Joyner and Boore (1981). Clearly, the data do not cluster about e median curve, but lie principally above it. Nine of the 77 peak :lues fall above the median +2 standard deviation peak acceleration ırve. This should occur only 2.5% of the time if the data had been awn from a population with the distribution assumed in the Joyner-ɔore regression model.

In an attempt to further understand the factors contributing to the scatter, we have classified the data by the general geology beneath each accelerograph site. The three divisions are rock (solid dots), alluvium or soil (open circles) and bay mud (x's). The distribution of younger bay mud used is that of Helley and others (1979) and Goldman (1969). Of the nine peak values that lie above the median +2 standard deviation peak acceleration curve, five are from bay mud sites, two from alluvium sites and two from rock sites. This simple classification does not explain the higher-than-expected peak accelerations even though there is some slight tendency for rock sites to record lower peak accelerations than alluvium sites at comparable distances, and for bay mud sites to record higher peak accelerations than alluvium sites at comparable distances. Also, the data do not cluster into easily separable groups using this simple scheme. Perhaps a more realistic classification, incorporating thicknesses of bay mud and alluvium as well as seismic velocities, would yield a clearer picture of the effects of local geology on peak acceleration.

PEAK GROUND VELOCITY

To date, 26 ground response accelerograms have been digitized and processed to velocity as well as displacement time histories as well as spectra (CSMIP, 1989; Huang and others, 1990). Table 1 lists the peak velocity and displacement values obtained from the accelerograms recorded at those stations.

Figure 2 is a plot of peak ground velocity as a function of distance for these data. The classification of site geology into rock, alluvium and bay mud, as well as the symbols are the same as in Figure 1. The peak velocities, like the peak accelerations, are generally higher than would be predicted by the standard Joyner-Boore (1981) regression. Only three points lie at or below the median rock velocity curve. Four data points (two bay mud sites, one alluvium site and one rock site) lie above the median +2 standard deviation peak velocity curve for soils. However, unlike the peak acceleration data, the available peak velocity data do seem to clearly divide into two groups based on site

:alifornia Department of Conservation, Division of Mines and Geology, Strong Motion Instrumentation Program

geology. In general, the peak velocity recorded on rock sites is lower than the peak velocity recorded on alluvium and bay mud sites at comparable distances. Also, the peak velocity recorded on rock sites appears to attenuate less rapidly with distance than that predicted by the Joyner-Boore regression. This may be due to the increased contribution of long-period surface wave energy to the ground motion with increasing distance from the fault rupture. Remarkably, the alluvium and bay mud data, taken as one group, show no apparent attenuation of peak velocity for distances between 9 and 80 km! Of course, this preliminary observation may change as more data are processed.

PEAK GROUND DISPLACEMENT

Figure 3 shows a plot of peak ground displacement as a function of distance for the same 26 stations as in Figure 2. The symbols and the grouping by geology are the same as in Figures 1 and 2. The scatter in peak displacement is the largest at distances between 25 and 35 km. In that distance range, stations Hollister and Agnew, located on alluvium, had peak displacements of 30 and 18 cm, respectively. In contrast, Gilroy stations #6 and #7, located on or near rock, had peak

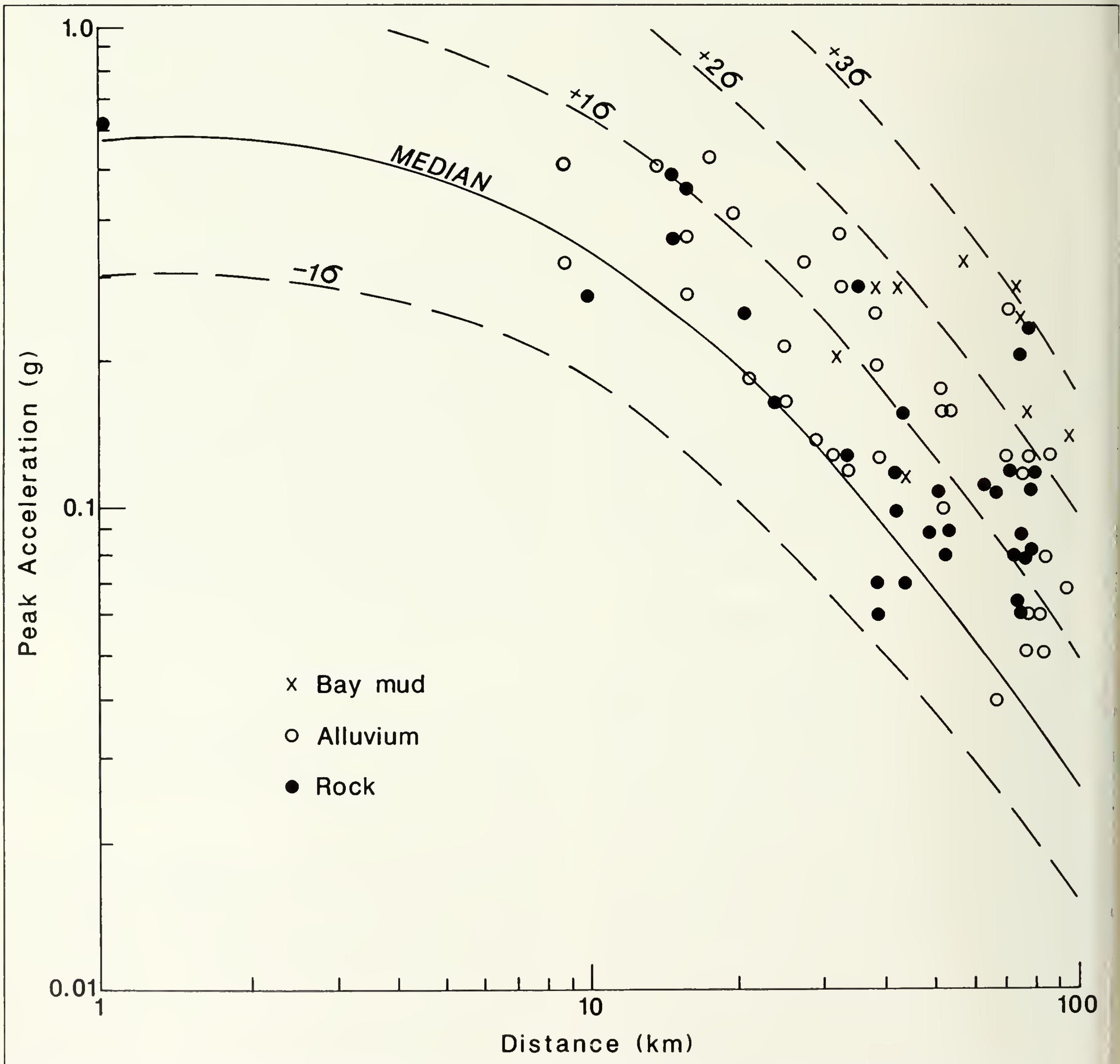


Figure 1. Peak horizontal acceleration versus distance. Distance measured from the surface trace of the San Andreas fault above the Loma Prieta aftershock zone. Largest of the two horizontal components is plotted. Solid line is the median curve of Joyner and Boore (1981) for a moment magnitude 6.9 earthquake. Dashed lines indicate median -1, +1, +2 and +3 standard deviations. Solid dots indicate stations located on (or near) rock; open circles, on alluvium; x's, on bay mud.

displacements between 3 and 5 cm. Displacements measured at sites located on either rock or alluvium/bay mud do not show significant attenuation in the distance range between 15 and 80 km. The largest values obtained thus far are from stations located on alluvium rather than bay mud and probably result from factors other than simple near-surface geology. This inference is not surprising as the longer periods that dominate the displacement time histories sense deeper structure to a greater extent than the shorter periods dominant in the velocity or acceleration time histories.

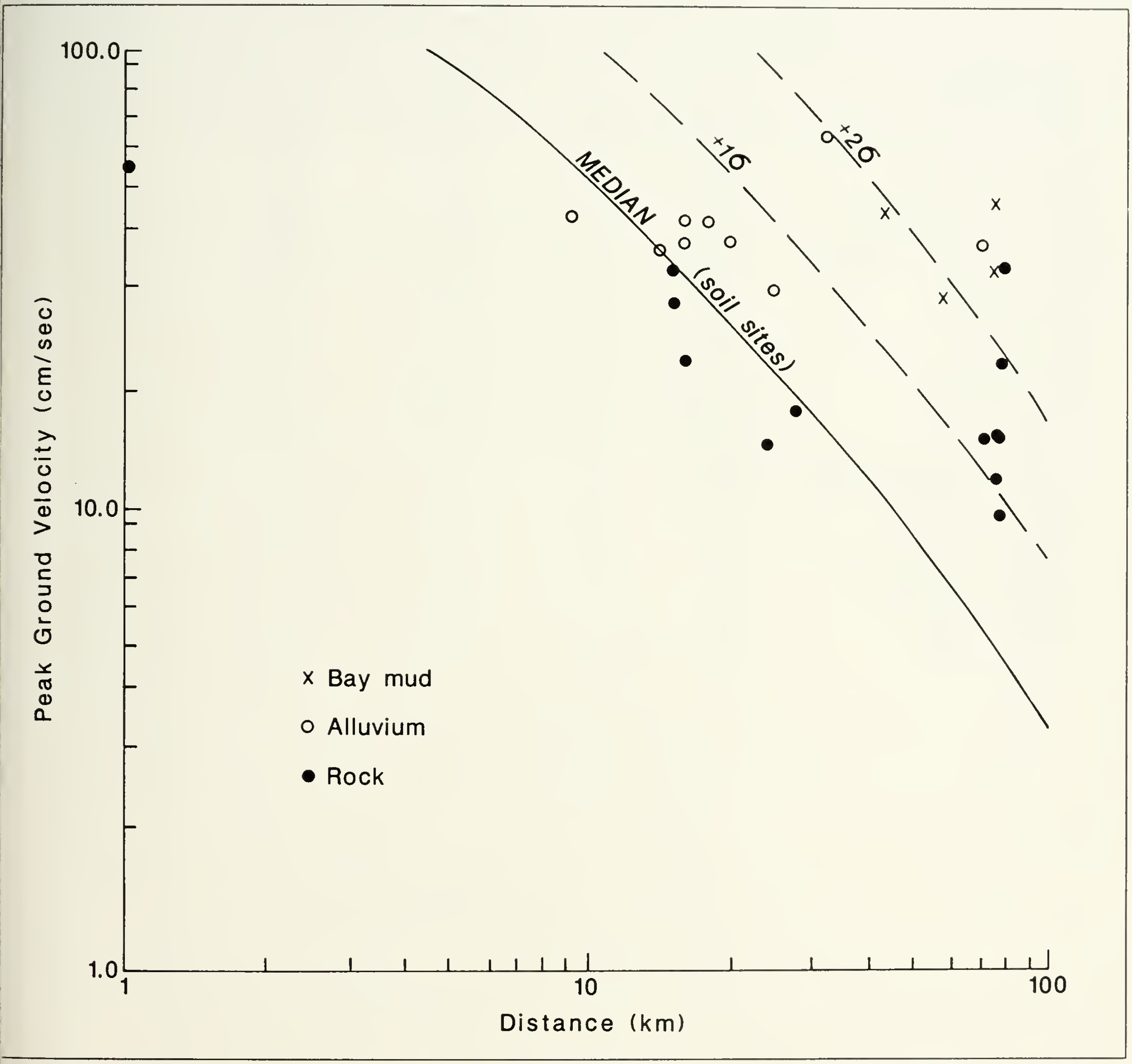


Figure 2. Peak horizontal velocity versus distance. Curves show Joyner-Boore curves as in Figure 1 for soil sites, symbols are the same as in Figure 1.

Table 1

Peak Ground Acceleration, Peak Ground Velocity and Peak Ground Displacement Obtained from 26 Processed Accelerograms Recording the Loma Prieta Earthquake

Station (I. D. Number)	Geology	Distance[1] (km)	Peak Horizontal Acceleration (g)	Peak Velocity (cm/sec)	Peak Displacement (cm)
Corralitos (57007)	rock	1	0.64	55.2	11.5
Saratoga (58235)	alluvium	9	0.33	43.6	28.0
Capitola (47125)	alluvium	14	0.54	36.1	11.0
Gavilan College (47006)	rock	15	0.37	28.9	5.8
Gilroy #1 (47379)	rock	15	0.50	33.8	6.5
Gilroy #2 (47380)	alluvium	16	0.37	39.2	10.9
UCSC-Lick Lab (58135)	rock	16	0.47	21.2	6.8
Gilroy - 2-story building (57476)	alluvium	16	0.28	43.5	9.7
Gilroy #3 (47381)	alluvium	18	0.55	43.8	14.3
Gilroy #4 (57382)	alluvium	20	0.42	39.1	8.5
Gilroy #6 (57383)	rock	24	0.17	13.9	5.0
Agnew (57066)	alluvium	25	0.17	30.9	18.1
Gilroy #7 (57425)	rock	28	0.33	16.6	3.4
Hollister (47524)	alluvium	33	0.38	62.8	30.2
Foster City (58375)	bay mud	44	0.29	45.4	14.7
SFO (58223)	bay mud	66	0.33	29.3	5.9
SF-Diamond Hgts (58130)	rock	73	0.12	14.3	4.3
Oakland- 2-story office bldg. (58224)	alluvium	73	0.26	37.9	8.1
Oakland-wharf (58472)	bay mud	76	0.29	42.3	9.9
SF-Rincon Hill (58151)	rock	76	0.09	11.6	4.9
Yerba Buena Island (58163)	rock	77	0.06	4.7	4.1
SF-Telegraph Hill (58133)	rock	78	0.08	9.6	2.8
SF-Pacific Heights (58131)	rock	78	0.06	14.3	4.9
Treasure Island (58117)	bay mud	79	0.16	3.4	12.2
SF-Presidio (58222)	rock	79	0.21	33.5	4.1
SF-Cliff House (58132)	rock	80	0.11	21.0	6.5

[1]Distance to the nearest point on the fault inferred from the aftershock distribution as given in Shakal and others (1989).

DISPLACEMENT POLARIZATION

Particle motion diagrams for the horizontal ground displacements ıave been plotted to examine the polarization of ground motion at various stations. The direction of polarization is defined as the ›referred direction of particle motion. An example of ground motion ›olarization for this earthquake is shown in Figure 4, which shows the ıorizontal ground displacement obtained from the Yerba Buena acelerogram. At this station, the largest excursions are fairly strongly ›olarized at an azimuth of 070°, approximately transverse to the picenter-station ray. The polarizations obtained from the displacenent data are plotted in Figure 5 for the 26 stations considered above. A circle indicates that there is little or no preferred polarization direction in the particle motion diagram for the station. Figure 5 shows that many signals are polarized in the transverse direction to the local ray direction. Since transverse polarization is a characteristic of SH or Love waves we infer that the predominant ground motion at these stations was composed principally of these wave types. Variations from the transverse direction of less than 20° occur at stations in the San Francisco - Oakland area with a tendency for the polarization to rotate clockwise as station location moves from west to east. Exceptions to transverse polarization are at the Santa Cruz and the San Francisco Airport stations where the polarization is approximately isotropic, and the stations at Agnew and Capitola that are approximately radially polarized.

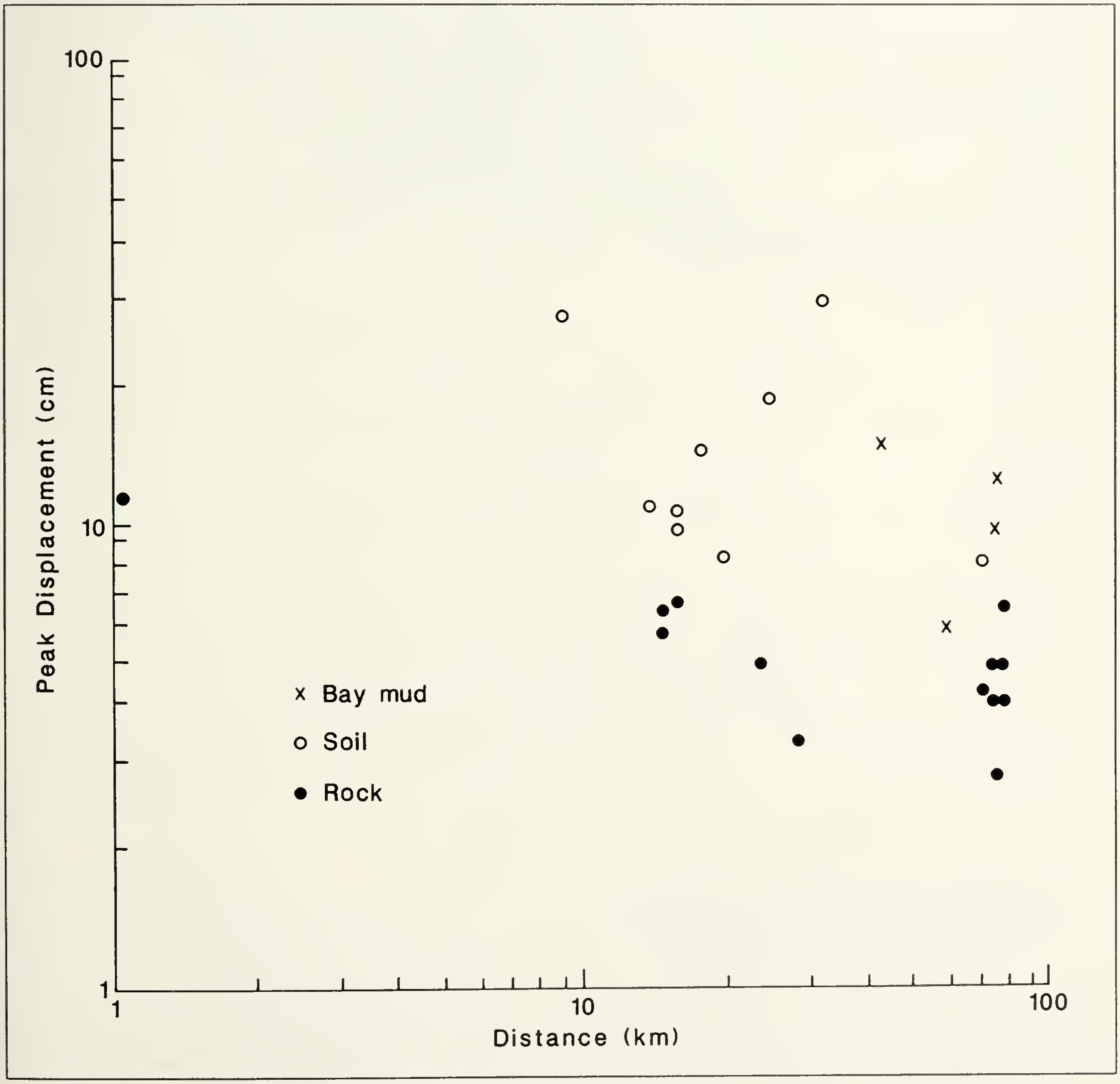


Figure 3. Peak horizontal displacement versus distance. Symbols are the same as in Figure 1.

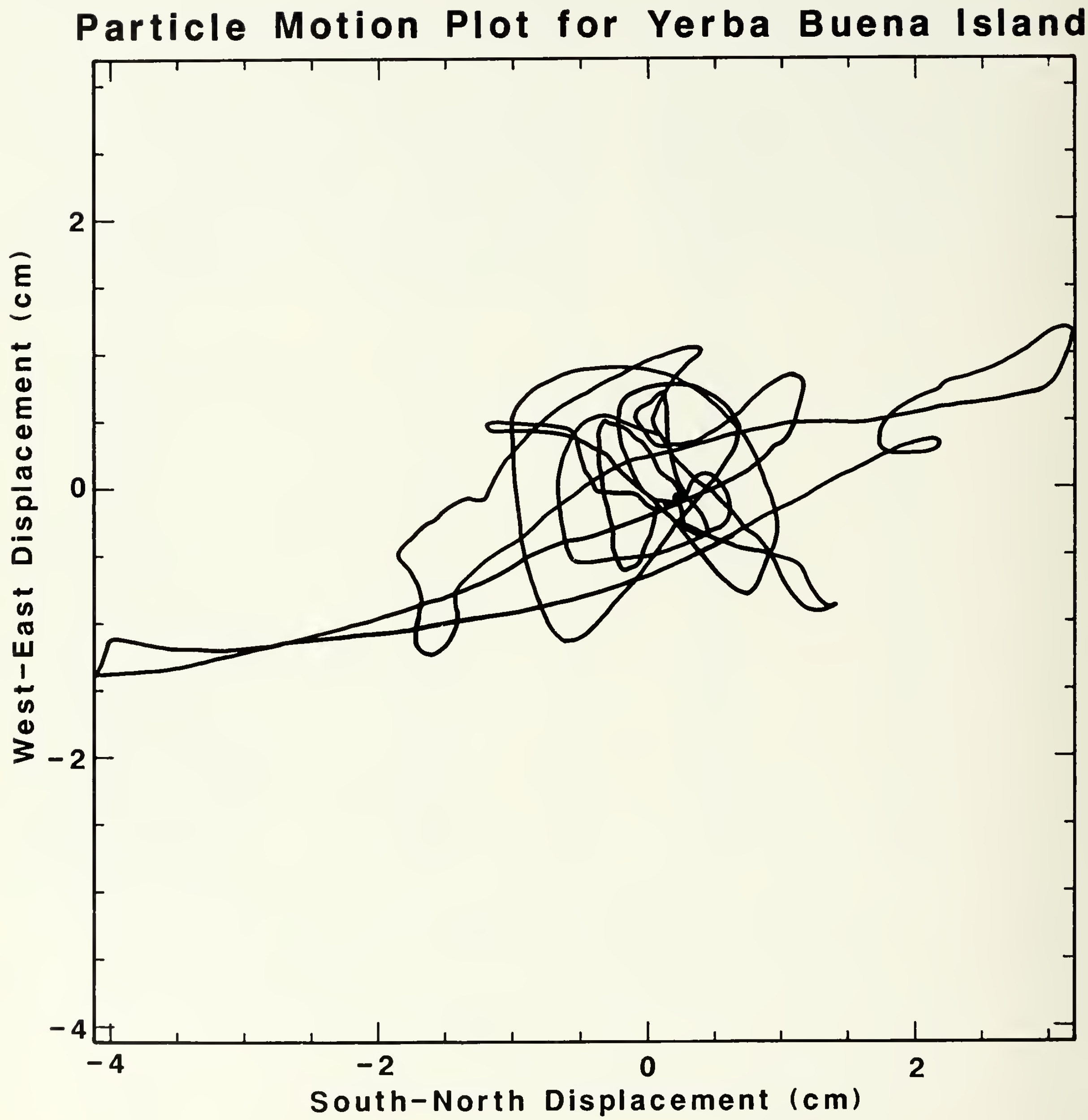
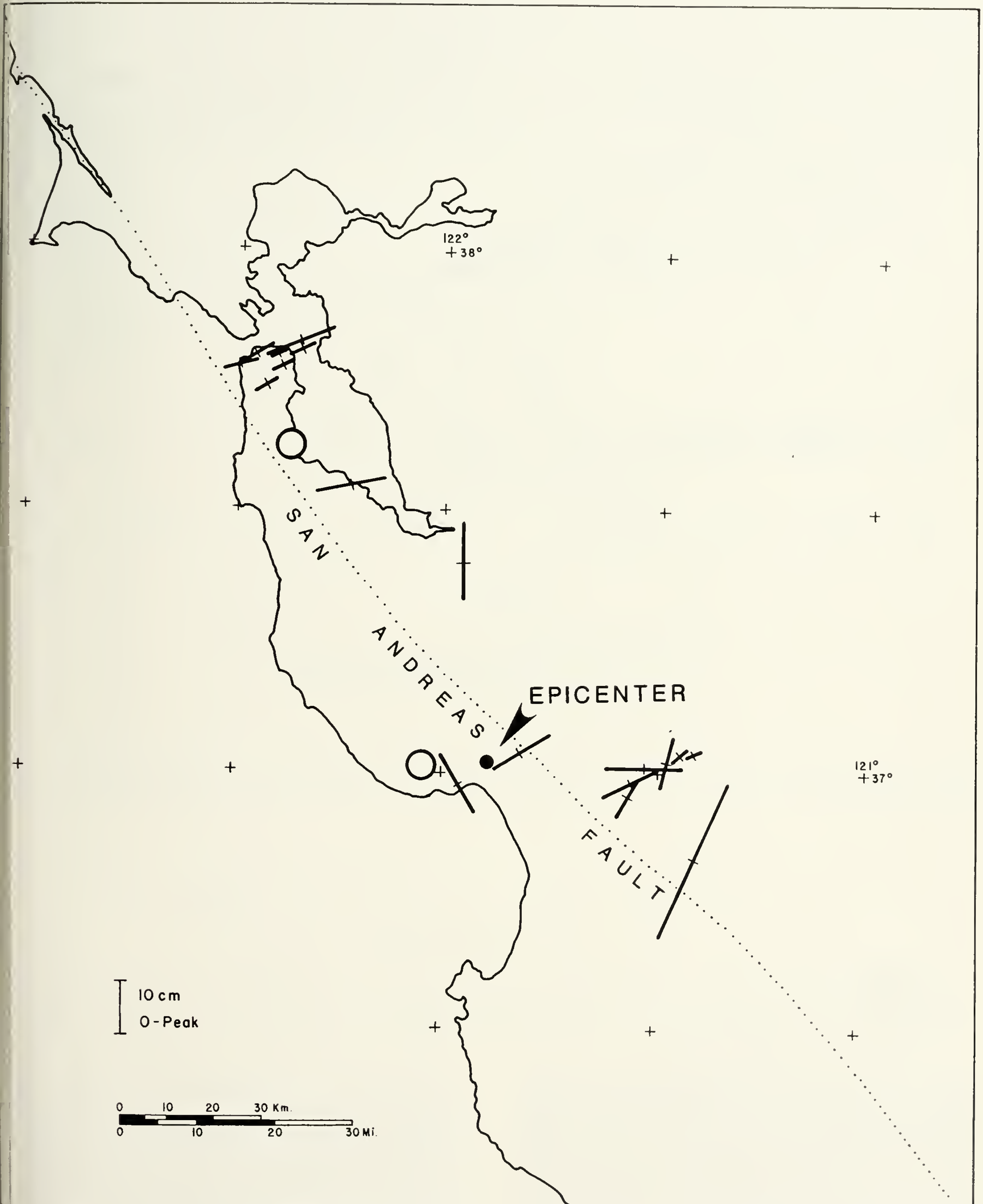


Figure 4. Particle motion diagram for horizontal displacement obtained from the Yerba Buena accelerogram. Peak-to-peak displacement is 7.8 cm at an azimuth of 071°.

VARIATION OF STRONG GROUND MOTION AT NEARBY GROUND RESPONSE STATIONS

It is clear that more detailed studies of the variation of ground motion with distance and near-surface site geology are needed to understand the effect of these factors as well as others on strong ground motion. Closely spaced stations have the advantage of minimizing the effects of some of the factors contributing to the variation of ground motion, such as distance to the source and earthquake source mechanism. If the stations are located on different geologic formations, the relative effects of the different site geology can be observed. The next two sections discuss the ground motion data from an array of six stations near Gilroy and from a rock-soil station pair near San Francisco.



Fi re 5. Measured polarizations of horizontal displacements for processed SMIP accelerograms. Direction of line indicates azimuth of polarization; a circle indicates v(weak or no obvious polarization direction. Length of line is proportional to peak displacement. Line is centered at station.

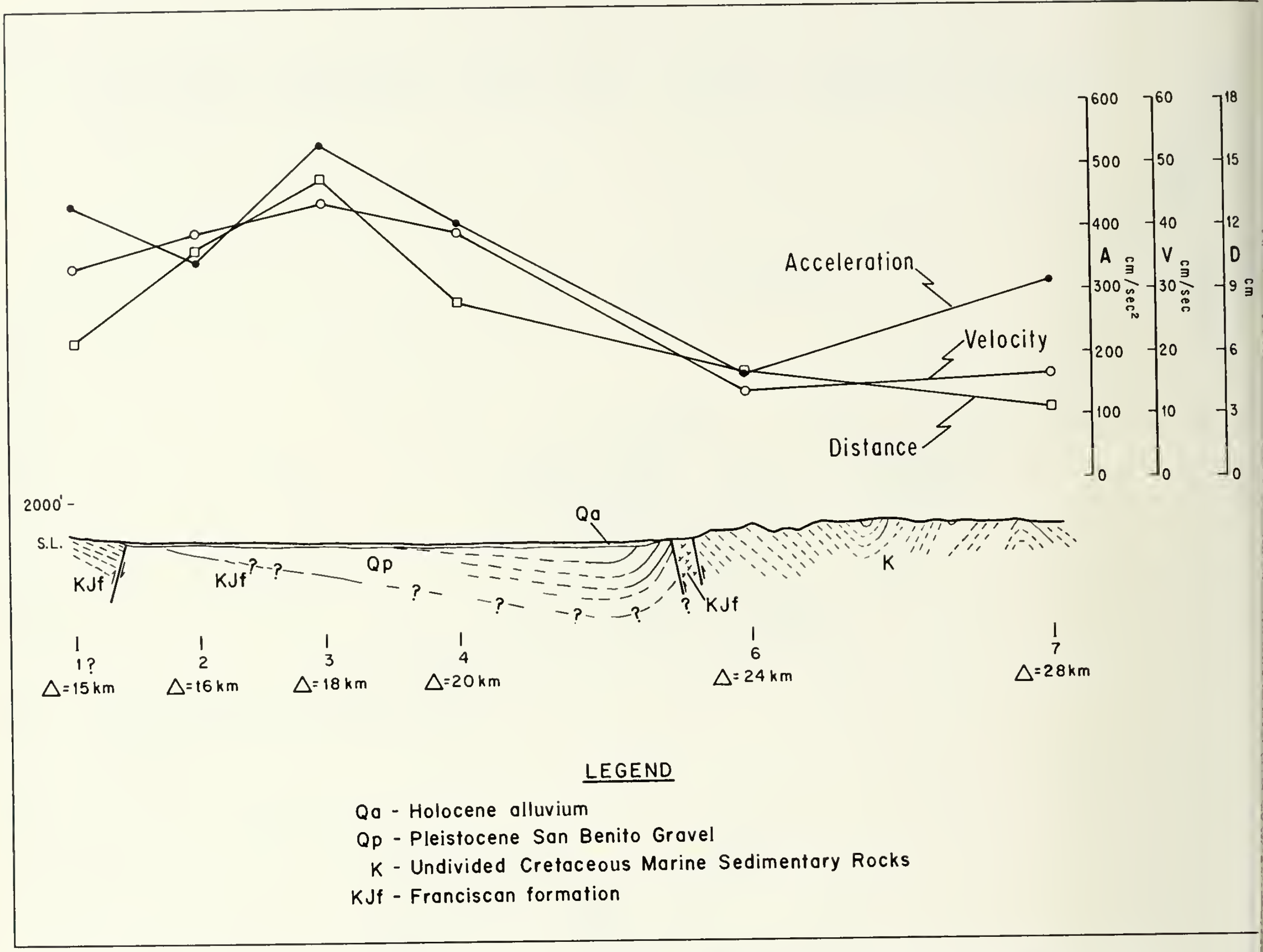
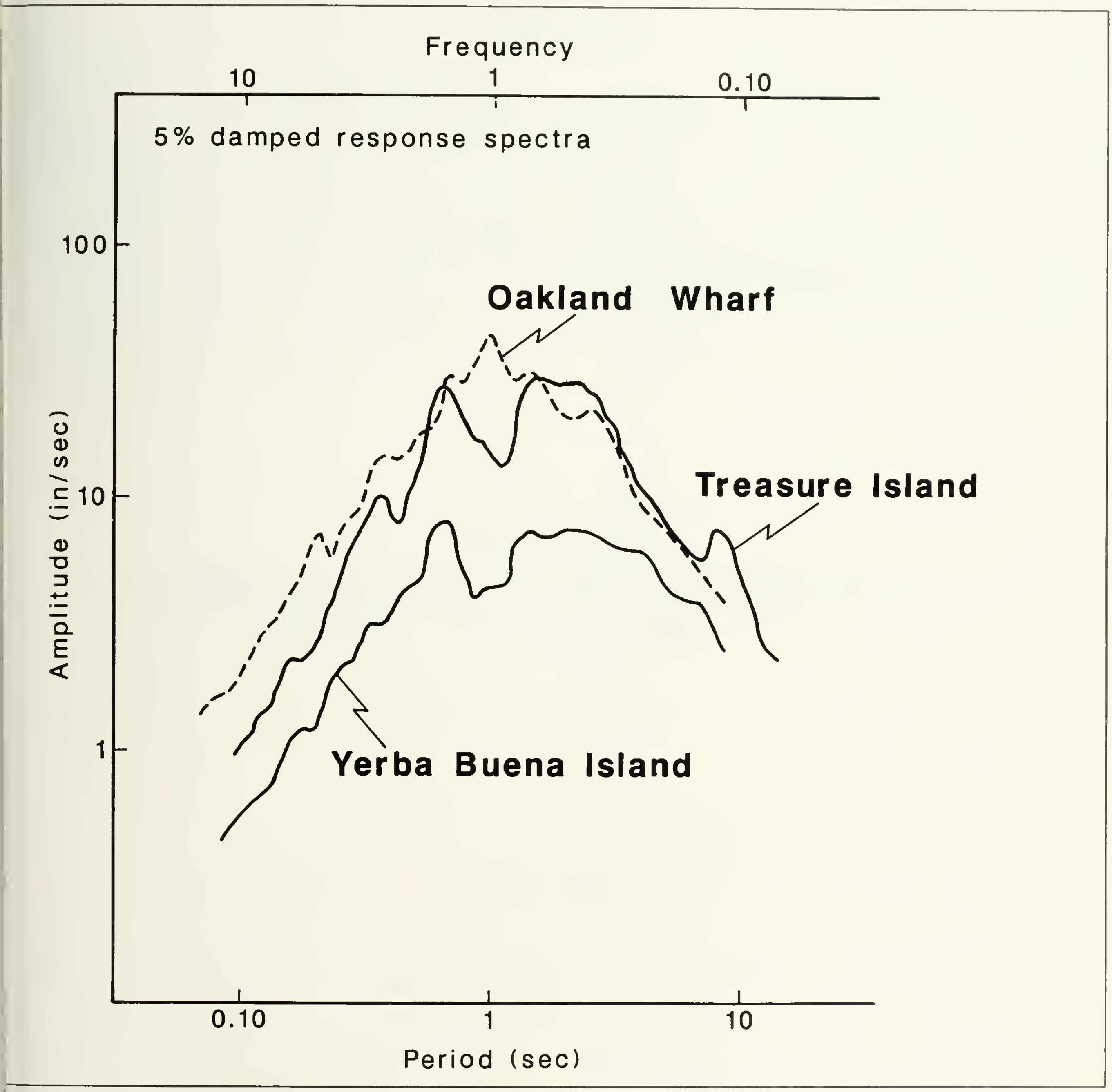


Figure 6. Geologic cross section across the Santa Clara Valley in the vicinity of the Gilroy array. Geologic symbols are: Qa, Qp: Quaternary sediments; KJf: Franciscan Formation. Locations of stations are indicated by the numbers 1, 2, 3, 4, 6, and 7. Peak ground motion values are plotted above the location of eac station of the Gilroy Array.

Gilroy Array

An array of seven stations extends from the Coast Range across the Santa Clara Valley (see Figure 1 of Shakal and others, this volume) and is instrumented cooperatively with the USGS. It was installed to provide data on the response of the deep alluvial valley to strong shaking. Figure 6 shows a structural cross section of the valley constructed from the data of Dibblee (1973) and Mooney and Colburn (1985). Although the details of cross section are not constrained, the asymmetrical shape of the valley and the maximum alluvium thickness of approximately 1,000 m is known from borehole and seismic data. The locations of the six currently operating stations are also indicated in Figure 6. Station #1 and Gavilan College are located on Franciscan rocks of the Coast Range. Stati #2, #3, and #4 are located on alluvium in the Santa Clara Vall Stations #6 and #7 are located on (or near) rocks of the Great Val Sequence. In addition, station #6 is located close to the Calave fault zone. In Figure 6, the measured peak ground accelerati velocity and displacement are plotted above each station. maximum values occur at station #3, and are generally higher wit the valley than on the bordering rock. The lowest values occu stations #6 and #7, the furthest array stations from the fault rupt Waves generated by the Loma Prieta earthquake must cross sheared rocks of the Calaveras fault zone to reach these two stati



gure 7. 5% damped response spectra from the Yerba Buena Island (090° component), Treasure Island (090° component) and Oakland Outer Harbor Wharf (035° ›mponent) acceleration, velocity and displacement waveforms. Treasure and Yerba Buena islands data are plotted as solid lines, Oakland wharf as dashed lines.

erba Buena - Treasure Island Stations

The stations at Yerba Buena Island and Treasure Island were stalled specifically as a rock (Yerba Buena Island) - soil (Treasure land) pair. Treasure Island is a manmade island, built of fill on a allow sand spit north of Yerba Buena Island. This is the first gnificant data recorded by this pair of stations. Amplification of ak acceleration, velocity and displacement recorded at the soil site mpared to the rock site are 2.4, 2.3 and 3.0, respectively, for the st-west component of motion (largest horizontal component). The lative amplification of ground motion at Treasure Island can also be seen in the response spectra, shown in Figure 7. The shapes of the Treasure Island and Yerba Buena Island response spectra (5% damped) are similar. The Treasure Island spectrum is amplified by a factor of about four near a period of 2 seconds and the amplification decreases toward both longer and shorter periods. Also shown in Figure 7 is the response spectrum for the Oakland Wharf station (component 035°) located on fill deposited on a thin layer of bay mud over alluvium. The long-period spectral level is similar to that at Treasure Island, but the short-period spectral level is higher, also reflected in the larger peak acceleration recorded at the Oakland Wharf.

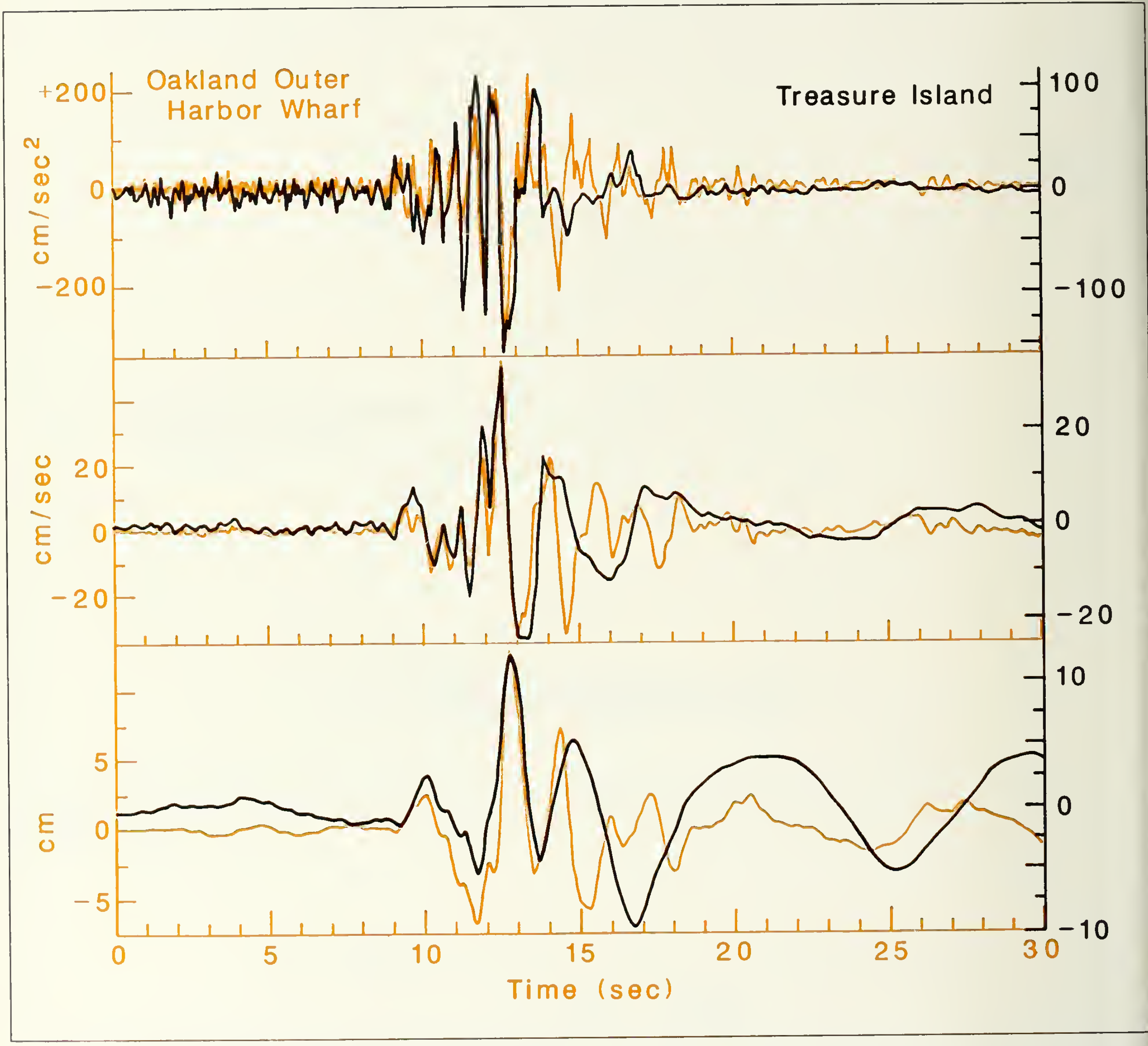


Figure 8. Comparison of Treasure Island and Oakland Outer Harbor Wharf acceleration, velocity and displacement waveforms. East-west components are plotted. Treasure Island data are plotted as black lines, Oakland Wharf as colored lines.

One interesting feature in the Treasure Island accelerogram, shown in Figure 8, is the sharp decrease in acceleration at about 15 seconds after the start of the record. Following that decrease, the accelerations appear to be considerably subdued, relative to the earlier part of the record. Significant liquefaction occurred at Treasure Island, and this feature in the accelerogram may reflect the effect of liquefaction on ground motion. A comparison with the time histories rotated to the east-west direction at the Oakland Wharf only 5.2 km to the east of Treasure Island is shown in Figure 8. The east components of acceleration, velocity and displacement for each station are shown. For the first 15 seconds of the record, the waveforms ar[e] remarkably similar, with the Oakland Wharf records having some[-] what larger amplitudes. Unlike the ground motion at Treasure Islan[d] the ground motion at Oakland Wharf does not show a significant dro[p] in acceleration amplitudes after the initial 15 seconds nor does long[-] period motion dominate late in the record. At Treasure Islan[d] following the presumed onset of liquefaction, the acceleration quickl[y] falls and remains at rather low levels. Afterward, longer periods, see[n] in the displacement record, dominate the motion.

DISCUSSION

This paper has considered some aspects of the processed strong-motion data from the Loma Prieta earthquake, concentrating on the variability of strong ground motion with distance and with site geology. Both site geology and distance from the fault rupture have an important effect on the peak values of strong ground shaking recorded from the earthquake. Peak values of strong ground shaking tend to be amplified at alluvium and bay mud sites compared to nearby rock sites. The amount of amplification is generally frequency dependent with the smallest effect at high frequencies (> 5 Hz) for the soil sites (mainly deep alluvium) discussed in this paper.

Peak values of acceleration, velocity and displacement decrease, in general, with distance but not as rapidly for this earthquake as has been observed in previous earthquakes. Nearly 75 km from the fault rupture, peak ground acceleration values range from approximately 50 to 280 cm/sec/sec. These values are all greater than the median predicted for this distance. For both peak ground velocity and displacement the peak values of 63 cm/sec and 30 cm are observed at Hollister, an alluvial site 33 km from the fault rupture. These peak values have been exceeded in other earthquakes but only at significantly shorter distances from the fault rupture. The computed displacements also show strong transverse polarization in many cases. For example, in the San Francisco-Oakland area peak east-west displacements are two to three times as large as the peak north-south displacements.

ACKNOWLEDGMENTS

The California Strong Motion Instrumentation Program (CSMIP) extends its appreciation to the individuals and organizations which have permitted and cooperated in the installation of seismic strong motion equipment on their property. The authors would like to recognize the CSMIP technicians for their diligence and care in installing and maintaining the stations and in recovering records.

REFERENCES

alifornia Strong Motion Instrumentation Program, 1989, Plots of processed data for the interim set of 14 records from the Santa Cruz Mountains (Loma Prieta) earthquake of October 17, 1989: California Department of Conservation, Division of Mines and Geology, Report OSMS 89-08, 142 p.

bblee, T.W., Jr., 1973, Preliminary geologic maps of the Gilroy Hot Springs quadrangle, the Gilroy quadrangle, the Mt. Sizer quadrangle, the Morgan Hill quadrangle, Santa Clara County, California, and the Mt. Madonna quadrangle, Santa Clara and Santa Cruz counties, California: U.S. Geological Survey Open-File Report 73-59, scale 1:24,000.

ıldman, H.B., 1969, Geology of San Francisco Bay *in* Geologic and engineering aspects of San Francisco Bay fill: California Department Conservation, Division of Mines and Geology Special Report 97, p. 9-29.

ılley, 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.

ang, M.J., Cao, T.Q., Vetter, U.R., and Shakal, A.F., 1990, Second interim set of CSMIP processed strong motion records from the Santa Cruz Mountains (Loma Prieta) earthquake of October 17, 1989: California Department of Conservation, Division of Mines and Geology, Report OSMS 90-01, 201 p.

Joyner, W.B. and Boore, D.M., 1981, Peak horizontal acceleration and velocity from strong-motion records including records from the 1979 Imperial Valley, California, earthquake: Bulletin of the Seismological Society of America, v. 71, p. 2011-2038.

Maley, R., Acosta, A., Ellis, F., Etheredge, E., Foote, L., Johnson, D., Porcella, R., Salsman, M., and Switzer, J., 1989, U.S. Geological Survey strong-motion records from the Northern California (Loma Prieta) earthquake of October 17, 1989: U. S. Geological Survey Open-File Report 89-568, 85 p.

Mooney, W.D., and Colburn, R.H., 1985, A seismic-refraction profile across the San Andreas, Sargent and Caleveras faults, west-central California: Bulletin of the Seismological Society of America, v. 75, p. 175-191.

Shakal, A., Huang, M., Reichle, M. S., Ventura, C., Cao, T., Sherburne, R., Savage, M., Darragh, R., and Petersen, C., 1989, CSMIP strong-motion records from the Santa Cruz Mountains (Loma Prieta), California earthquake of 17 October 1989: California Department of Conservation, Division of Mines and Geology, Report OSMS 89-06, 196 p.

Shakal, A. F., DeLisle, M. J., Reichle, M. S., and Darragh, R. B., 1990, Strong ground shaking from the Loma Prieta earthquake of 17 October 1989 and its relation to near surface geology in the Oakland area: this volume, p. 29-46.

LANDSLIDE FEATURES AND OTHER COSEISMIC FISSURES TRIGGERED BY THE LOMA PRIETA EARTHQUAKE, CENTRAL SANTA CRUZ MOUNTAINS, CALIFORNIA

By

Thomas E. Spittler[1], Edwin L. Harp[2], David K. Keefer[2], Raymond C. Wilson[2], and Robert H. Sydnor[3]

ABSTRACT

Extensive landslides and coseismic fissures formed in a broad region in the central Santa Cruz Mountains during the M_S7.1 Loma Prieta, California earthquake of October 17, 1989. Hundreds of homes, a major state highway, and many county and private roads were damaged by earthquake-triggered landslides and surficial ground fissures in the epicentral area.

The origins of the coseismic fissures are complex and no single explanation can account for all the observed ground cracks. The majority of fissures are apparently related to landslides mobilized by intense seismic shaking. Some fissures may be related to tectonic uplift and extension of the hanging-wall block due to fault movement at depth. Detailed mapping of a 3,500 ha area with the highest density of surface fractures allows for the discrimination of causes for some fissures, but not all.

The landslides were triggered by strong ground motion up to 0.47 g vertical and 0.64 g horizontal peak acceleration as measured at the Corralitos CSMIP station located only 7 km from the epicenter. The earthquake occurred late in a dry autumn following two years of drought. Had the earthquake occurred during the winter or spring following several wet years, seismically-induced landslides probably would have been more widespread and would have caused substantially more damage.

INTRODUCTION

Earthquake-triggered landslides were a major effect of the Loma rieta earthquake. A regional reconnaissance by the U. S. Geological urvey (USGS) determined that earthquake-triggered landslides ccurred throughout an area of nearly 14,000 km^2 (Plafker and alloway, 1989, p. 23). The highest concentration of landslides trig-ered by the earthquake was in Santa Cruz County (Manson and hers, 1990). Teams of geologists with the California Department Conservation, Division of Mines and Geology (DMG) and the SGS began a cooperative systematic reconnaissance of the earth-uake-triggered landslides in the San Francisco Bay Area immedi-ely following the Loma Prieta earthquake. This reconnaissance efined an area near the San Andreas fault in the developed portion the epicentral region of approximately 3,500 hectares (ha) (Figure in which many of the largest landslides and most of the coseismic ssures formed (Spittler and others, 1990). The landslides and other ssures destroyed or damaged more than 100 residential structures the mapped area and may pose further hazards from renewed ovement in response to winter rainfall and consequent high local ound-water levels.

Following the initial survey, DMG and USGS geologists, in cooperation with geologists from other public and private agencies, prepared a set of maps of the area most impacted by landslides and fissures. The maps are at a scale of 1:4,800 and show observed surface cracks and compressional ridges that formed during the October 17, 1989 earthquake (Spittler and Harp, 1990). The large landslides and coseismic fissures are most abundant on ridge crests and slopes on the southwestern flank of the Santa Cruz Mountains, along and below the ridge that separates Santa Cruz County from Santa Clara County. The features are most prevalent along Summit Road between the intersections with Highway 17 and with Highland Way. This area is southwest of the surface trend of the San Andreas fault and northwest of the epicenter of the Loma Prieta earthquake, and is located on the upthrown block.

The strong ground shaking that accompanied the Loma Prieta earthquake was measured at the Corralitos California Strong Motion Intrumentation Program station 7 km from the epicenter. Accelerations were as strong as 47 percent of the acceleration of gravity in the vertical direction and 64 percent of gravity in a horizontal direction (Shakal and others, this volume). These ground motions are well in excess of those required to trigger the numerous landslides in the Santa Cruz Mountains (Wilson and Keefer, 1985).

alifornia Department of Conservation, Division of Mines and Geology, Environmental Protection Program
J. S. Geological Survey, Menlo Park
alifornia Department of Conservation, Division of Mines and Geology, Geologic Hazards Assessment Program

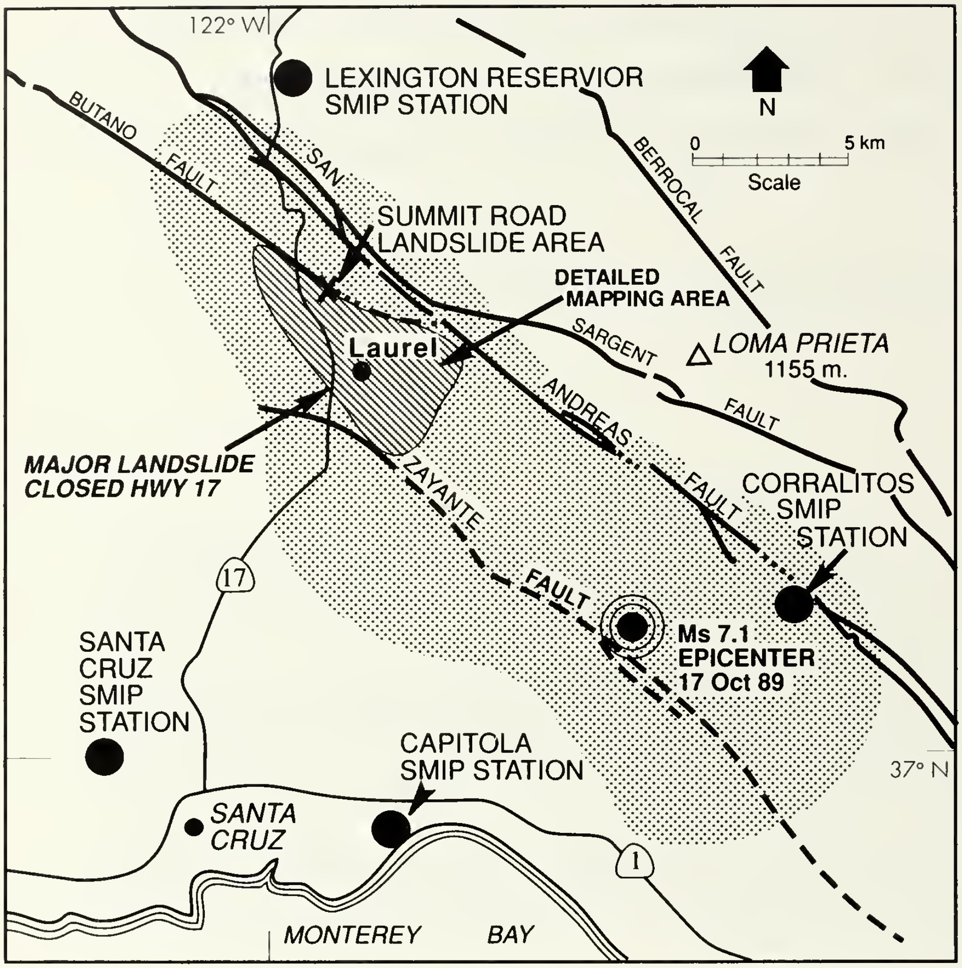


Figure 1. Index map of the epicentral area. Hachures indicate 3,500 ha area where detailed mapping occurred. Stippl area indicates the approximate region of widespread landsliding and ground cracking due to the earthquake. Bullet symbols indicate station locations of DMG's Strong Motion Instrumentation Program (SMIP).

The direct and indirect costs of the many earthquake-triggered landslides cannot yet be adequately determined. In addition to the direct losses of personal property caused by the landslides, State Highway 17 (Photo 1) was closed for 33 days, costing the California Department of Transportation (Caltrans) approximately $1.8 million to repair. This highway normally carries 60,000 vehicles per day. Indirect costs to commuters and businesses during the time the highway was closed were also greatly increased.

SAN ANDREAS SETTING

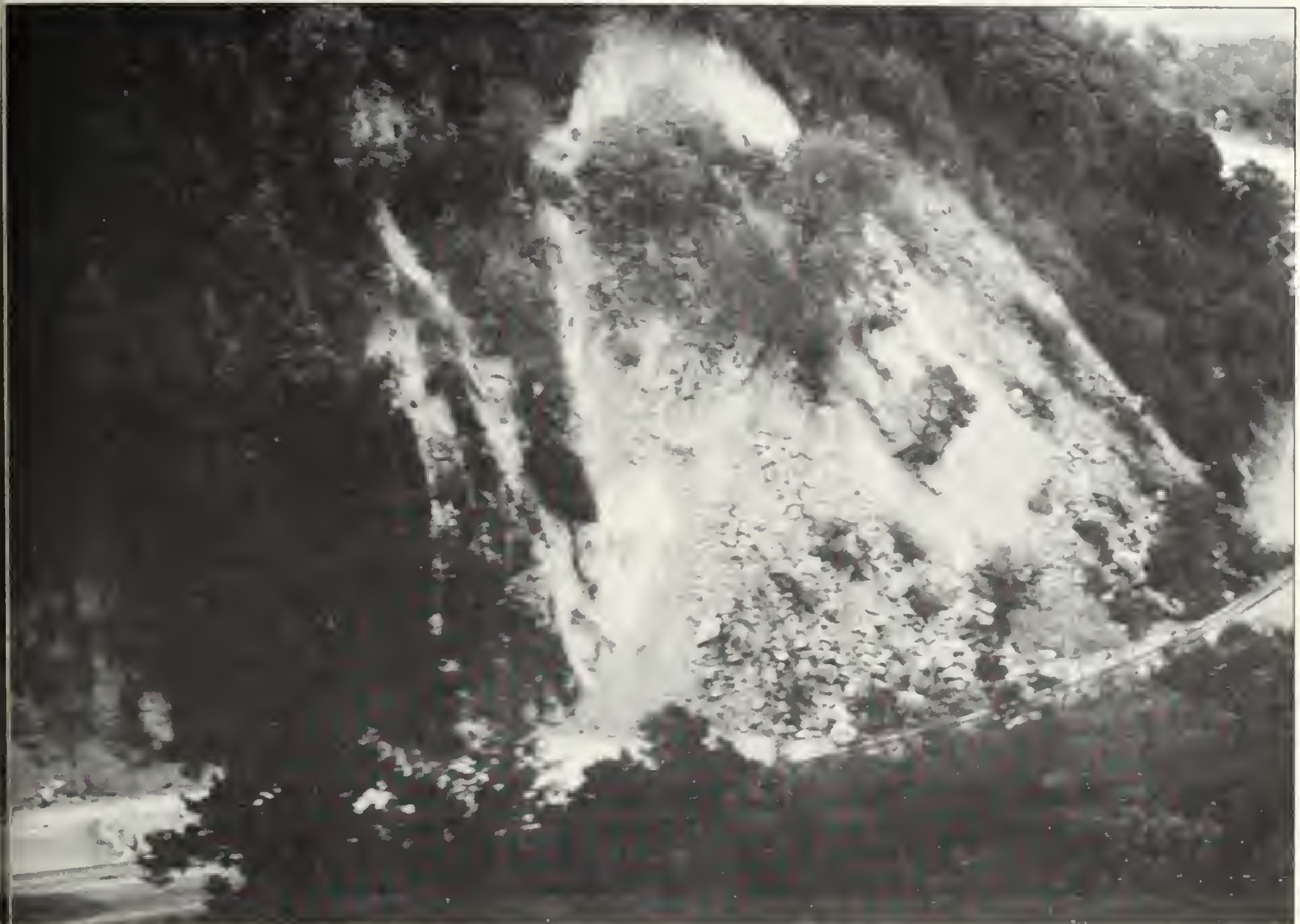
The right-lateral strike-slip San Andreas fault slices through California for over 900 km from Cape Mendocino to the Gulf of California, separating the Pacific tectonic plate west of the fault from the North American plate to the east. The Pacific plate is moving northwest at approxomately 4.8 cm/yr past the North American plate (DeMets and others, 1987). Along most of its length, the trend of the San Andreas fault follows a continuous arc and the fault plane is nearly vertical. In the epicentral area of the Loma Prieta earthquake in the central Santa Cruz Mountains, the fault makes a 7 degree bend to the left from the regional arc. Compression along this bend has resulted in a southwest dip and a reverse component of movement along the fault. The reverse thrusting accompanying earthquakes in this area is the cause of the rapid uplift of the mountains. The Loma Prieta earthquake was a part of this process.

Although no through-going surface fault rupture was observe along the San Andreas fault as a result of the Loma Prieta earthquak (Hart and others, this volume; U. S. Geological Survey Staff, 1990 seismic records from the earthquake and its aftershocks (Plafker an Galloway, 1989) and geodetic measurements taken before and aft the earthquake (Lisowski and others, 1990) define a rupture plan that dips 70 degrees to the southwest and extends from a depth of km to 18 km along a 37 km reach of the fault. Total displacemen across this rupture surface was about 1.6 ± 0.3 m right-lateral strik slip and 1.2 ± 0.3 m reverse dip slip (Lisowski and others, 1990)

GEOLOGY, GEOMORPHOLOGY AND CLIMATE

The Santa Cruz Mountains are a 120 km-long, 20 km-wide mou tain range that separates San Francisco Bay and the Santa Cla Valley from the Pacific Occan and Monterey Bay. The Santa Cru Mountains are highest in the southern portion, adjacent to th southern part of the bend in the San Andreas fault, and reach maximum elevation of 1,155 m at Loma Prieta, which was on th downthrown block of this earthquake.

Uplift of the Santa Cruz Mountains along folds and faults h exposed marine sandstones, mudstones, shales, and both extrusi and intrusive basaltic volcanic rocks. Rocks exposed west of th



oto 1. A major debris slide at "Laurel Hill" on State Highway 17 blocked the northbound lanes for 33 days. Aerial view is toward the southeast. Bedding planes he hard, jointed sandstone of the Purisima Formation dip about 60° south (to the right). Orthogonal joint planes dip northward (to the left), creating a wedge-ure in the over-steepened cutslope. (Airphoto by T. E. Spittler)

n Andreas fault are Tertiary sedimentary and volcanic formations posited in marine basins formed on older Salinian metamorphic d granitic bedrock (Clark, 1981). These rocks were deposited far the south of the Tertiary and Mesozoic sedimentary and volcanic ks that rest on Franciscan Complex basement east of the San dreas fault. Wagner (this volume) provides a more complete cussion of the geologic and tectonic setting of the Santa Cruz untains.

Within the 3,500 ha zone near the summit ridge of the Santa Cruz untains, the greatest number of earthquake-triggered landslides l fissures occurred. The area is underlain by poorly bedded to ssive, poorly sorted, moderately to poorly consolidated Tertiary sedimentary rocks of a micaceous shale member of the Butano dstone, a fine-grained facies of the Vaqueros Sandstone, and the es Mudstone and Two Bar Shale members of the San Lorenzo mation (Dibblee and others, 1978; Dibblee and Brabb, 1978; rk and others, 1989). North of the Butano fault, these formations e been mapped as dipping steeply into the slopes, and parallel to regional strike of bedding. In places south of the fault the bedding been mapped as dipping steeply into the slope in a recumbent, rturned anticline (Clark and others, 1989). Much of the bedding in this area has been affected by downslope creep which has progressed to depths of 3 to 10 m, as observed in local road cuts.

The San Francisco Bay area has a cool summer Mediterranean climate. Moderate to heavy rainfall in the winter months of November to April occurs in the Santa Cruz Mountains. Annual rainfall averages 60 to 150 cm (Rantz, 1971). Much of the rain falls during high-intensity storms. The 50-year return period 2-hour duration storm is over 3 cm per hour (California Department of Conservation, 1984), well in the range of a debris-flow triggering event (Campbell, 1975; Cannon and Ellen, 1985, 1988).

REGIONAL LANDSLIDE SETTING

The Santa Cruz Mountains have experienced a long history of landslide activity. The complex geomorphology of the mountains results from the interaction of rapid erosion and mass wasting and active tectonic uplift. Both shallow and deep landslides have resulted from the combination of steep slopes, weak rock, high rainfall quantities and intensities, and earthquakes. The rapid uplift, which is in response to movement along the San Andreas and other faults, has formed an immature convex topography with steep, narrow, actively eroding canyons. Continued downcutting of stream beds and undercutting of oversteepened slopes have resulted in many landslides. For example, the exceptionally wet winter of 1889-1890 triggered much more rotational landslide activity in the Coast Ranges than occurred during normal winters (Lawson, 1908).

A high-intensity winter storm in January 1982 triggered thousands of shallow debris flows in the San Francisco Bay area that killed 25 people, destroyed scores of homes, and caused more than $66 million in damage (Ellen and Wieczorek, 1988). Much of the damage was in the Santa Cruz Mountains, and was responsible for focusing the geologic community of northern California on debris-flow hazards. This same storm triggered a large rock-block glide landslide in the Love Creek watershed, approximately 11 km west of the center of the Summit Road area. A winter storm that affected the Santa Cruz Mountains in 1986 resulted in the first real-time landslide warning which, according to eyewitness accounts of landslide occurrence, accurately predicted the times of major landslide events (Keefer and others, 1987).

The 1906 San Francisco earthquake triggered many landslides in the Santa Cruz Mountains (Lawson, 1908). For example, a debris flow that failed in the headwaters of Deer Creek travelled for approximately one-half mile (1 km), plowed through a grove of redwood trees, some as tall as 200 feet (60 m), and wrecked a shingle mill with debris as thick as 30 to 60 feet (10 to 20 m). Lawson (1908) reports that on hillsides and ridge crests, at points not within the San Andreas Rift zone, cracks were common. Most are related to landslides, but some of the cracks had no apparent connection with landslides, actual or incipient. In the summit area of the Santa Cruz Mountains, Lawson reported that the ridge was full of cracks, ranging up to 2 to 3 feet (60 cm to 1 m) wide, and extending for 0.5 miles (0.8 km). The triggering of landslides by the Loma Prieta earthquake is consistent with the effects of other large earthquakes as tabulated by Keefer (1984).

Photo 2. Small debris slide adjacent to a house in the Santa Cruz Mountains. (Photo by T. E. Spittler)

P to 3. Radial fractures around spur ridges. The patched asphalt shows the fracture pattern across Highland Way in the Santa Cruz Mountains. Fracture sets c tinue up slope from the road where they arch over the crest of the spur ridges and join. The fractures also continue down slope. (Photo by T. E. Spittler)

EARTHQUAKE-TRIGGERED LANDSLIDES AND COSEISMIC FISSURES

An extensive network of fractures and fissures formed during the Lma Prieta earthquake, dissecting the summit ridge in a compli- ced pattern. Some of the fissures are interpreted as being of tectonic ogin, while numerous fractures are interpreted as headwall scarps, leral margins, and toes of landslides that are deep-seated rotational s nps or translational block glides.

Earthquake-triggered landslides formed in virtually every rock ut in the Santa Cruz Mountains. In general, the better consolidated, mre brittle formations failed through rockfalls and dry debris flows w le shales and other clay-rich formations developed rotational and tr nslational landslides as well.

The earthquake-triggered features are subdivided into four catego- ri by Manson and others (1990): (1) rockfalls, rock slides, soil falls, o soil slides; (2) slumps or block slides; (3) landslides-other, ii uding liquefaction features; and (4) other ground failures not c arly related to liquefaction, landslides, or faults.

Manson and others (1990) report that rockfalls, rock slides, soil falls, and soil slides of less than 100 m^3 were the most common types of landslides triggered by the earthquake (Photo 2). Thousands of these landslides occurred over a large portion of the Santa Cruz Mountains and affected the coastline between Big Sur, 130 km south of the epicenter, and Marin County, 120 km north of the epicenter. These landslides are characterized by rapid movement down steep slopes, including oversteepened cut slopes for roads and house pads.

Throughout the epicentral area, roads that are midslope between the crests and toes of the slopes are broken by radial fractures that trend perpendicular to the long dimension of the road and are concentrated around the axes of steeply-plunging, steep-sided spur ridges (Photo 3). Displacement vectors are oriented into the spur ridges and down-slope along the spur axes.

Some of the fractures and fissures mapped by Spittler and Harp (1990) and USGS Staff (1990) are evidently not related to landsliding. These features include most cracks located along linear ridgetop depressions and linear fractures that extend across landslide topography. The origin of these features is not entirely clear. The set of fractures that form a shallow graben south of Summit Road 6 km east

Photo 4. Incipient landslide scarp within the Villa del Monte subdivision along the summit of the Santa Cruz Mountains. (Photo by J. P. Schlosser)

of Highway 17 has been interpreted in several ways. Ponti and Wells (1990) suggest that the Summit Road surface fractures probably formed as a result of (1) strong ground shaking that resulted in large-scale slumping of the hillsides and/or collapse of the ridge crests, and (2) tectonic uplift and extension of the hanging-wall block due to fault movement at depth. Cotton and other (this volume) propose that these fissures ar bedding plane faults which are second-orde bending-moment faults related to coseismi active folding processes, as described by Yeat (1986). A third view (Hart and others, thi volume) is that the graben formed by gravita tional spreading induced by strong groun shaking that occurred along the summit ridge This model suggests that the ridgetop depres sions are similar to sackungen. However, th bedrock lithology, the topography, and th Quaternary geologic history of the Santa Cru Mountains are significantly different from th brittle crystalline igneous and metamorph rocks and the steep glaciated terrain whe sackung have been described elsewhere in th western United States (Varnes and other 1989).

Fractures are most common on long, narro steep-sided ridges. Most of these ridgeto fractures exhibit extension, and back-facin scarps also occur. Some of the extension partings along the axes of narrow, steep-sid ridgetops can be explained as having formed response to ground shaking accelerations directed perpendicular the axis of the ridge. These accelerations may have been greater th 1.0 g in some areas as indicated by stones, logs, and concrete sla that have been apparently thrown from their original positions wi little or no rolling. Topographic amplification of the strong grou

Photo 5. Headwall scarp of large landslide near Schultheis Road. (Photo by J. P. Schlosser)

Photo 6. Landslide scarp adjacent to a house in the Villa Del Monte area, about 3 km east of Highway 17. (Photo by J. P. Schlosser)

haking is a possible cause for the domi-ance of fractures along ridgetops. Topo-raphic amplification is also suggested by bservations of broken tops of tall trees iore commonly along ridgetops than in her areas and the appearance of a greater nount of damage to structures of similar onstruction on ridgetops relative to side opes and valley bottoms (Spittler and ydnor, 1990). In several areas the ridge-p fractures end where ridges widen eyond approximately 100 m) or where opes are inclined less steeply than about 5 percent. In most areas the ridgetop fis-res appear to be parallel to the bedding or inting of the underlying sedimentary rmations (Ponti and Wells, 1990). How-er, this may be an artifact of the parallel gnment of ridges to the underlying struc-ral trend of the geology.

Many of the large, deep landslides in the mmit ridge area that were triggered by e Loma Prieta earthquake are within rtions of ancient large landslide com-exes as mapped by Dibblee and others 979); Cooper-Clark and Associates 975); and Clark and others (1989). The distinctive hummocky to-graphy and disrupted bedrock units observed in road cuts and ong stream channels in this area indicate repeated episodes of ndslide movement.

Most recognizable among landslide-related cracks are those that m headwall scarps. In many localized areas the heads were the ly portions of the landslides that moved during the earthquake. e arcuate, concave-down pattern of the headwall scarps form oad frowns on the landscape (Photo 4). Where more than just the permost portion of a landslide has failed, the headwall fractures mmonly have the largest displacements of all of the landslide-ated cracks. Displacements across the scarps of the deep-seated mps along Schultheis Road and Morrell Cutoff exceed 1.0 m hoto 5). The sense of displacement across fissures forming these arps is most commonly extensional and slope-parallel dip-slip, ley-side down. An arcuate, en echelon pattern of extensional sures, with right-stepping fractures along left-lateral margins and t-stepping fractures along the right ones, was observed along ny of the mapped landslides. Many of the headwall scarps are ated along preexisting scarps (Photo 6).

Fractures that formed along the margins of landslides generally hibit a sense of shear displacement consistent with the relative placement of the landslide mass. However, there are numerous as where the relative displacement of the landslide mass is not ar and the relation of the sense of displacement across individual cracks to the overall mass movement also is unclear. The least common deformational features related to the earthquake-triggered landslides are well-defined folds or bulges with fresh fractures that delineate areas of compression at the toes of landslides.

Landslides and coseismic fissures were developed by the Loma Prieta earthquake despite its occurrence late in the dry season following nearly two years of drought. Although wet areas, springs, and shallow wells in the summit ridge area indicate the presence of locally perched ground-water zones, the severe rainfall deficit suggests that seismically induced pore-water pressures were substantially less than those that have occurred during earlier earthquakes. Had the earthquake occurred during a wet period, landslide problems would undoubtedly have been worse.

CONCLUSION

The triggering of landslides by the Loma Prieta earthquake was not a unique phenomenon. Concern must now be directed toward the threat of an acceleration of landslide activity in the highly slide-prone Santa Cruz Mountains. Now that many slide planes have been reactivated, the stability of slopes, some of which have many houses on them (Photo 6), could be greatly reduced, and a wet winter could trigger additional landslide movement on some of these slides. This concern was emphasized by the observations of post-seismic movement by G. K. Gilbert following the 1906 Great San Francisco earthquake (Lawson, 1908).

ACKNOWLEDGMENTS

The authors are indebted to the numerous geologists who assisted in mapping the surficial effects of the Loma Prieta earthquake. Special thanks re given to Paia Levine, Mary Ann McKittrick, David Hope, and Peter Parkinson of the County of Santa Cruz for providing logistical support ollowing the earthquake and for coordinatiing the work of the County with that of the Division of Mines and Geology and the U. S. Geological urvey. Bruce R. Clark of Leighton and Associates provided three staff geologists for assistance in the mapping effort, and Gary B. Griggs of e University of California at Santa Cruz arranged for graduate student help. Levine, McKittrick, and Griggs, as well as Gerald E. Weber and rian Walls, worked with the authors on directing the course of slope stability investigations following the earthquake. We appreciate the oughtful and insightful reviews by Daniel J. Ponti and Michael J. Rymer of the U. S. Geological Survey.

REFERENCES

California Department of Conservation, 1984, California precipitation intensity maps, 50-year return period with 8 different durations: unpublished report to the California Department of Forestry, 20 p.

Campbell, R.H., 1975, Soil slips, debris flows, and rainstorms in the central Santa Monica Mountains and vicinity, southern California: U.S. Geological Survey Professional Paper 851, 51 p.

Cannon, S.H., and Ellen, S.D., 1985, Rainfall conditions for abundant debris avalanches, San Francisco Bay region: California Geology, v. 38, no. 12, p. 267-272.

Cannon, S.H., and Ellen, S.D., 1988, Rainfall that resulted in abundant debris flow activity during storms, *in* Ellen, S.D. and Wieczorek, G.F., editors, Landslides, floods, and marine effects of the storm of January 3-5, 1982 in the San Francisco Bay region: U.S. Geological Survey Professional Paper 1434, p. 27-33.

Clark, J.C., 1981, Stratigraphy, paleontology, and geology of the central Santa Cruz Mountains, California Coast Ranges: U.S. Geological Survey Professional Paper 1168, 51 p.

Clark, J.C., Brabb, E.E., and McLaughlin, R.J., 1989, Geologic map of the Laurel 7.5-minute quadrangle, Santa Cruz and Santa Clara counties, California: U.S. Geological Survey Open-File Report 89-676, scale 1:24,000.

Cooper-Clark, and Associates, 1975, Preliminary map of landslide deposits in Santa Cruz County, in Seismic Safety Element, Santa Cruz, CA: Santa Cruz County Planning Department, map scale 1:62,500.

Cotton, W.R., Fowler, W.L., and Van Velsor, J.E., 1990, Coseismic bedding plane faults and ground fissures associated with the Loma Prieta earthquake of October 17, 1989: this volume, p. 95-103.

DeMets, C., Gordon, R.G., Stein, S., and Argus, D.F., 1987, A revised estimate of Pacific-North American plate boundary zone tectonics: Geophysical Research Letters, v. 14, p. 911-921.

Dibblee, T.W. Jr., Brabb, E.E., and Clark, J.C., 1978, Preliminary geologic map of the Laurel quadrangle, Santa Cruz and Santa Clara counties, California: U.S. Geological Survey Open-File Report 78-84, 1 plate, scale 1:24,000.

Dibblee, T.W. Jr., and Brabb, E.E., 1978, Preliminary geologic map of the Los Gatos quadrangle, Santa Cruz and Santa Clara counties, California: U.S. Geological Survey Open-File Report 78-453, 1 plate, scale 1:24,000.

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

Hart, E.W., Bryant, W.A., Wills, C.J., and Treiman, J.A., 1990, The search for fault rupture and significance of ridgetop fissures: this volume, p. 83-94.

Keefer, D.K., 1984, Landslides caused by earthquakes: Geological Society of America Bulletin, v. 95, 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.

Lawson, A.C., ed., 1908, The California Earthquake of April 18, 1906: Report of the State Earthquake Investigation Committee, Carnegie Institution of Washington, Publication 87, v. 1, 451 p.

Lisowski, M., Prescott, W.H., Savage, J.C., and Svarc, J.L., 1990, A possible geodetic anomaly observed prior to the Loma Prieta, California, earthquake: Geophysical Research Letters, v. 17, p. 1211-1214.

Manson, M. W., Keefer, D.K., and McKittrick, M.A., compilers, 1990, Preliminary reconnaissance location map of landslides and other geologic features related to earthquake shaking in the Santa Cruz Mountains, California, resulting from the Loma Prieta earthquake of October 17, 1989: California Division of Mines and Geology Open-File Report 89-29.

Plafker, G. and Galloway, J.P., eds, 1989, Lessons learned from the Loma Prieta, California, Earthquake of October 17, 1989: U. S. Geological Survey Circular 1045, 48 p.

Ponti, D. J., and Wells, R. E., 1990, Extent and origin of surface fractures in the Summit Road-Skyland Ridge area, *in* Schwartz, D. P., and Ponti, D. J., eds., Field guide to the neotectonics of the San Andreas fault system, Santa Cruz Mountains, in light of the 1989 Loma Prieta earthquake: U. S. Geological Survey Open-File Report 90-274, p. 27-30.

Prescott, W.H., Lisowski, M., Johnston, M.J.S., Schulz, S.S., Savage, J.C., and Clark, T.A., 1990, Deformation before, during and after the Loma Prieta earthquake of October 1989: EOS, Transactions of the American Geophysical Union, v. 71, no. 8, p. 291 (abstract).

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.

Shakal, A.F., DeLisle, M.J., Reichle, M.S., and Darragh, R.B., 1990, Strong ground shaking from the Loma Prieta earthquake of 17 October 1989, and its relation to near surface geology in the Oakland area: this volume, p. 29-46.

Spittler, T.E., and Harp, E.L., 1990, Preliminary map of landslide features and coseismic fissures triggered by the Loma Prieta earthquake of October 17 1989: California Division of Mines and Geology Open-File Report 90-6, map scale 1:4,800.

Spittler, T.E., Sydnor, R.H., Manson, M.W., Levine, P., and McKittrick, M.A., 1990, Large-scale mapping of landslides in the epicentral area of the Lom Prieta earthquake of October 17, 1989, Santa Cruz County, California: EOS, Transactions of the American Geophysical Union, v. 71, no. 8, p. 290 (abstract).

Spittler, T.E., and Sydnor, R.H., 1990, Landslides and ridge-top failures associated with the epicentral area of the Loma Prieta earthquake of October 17, 1989: EOS, Transactions of the American Geophysical Unio v. 71, no. 8, p. 290 (abstract).

U. S. Geological Survey Staff, 1989, Preliminary map of fractures formed in the Summit Road-Skyland Ridge area during the Loma Prieta, California, earthquake of October 17, 1989: U.S. Geological Survey Open-File Report 89-686, 1 plate, scale 1:12,000.

U.S. Geological Survey Staff, 1990, Surface fractures and ground failure associated with the Loma Prieta, California, earthquake of October 17, 1989: EOS, Transactions of the American Geophysical Union, v. 71, no. p. 291 (abstract).

Varnes, D.J., Radbruch-Hall, D.H., and Savage, W.Z., 1989, Topographic ar structural conditions in areas of gravitational spreading of ridges in the western United States: U.S. Geological Survey Professional Paper 149€ 28 p.

Wagner, D.L., 1990, Geologic and tectonic setting of the epicentral area of t Loma Prieta earthquake, Santa Cruz Mountains, central California: this volume, p. 1-10.

Wieczorek, G.F., Harp, E.L., Mark, R.K., and Bhahacharyya, A.K., 1988, Debris flows and other landslides in San Mateo, Santa Cruz, Contra Cos Alameda, Napa, Solano, Sonoma, Lake, and Yolo counties, and factors influencing debris-flow distribution, *in* Ellen, S.D. and Wieczorek, G.F., e Landslides, floods, and marine effects of the storm of January 3-5, 1982, the San Francisco Bay region: U.S. Geological Survey Professional Pa 1434, p. 133-161.

Wilson, R.C., and Keefer, D.K., 1985, Predicting areal limits of earthquake-induced landsliding, *in* Ziony, J. I., ed., Evaluating earthquake hazards i the Los Angeles region: U. S. Geological Survey Professional Paper 13 p. 317-345.

Yeats, R.S., 1986, Active faults related to folding, *in* Active tectonics: Natio Academy Press, Washington, D. C., p. 63-79.

COASTAL BLUFF LANDSLIDES IN SANTA CRUZ COUNTY RESULTING FROM THE LOMA PRIETA EARTHQUAKE OF 17 OCTOBER 1989

By

Robert H. Sydnor[1], Gary B. Griggs[2], Gerald E. Weber[3], Richard J. McCarthy[4], and Nathaniel Plant[2]

ABSTRACT

The 1989 Loma Prieta earthquake caused widespread landsliding along coastal bluffs. Most coastal landslides occurred within 9 to 20 km of the epicenter where shaking of Modified Mercalli Intensity VII or greater occurred. Strong ground-motion from a CSMIP free-field station at Capitola (only 0.4 km from the coastal bluffs) measured peak accelerations of 0.54 g horizontal and 0.60 g vertical.

One fatality and several million dollars in damage were attributed to coastal landslides during this earthquake. The segment of the coast where landslides were most prevalent includes Capitola Beach, New Brighton State Beach, Seacliff State Beach, Rio Del Mar, La Selva Beach, Manresa State Beach, and Sunset Beach.

Engineering geologists from the University of California at Santa Cruz, the California Division of Mines and Geology, the California Coastal Commission, and several local consulting engineering geology firms performed a rapid reconnaissance of the coastline to evaluate landslides immediately following the earthquake.

Three kinds of coastal landslides occurred: (1) Block falls in sedimentary bedrock cliffs, (2) translational landslides in friable sandstone cliffs, and (3) sand flows in Quaternary dune deposits. Most of the coastal landslides occurred in the Pliocene Purisima Formation and the Pleistocene Aromas Sand because these formations form the seacliffs that received the highest intensity of seismic shaking (within 9-20 km of the epicenter).

Prudent land-use decisions based on detailed engineering geologic mapping and geotechnical analyses will minimize the exposure of structures to damage by coastal landslides.

INTRODUCTION

The coastal bluffs in central and southern Santa Cruz County are cated only about 9 to 20 km from the epicenter of the 1989 Loma ieta Earthquake. Intense seismic shaking caused landslides at merous locations along the coastline from Monterey to Marin unty. One person was killed by a rockfall below a sea cliff and veral million dollars in damages were attributed to coastal land-des triggered by this earthquake.

Coastal bluff landslides due to seismic shaking are a significant ologic hazard. Because ocean view property and homes are in mand, available land is either already built upon or is under essure for development. The purposes of this paper are: (1) to nsider seismic shaking from earthquakes as a punctuated geomor-ic process which affects coastal bluff morphology, (2) to summa-e strong ground-motion records which pertain to coastal bluffs, to describe the occurrence of seismically-induced coastal land-des, and (4) to consider land-use implications and planning ights related to coastal landslides.

The scope of this paper is limited to reconnaissance-level field work in southern Santa Cruz County where coastal landslides were most prevalent. Not all seismically-induced coastal landslides are described.

GEOLOGIC SETTING

Santa Cruz County and most of central California is noted for its rugged and picturesque emergent coastline characterized by precipitous cliffs experiencing active surf erosion. This modern seacliff is but the latest of a series of Pleistocene seacliffs represented by the well-preserved flight of marine terraces present on the seaward side of the Santa Cruz Mountains. Marine terrace studies (Bradley, 1957; Bradley and Griggs, 1976; Alexander, 1953; Weber and others, 1979; Weber and Griggs, 1990; Anderson, 1990) indicate the Santa Cruz Mountains have formed in response to long-term regional uplift over the past 1.2 ma. This episodic coseismic uplift may be associated with Loma Prieta-type earthquakes. The localized deformation of shoreline angles appears to be related to seismic

alifornia Department of Conservation, Division of Mines and Geology, Geologic Hazards Assessment Program
oard of Earth Sciences, University of California, Santa Cruz
eber & Associates, 120 Westgate Dr., Watsonville
alifornia Coastal Commission, 631 Howard St., San Francisco

events, as does the regional uplift. Uplift is most likely related to fault motion resulting from localized convergence at a restraining bend along the San Andreas fault.

Previous Work

Active coastal erosion and slope failures along the modern sea cliff are continuing processes that reflect the rapidity of changes that characterize an active emergent coastline. Both slope failure and cliff erosion have long been recognized as a problem with respect to California coastal development (e.g., Cleveland, 1975; Habel and Armstrong, 1977; Atwater, 1978; Griggs and Johnson, 1979; Kuhn and Shepard, 1984; Griggs and Savoy, 1985).

Previous Earthquakes

Although landslide-generating earthquakes are typically episodic and widely spaced in time, they may still reflect a major geomorphic process that helps shape the cliffs and coastline. During the past 124 years, two other major seismic events (1865 and 1906) apparently caused slope failures in northern Monterey Bay (Griggs, 1973; Plant and Griggs, 1990). The effects of the 1838 and 1926 earthquakes on coastal bluff stability are not known. However, the 1838 event on the San Andreas fault may have had an effect similar to 1865 and/ or 1906, while the two 1926 Monterey Bay earthquakes apparently had a relatively minor effect on the sea cliff.

Coastal Bluff Processes

Severe seismic shaking is but one process affecting sea cliff stability. Rock type, orientation and development of structures in the rocks, surf erosion, weathering and episodic intense storms all interact to create the geomorphic environment that shapes the cliffs. All processes except active surf zone erosion at the base of the cliff act to degrade the cliff and decrease the slope angle. Active surf erosion acts to steepen the slope angle. However, all processes cause the sea cliff to migrate inland. Figure 1 summarizes the approximate range in frequency of events and processes which affect coastal bluffs in northern Monterey Bay in the context of geologic time.

Dynamic Equilibrium

The modern sea cliff is an evolving landform that exists within the dynamic interplay (equilibrium) of surf erosion that steepens the cliff and mass movements that wear down the cliff. The cliff will exist in this interaction between processes until its base is elevated above the active surf zone by either a drop in sea level or tectonism. Once the surf abandons the sea cliff it begins to slowly degrade and evolve toward an erosional equilibrium slope.

Present along northern Monterey Bay are both sea cliffs in the dynamic equilibrium of surf zone and mass movement, and cliffs which are almost isolated from the active surf zone. North of New Brighton Beach the sea cliff is under continual wave attack. Here the cliff maintains a near-vertical profile in bedrock and steep (±45°) slopes in the capping terrace deposits. The cliff profile does not degrade but is maintained in dynamic equilibrium by the wave erosion.

South from New Brighton to Sunset Beach, the sea cliff is protected much of the time by a broad beach, as well as an extensive series of seawalls and revetments. Therefore, waves only reach the base of the cliff during periods of very large storms coincident with high tides (e.g., the 1983 winter). As a result, terrestrial processes such as runoff and mass movement tend to be more important geomorphic processes than wave erosion for this segment of the coastline.

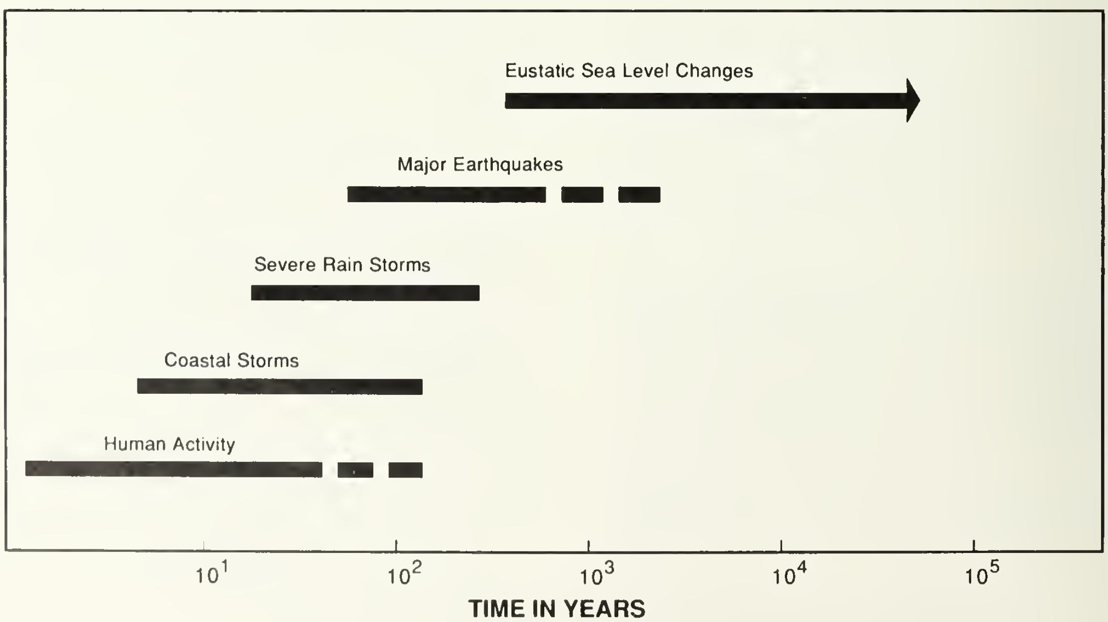


Figure 1. Approximate frequency range of events/processes affecting coastal bluffs in northern Monterey Bay.

Prior to the 1989 Loma Prieta earthquake, the scale of seismically-induced slope failures in this area was somewhat unknown. This ype of slope failure can be a significant factor in the degradation and evolution of all sea cliffs but is most noticeable where cliffs are ess exposed to wave action. The absence of erosion at the toe of he cliff results in the development of gentler slopes (near the angle-of-repose) in the marine terrace deposits that cap the cliff. Large alus aprons formed at the base of these cliffs reflect the toppling, alling, and avalanching processes acting on the sea cliff. On an ctive sea cliff in dynamic equilibrium, seismically-induced slope ailures are not as obvious as on an abandoned sea cliff.

A significant effect of seismic shaking on coastal bluffs is the emoval of loose weathered material from the cliff face. The process s comparable in effectiveness to non-seismic slope failure in moving earth materials off the cliff face, and exposing fresh rock to weathering, although it occurs much less frequently (Figure 1). Consequently earthquake-induced slope failure increases both the ate of retreat of active sea cliffs and the degradation of abandoned ea cliffs. These earthquake events also act as an intermittent ontributory source of sediment to the littoral drift along the coast.

Six distinct geologic/geomorphic parameters affecting coastal luff stability occur together within the Santa Cruz County segment f the California coastline: (1) steep cliffs, (2) weak sedimentary edrock capped by Quaternary terrace deposits, (3) active faulting nd a high level of regional seismicity, (4) active marine erosion, (5) pisodic intense storms, and (6) adverse impact of development by an.

rosion Rates

Erosion rates along the cliffs of southern Santa Cruz County vary om about 5 to 50 cm/yr and are controlled primarily by lithology, ructure, stratigraphy, and exposure to wave action (Griggs and ohnson, 1979; Griggs and Savoy, 1985). Erosional processes fecting the cliffs include hydraulic impact and scour from winter orms, landsliding due to intense rainfall, seismically-induced ndslides, and ground-water seepage. The latter includes lateral igration of septic effluent from cliff-top homes and adverse effects domestic irrigation water (lawn and garden watering).

ack of Antecedent Rainfall

In the autumn of 1989, Santa Cruz County was still experiencing severe multi-year drought, with no unusually heavy rainfall since e Valentine's Day storms of 1986. The coastal bluffs were latively dry from a geotechnical viewpoint, except for local fects of domestic landscape irrigation and sewage disposal leach-elds. The first rainfall for the winter season did not come until four ys after the main shock. Thus it is believed that pore-water essure was not a leading factor in coastal bluff failure for this ent. However, had the earthquake occurred in mid-winter after pical heavy winter rainfall, it is possible that more extensive ndsliding would have occurred along the coastal bluffs.

In summary, a seacliff profile is maintained by wave erosion at its e. Without active wave erosion, mass-wasting processes degrade astal cliffs. Earthquakes are an important episodic process which affect seacliffs. There was no antecedent rainfall prior to the earthquake which could have set the stage for more extensive landsliding.

EARTHQUAKE EFFECTS

The epicenter of the 17 October 1989 Loma Prieta Earthquake was located only about 9 km inland from the nearest segment of the coastline (Aptos - Capitola); the focal depth was 17.6 km. Strong shaking along the coastline lasted for about 17-23 seconds. Based on preliminary reports, Modified Mercalli Intensity VII shaking occurred along the Santa Cruz coastline, diminishing to MMI VI near Half Moon Bay (Stover and others, 1990). However, slightly inland from Capitola - New Brighton Beach area the intensity of shaking was MMI VIII. Thus the most populous and densely developed segment of the coastal bluffs in Santa Cruz County received the highest intensity of shaking.

Within the epicentral area there appeared to be topographic amplification of shaking on narrow ridge crests (Spittler and Sydnor, 1990; Spittler and others, 1990). Ground cracking was found along the edges of coastal cliffs and narrow promentories. This may have been due to lack of lateral support during intense shaking rather than topographic amplification.

Strong Motion Records Near the Coast

Four strong-motion instrument stations operated by the California Division of Mines and Geology, Strong Motion Instrumentation Program (CSMIP), provide quantitative records of shaking. Prior to October 1989, there were no strong motion records in the near-field of a significant earthquake which could be related to coastal landslides.

The 1989 Loma Prieta epicenter, the coastal cliffs, and the four strong-motion instruments were all relatively close to each other. Figure 2 is an index map which shows the proximity of the coastal cliffs to the epicenter and CSMIP stations. An isoseismal line which separates Modified Mercalli Intensity VII from VIII is also shown, based on Stover and others (1990).

The data from the 1989 earthquake that apply to coastal Santa Cruz County are summarized in Table 1; refer to Shakal and others (1989) for the complete report. The three stations at Corralitos, Capitola, and UC Santa Cruz are free-field stations; the fourth station at Watsonville is an instrumented building and ground motion for the first floor is tabulated.

Peak Acceleration Affecting Cliffs

For coastal cliffs nearest the epicenter, the range of peak *horizontal* ground motion was apparently on the order of 0.47 g to 0.64 g, and the range of peak *vertical* ground motion was about 0.40 g to 0.66 g. These data are significant for three reasons: (1) the records indicate consistently high ground-motion between the four CSMIP stations records, so no single record can be considered an anomaly; (2) correlation can be made between regional occurrence of landslides and quantitative strong motion; (3) the recorded peak accelerations offer an opportunity to compare actual peak ground-motion data with seismic coefficients typically used in slope stability analyses by geotechnical engineers.

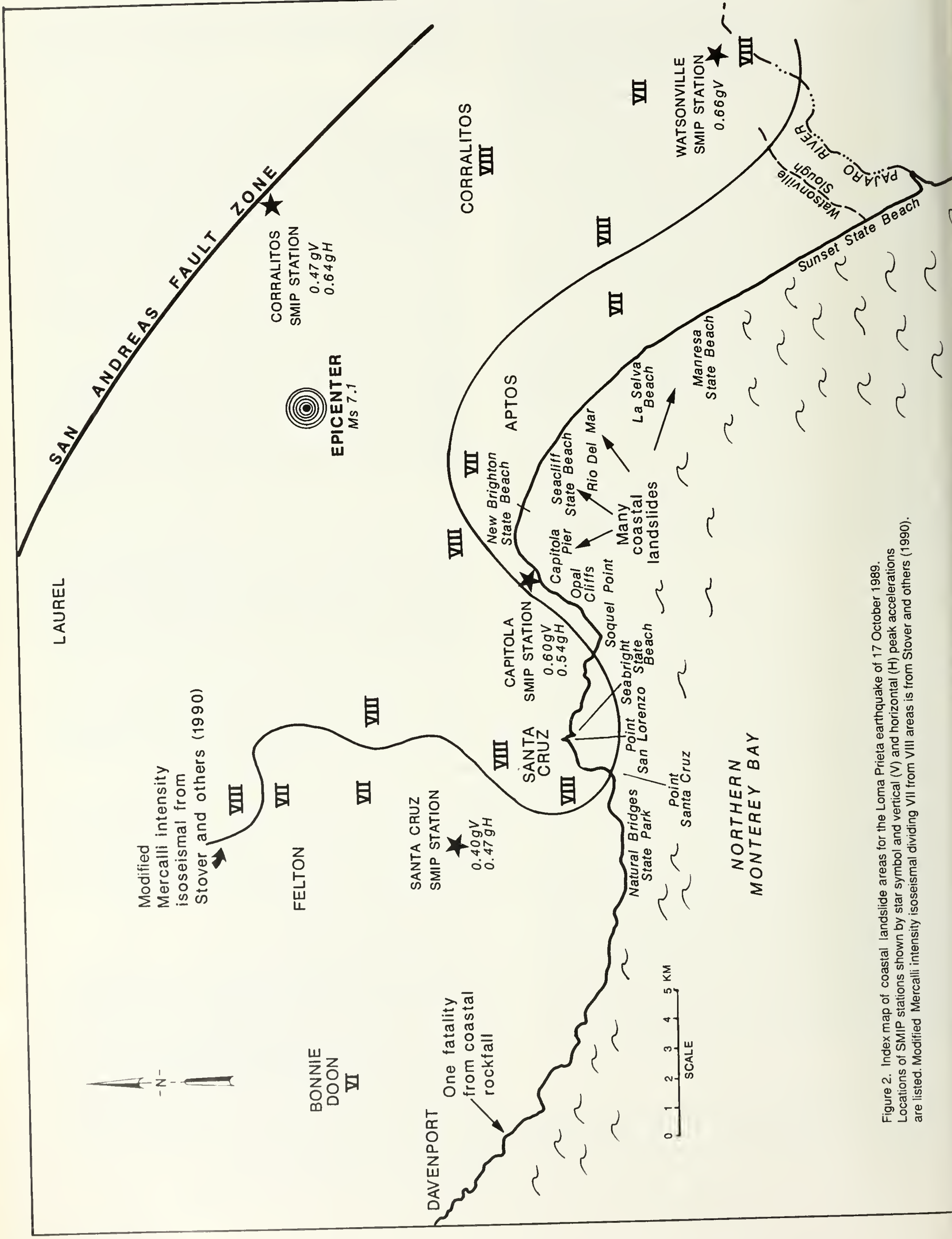


Figure 2. Index map of coastal landslide areas for the Loma Prieta earthquake of 17 October 1989. Locations of SMIP stations shown by star symbol and vertical (V) and horizontal (H) peak accelerations are listed. Modified Mercalli intensity isoseismal dividing VII from VIII areas is from Stover and others (1990).

TABLE 1
Near-Field Strong Motion Affecting the Santa Cruz Coastline
1989 Loma Prieta Earthquake

Location of CSMIP Station	Epicentral Distance	Acceleration (gravity)		Peak Velocity cm/sec	Peak Displacement cm
Corralitos SMIP #57007	7 km	90°	0.50g		
Eureka Canyon Road		Up	0.47g		
(12.4 km inland from		360°	0.64g	55.2	11.5
Seacliff State Beach)					
Capitola SMIP #47125	9 km	90°	0.47g		
County Fire Station		Up	0.60g	36.1	11.0
(only 0.4 km inland		360°	0.54g		
from Capitola Beach)					
Santa Cruz SMIP #58135	16 km	90°	0.44g		
UCSC Lick Observatory		Up	0.40g		
(5.5 km inland from Cowell Beach)		360°	0.47g	21.2	6.8
Watsonville SMIP #47459	18 km	45°	0.28g		
4-story commercial building		Up	0.66g	--	--
(first floor data)		360°	0.39g		
(This is not a free-field site.)					
(6.1 km inland from Sunset State Beach)					

Data from Shakal and others, 1989; and Reichle and others, this volume.

ntensity of Shaking

The highest reported intensity of shaking along the coastline was MMI VIII from Point Santa Cruz to Soquel Point (Figure 2). From Point Santa Cruz northward to Half Moon Bay, the intensity of shaking was MMI VII. From Soquel Point southward to the mouth of the Salinas River the intensity of shaking was also MMI VII. However, most of the intensities reported by Stover and others (1990) were apparently several km inland along the marine terraces; only a few localities are plotted along the coastline. Based on field evidence of ground cracks along the edges of seacliffs, our reconnaissance in the Capitola to Rio Del Mar area indicates that MMI VIII shaking occurred locally.

Seismic intensity is a subjective numerical index describing the severity of an earthquake in terms of effects on the earth's surface and on structures. Seismic intensity depends in a complicated way not only on ground acceleration, but also on wave period, properties of rock and soil subgrade, local geologic structure and topography, epicentral distance, etc. According to the method of Murphy and O'Brien (1977) the peak accelerations recorded at Capitola and UC Santa Cruz could equate with intensity of MMI VII+. The calculated intensity is in cautious agreement with observed intensity along the coastline within 20 km of the epicenter.

Duration of Shaking

The recorded duration of significant shaking (bracketed at ≥0.10g and ≥0.05g) for the Corralitos CSMIP Station was 11 and 16 seconds respectively, for Capitola was 17 and 31 seconds, and for Santa Cruz was 17 and 19 seconds. This is slightly less than, but in general agreement with, duration of shaking formulas given by Bullen and Bolt (1985, p. 444) which yield estimated durations of 14 and 28 seconds, respectively, for a M7.1 event. Landslides are more likely to mobilize at longer durations of significant ground motion, especially >0.10g.

Geotechnical Applications

Future analysis and modeling of the near-field Loma Prieta CSMIP records by seismologists, furthering concepts described by Aki (1988) and Joyner and Boore (1988), may increase our understanding of local geologic effects on seismic shaking. In turn, this will provide better insight into the geotechnical analysis of coastal bluff stability. There are also important earthquake engineering implications for the design of offshore petroleum facilities. Seismically-induced submarine landslides may adversely affect petroleum pipelines and other offshore facilities.

In summary, the coastal bluffs nearest the epicenter experienced MMI VII to VIII shaking. The bracketed duration was about 17 to 23 seconds. Ground accelerations were uniformly high in both vertical and horizontal directions, resulting in landslides on the free faces of coastal cliffs. The recorded peak accelerations offer an opportunity to compare actual peak ground-motion data with seismic coefficients typically used in slope stability analyses by geotechnical engineers. The edges of coastal cliffs and promontories appear to be vulnerable to the effects of strong shaking. This may be due to the lack of lateral support.

COASTAL RESPONSE ACTIVITIES

Rapid reconnaissance of the Santa Cruz coastline was performed during October 18-22, following the main shock on October 17, 1989. The team was organized by the Santa Cruz County Geologist with assistance from the University of California at Santa Cruz, local consulting engineering geologists, the California Division of Mines and Geology (DMG), and the California Coastal Commission. Such reconnaissance will likely occur after future large earthquakes, thus it is important to keep the following events in mind.

Coastal Reconnaissance

The emphasis was to determine which structures (homes, roads, etc.) were in danger from coastal landslides. Bluff-top homes that were deemed to be geologically unsafe to occupy were posted with a formal written notice from the County Building Official. Those cliff areas where the landslide damage was minor or cosmetic were quickly checked and the information given to homeowners. The geologic field effort was concentrated on those coastal landslide areas where it would be effectively used for timely decisions.

Permit Assistance

The County Geologist and County Building Official provided flyers and information booklets to homeowners regarding emergency reconstruction permits (grading and building). Within the coastal zone, the California Coastal Commission issued emergency clean-up permits, with an explanation that homeowners were subsequently obligated to obtain regular permits.

USGS Advisories

Many homeowners affected by coastal landslides were apprehensive about aftershocks during the first week following October 17th. The aftershock probabilities developed by Reasenberg and Jones (1989) of the U.S. Geological Survey (USGS) were helpful. When heavy rainfall was forecast for October 20-21-22, a citizen's advisory message regarding coastal landslides was issued to the news media by William M. Brown III, geologist with the USGS at Menlo Park.

Coastal Video Inventory

A complete inventory of coastal landslides was made on November 1, 1989 by geologists from the University of California, Santa Cruz. A chartered aircraft was used to photograph and videotape the coastline at low altitude between Bolinas and Monterey (Plant and Griggs, 1990). The videotape proved to be an efficient and economical method of acquiring geologic data for a strip map of the coastline. It also provided an important archive for future reference. Individual coastal sites were subsequently mapped at a scale of 1:1,200.

TYPES OF COASTAL LANDSLIDES

Coastal bluff failures resulting from the Loma Prieta earthquake occurred between Marin County and Monterey County in a variety of lithologies and geomorphic environments. Landslides were most prevalent in northern Monterey Bay between Seabright Beach to the north and Sunset State Beach to the south (Figure 2). This coastal segment received seismic shaking of MMI VII to VIII.

Three general types of seismically-induced landslides occurred in the coastal bluffs: rock falls, translational slides, and sand flows (Figures 3, 4, and 5). Sedimentary bedrock cliffs are particularly susceptible to seismically-induced landslides where they are closely jointed, or the bedrock is friable. Terrace deposits are particularly susceptible to slope failure where vertical soil peds are well-developed, or where basal terrace gravels lack a cohesive matrix. Site conditions of bedrock lithology, bedrock cementation, terrace thickness, cliff morphology, bedding plane orientation, groundwater seepage, joint structure and joint spacing, angle of repose of protective talus aprons, and local wave erosion at the base of the cliff are principal natural parameters which control precise occurrence of coastal landslides.

The three kinds of seismically-induced landslides are discussed in order of prevalence with selected examples given in a general north-to-south order. In several localities, complex landslides of more than one type occurred adjacent to one another on the same cliff face (vertically or laterally), so that a clear distinction is not always possible.

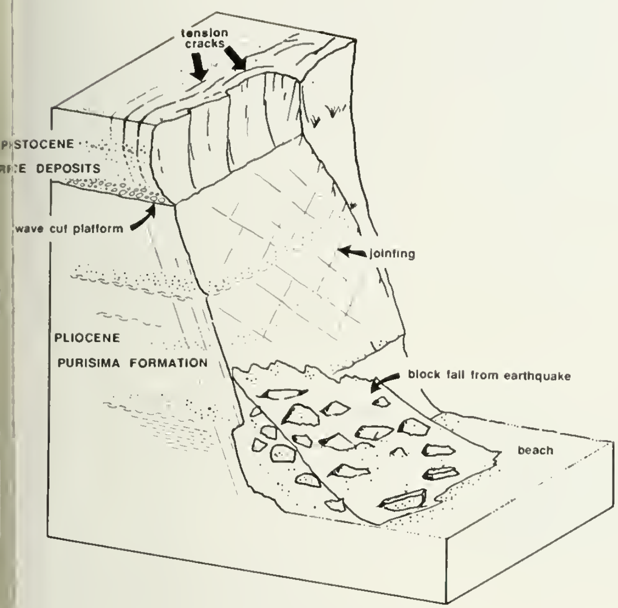
ROCK FALLS

Geologic Setting

As a result of intense seismic shaking from the Loma Prieta earthquake, there were numerous rock falls and block falls along the coastline of northern Monterey Bay. Undercut and weakened bedrock and fractured promontories collapsed along with bluff-top terrace deposits. Failure along joint surfaces allowed large blocks to separate from more intact rock. The size of these failures was dependent on joint spacing and orientation, cliff height, and toe support at the base of the cliff. High cliffs with widely spaced, subvertical joints and inadequate toe support sustained the largest instantaneous and incipient failures in weakened or undercut sedimentary rock (Plant and Griggs, 1990).

Between Seabright Beach at Santa Cruz and New Brighton State Beach near Aptos, seacliffs are cut into a marine terrace that is up to 25 m high. This terrace consists of an uplifted wave-cut bedrock platform that is overlain by about 3 to 7 m of terrace deposits. The base of the coastal cliffs along much of this area is actively being eroded by the surf, and the cliff is in dynamic equilibrium between surf-dominated processes and mass-movement processes. The sea cliff is nearly vertical in bedrock, with ≈45° slopes in the capping marine terrace deposits. In this geomorphic setting the basal cliff in siltstone bedrock retreats rapidly enough so that the slopes in the marine terrace deposits never achieve an equilibrium profile.

The bedrock is the Pliocene Purisima formation, a flat-lying, thickly bedded to massive, tuffaceous mudstone, siltstone, and sandstone (Clark, 1981; Brabb, 1989). Although well-indurated



igure 3. Block diagram showing seacliff structure and typical failure style in eacliffs underlain by well-jointed Pliocene Purisima Formation siltstone. Note ne tension cracks in the Pleistocene terrace deposits and undercut seacliff rom Plant and Griggs, 1990).

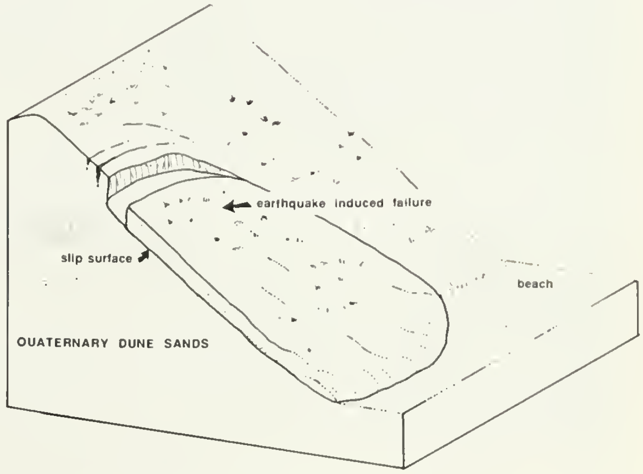
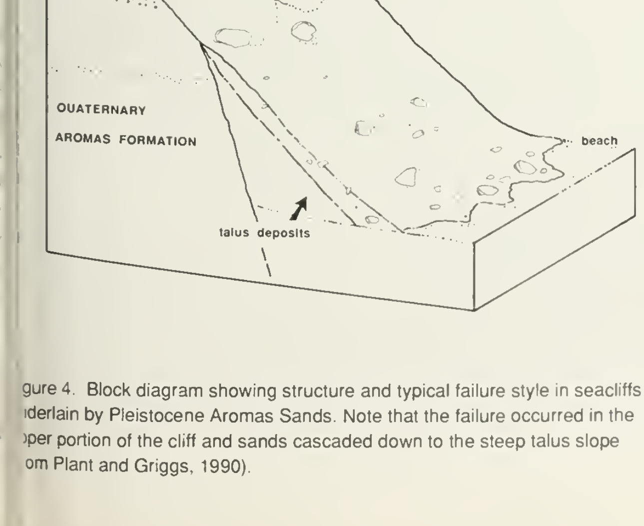


Figure 5. Block diagram of dry sand flow in weakly consolidated dunes. Note the tension cracks in the cohesive surface layer (from Plant and Griggs, 1990).



gure 4. Block diagram showing structure and typical failure style in seacliffs nderlain by Pleistocene Aromas Sands. Note that the failure occurred in the pper portion of the cliff and sands cascaded down to the steep talus slope om Plant and Griggs, 1990).

the Purisima formation is extensively jointed and susceptible to both topples and slumps, and also wedge-failure along intersecting joint surfaces where exposed in steep (60° to 80°) cliff faces (Photo 1).

The unconsolidated terrace deposits typically consist of marine pebble-to-cobble conglomerate overlain by eolian sands, and/or fluvial sands and conglomerates capped by a well-developed A-B soil horizon. Groundwater seepage occurs in the permeable basal terrace gravels along the surface of unconformity above the less permeable Purisima formation. Where the groundwater exits in the cliff face, local failure of the terrace deposits may occur.

The nearly vertical cliffs in this area are actively eroding where they are not protected by revetments, seawalls, or a wide sandy beach. Where unprotected, cliff erosion rates are in the range of 30-60 cm/yr for this exposure of the siltstone facies of the Purisima formation (Griggs and Johnson, 1979).

Talus Cones

From New Brighton State Beach to the vicinity of Aptos Creek, the toe of the seacliff is not actively being eroded by wave action. Development of homes, roads, seawalls, and other structures all protect the toe of the cliff at this time. However, it is of interest to note that substantial talus cones are present along the base of this cliff and the talus cones were present at the time of road construction, etc. The size of the talus cones along this segment of coast (and south to Sunset Beach) suggests the sea cliff is isolated from active wave erosion for years at a time due to the protective beach. The aerial photograph record, however, indicates that periodically the beach is eroded and waves remove the talus which has accumulated.

Photo 1. Joint-controlled wedge failure in the Pliocene Purisima Formation. Marine erosion processes undercut these cliffs, which failed along intersecting joint planes. (Photo by Gary B. Griggs)

The presence of coalescing talus aprons at the base of a late Holocene sea cliff suggests a major change in the interplay of coastal processes during the past several hundred to several thousand years. The low frequency of occurrence of active erosion at the base of the sea cliff could be related to either recent tectonic uplift, or the temporary development of wide beaches along this portion of the sea cliff.

Preliminary studies of marine terrace deformation in the Soquel-Aptos area (Anderson, 1990) suggest that the potential initial abandonment of the sea cliff by active surf zone erosion may be related to coseismic uplift of the coastline associated with Loma Prieta-type earthquake events. Repeated coseismic uplift over time is probably sufficient to raise the base of the cliff above the active surf zone processes, thereby stranding the sea cliff. A similar geologic setting is present south to Sunset Beach; this sea cliff is protected from wave erosion by a talus pile developed at the toe of the late Holocene sea cliff.

Terrace Deposit Failures

The thickness, lithology, and induration of the terrace deposits vary considerably throughout this area (Seabright to New Brighton) and also south to the Sunset Beach area. A soil with a well-developed A and B horizon forms the upper 2 m of terrace deposits. The slight cementation by soil clays and iron oxides of the unconsolidated sands in the B horizon and the development of vertical ped-like soil structures result in the formation of a vertical cliff face. This 2 to 4 m-high vertical slope is closely jointed in a zone 1 to 2 m wide adjacent to the cliff. The vertical joint-like structures that were formed by soil processes resulted in slope failures dominated by earth topples and falls during the Loma Prieta earthquake. Some rotational slumps formed within the upper soil-structure dominated portions of the terrace deposits, but most of the seismically-induced failures appeared to be falls and topples. Numerous areas of extensive ground cracking and scarp formation at the top of the bluff appeared to be the result of incipient topples and falls.

Another mode of failure occurred below the soil horizon in the sandy terrace deposits. Seismic shaking generated sand flows and slab-like failures in these weakly consolidated deposits. Material was either shaken off the upper cliff face or flowed down near angle-of-repose slopes to the top of the vertical cliff in the Purisima where the sand avalanched to the base of the cliff. It appears that much of the material that toppled off the upper cliff face was transported across the near angle-of-repose slopes by flow to the cliff edge.

Fatality from Rock Fall

At Bonny Doon Beach near Davenport (Figure 2), one person was killed during the earthquake by a coastal bluff rockfall which occurred in the intensely jointed Santa Cruz Mudstone.

Photo 2. Coastal landslides at Point San Lorenzo, Seabright State Beach. Block fall at center left and rotational slump at center. Note park bench at top of terrace surface is within the landslide block. New protective fencing with warning signs has been placed farther inland; older fencing dangles precariously. (Photo by Robert H. Sydnor)

Point San Lorenzo

Located just east of the Santa Cruz Boardwalk, Point San Lorenzo s a picturesque 10 m-high vertical headland in Purisima sandstone capped by a 1 m thick soil. It is flanked by a wide sandy beach. This popular state beach is frequented by thousands of tourists each week luring the summer season. Park benches had been set up at the edge of the seacliff. The earthquake caused both block falls and rotational lumps on these cliffs (Photo 2). The park benches and protective ences had to be relocated farther inland after tension cracks were letected landward of the benches. A fence was also constructed long the base of the cliffs with warning signs for persons on the beach. A prudent mitigative measure in a heavily-used park setting vould be to induce failure or otherwise complete the landslide rocess where there are impending rock falls.

oto 3. Coastal cliff failure below the Crest Apartments, Depot Hill, Capitola. Bedrock is the ensely jointed Purisima siltstone. (Photo by Gary B. Griggs, November 1989)

Crest Apartments at Depot Hill

A seismically-induced rockfall occurred at Depot Hill in Capitola, where the 1967-era Crest Apartments were constructed at the edge of the cliff with virtually no set-back. Although a cantilevered grade-beam foundation was used, it proved to be ineffective because of the continued undercutting and the inherent weakness of the jointed siltstone bedrock (Photo 3). Earthquake-induced failure led to partial loss of caisson support, and cracking of the slab and perimeter wall of the apartments. The shoreline protection and engineering efforts which were still in the planning process at the time of the earthquake were reevaluated by the project engineering geologist, geotechnical engineer, and structural engineer. Tension cracks were apparent up to 10 m inland from the cliff edge. Based on the earthquake effects on the site and damage to the structure, six threatened apartment units are being demolished. The Crest Apartments are accessed from above by Cliff Drive. This city road has been permanently closed to through traffic and "dangerous cliff" warning signs have been posted.

Pot Belly Beach

At privately-owned Pot Belly Beach (0.2 km east of New Brighton State Beach), a row of 12 expensive homes was built on the beach at the base of the 20 m-high bluff. A private driveway runs laterally along the base of the near-vertical bluffs. To gain adequate width for the driveway, a 1 to 2 m-high wall was constructed at the base of the bluffs. The wall was constructed using vertically-standing telephone poles. Each pole was embedded less than 0.5 m and neither tied back nor tied together. A dense grove of eucalyptus trees was planted on the face of the bluff. Bedrock consists of a friable sandy facies of the Purisima formation; the slopes are variable, 40° to 60°.

Rockfalls and translational landsliding were induced by the earthquake (Photo 4). Top-heavy eucalyptus trees overturned and fell across the driveway towards the homes. The wall could not resist the overturning moments from the landslide mass and many vertical poles overturned. The driveway was covered with a mass of sand, eucalyptus branches, and telephone poles. Fortunately, there was no structural damage to the homes because the sandstone blocks disaggregated as they fell downslope.

Seacliff State Beach and Las Olas Drive

The longest continuous segment of coastal landsliding occurred at Seacliff State Beach and adjacent Las Olas Drive. Here the Purisima Formation is characterized by a sandstone facies. The cliffs are 30 to 38 m in height. The sandstone is interbedded, pebbly, cross-bedded, moderately indurated, and weakly jointed. The terrace deposits are about 5 m in thickness and consist of poorly consolidated sands and interbedded pebbles, as well as a poorly-sorted fluvial conglomerate. A

Photo 4. Coastal bluff landslide at Pot Belly Beach, 0.2 km east of New Brighton State Beach. Vertical telephone poles were an ineffective retaining wall. (Photo by Robert H. Sydnor)

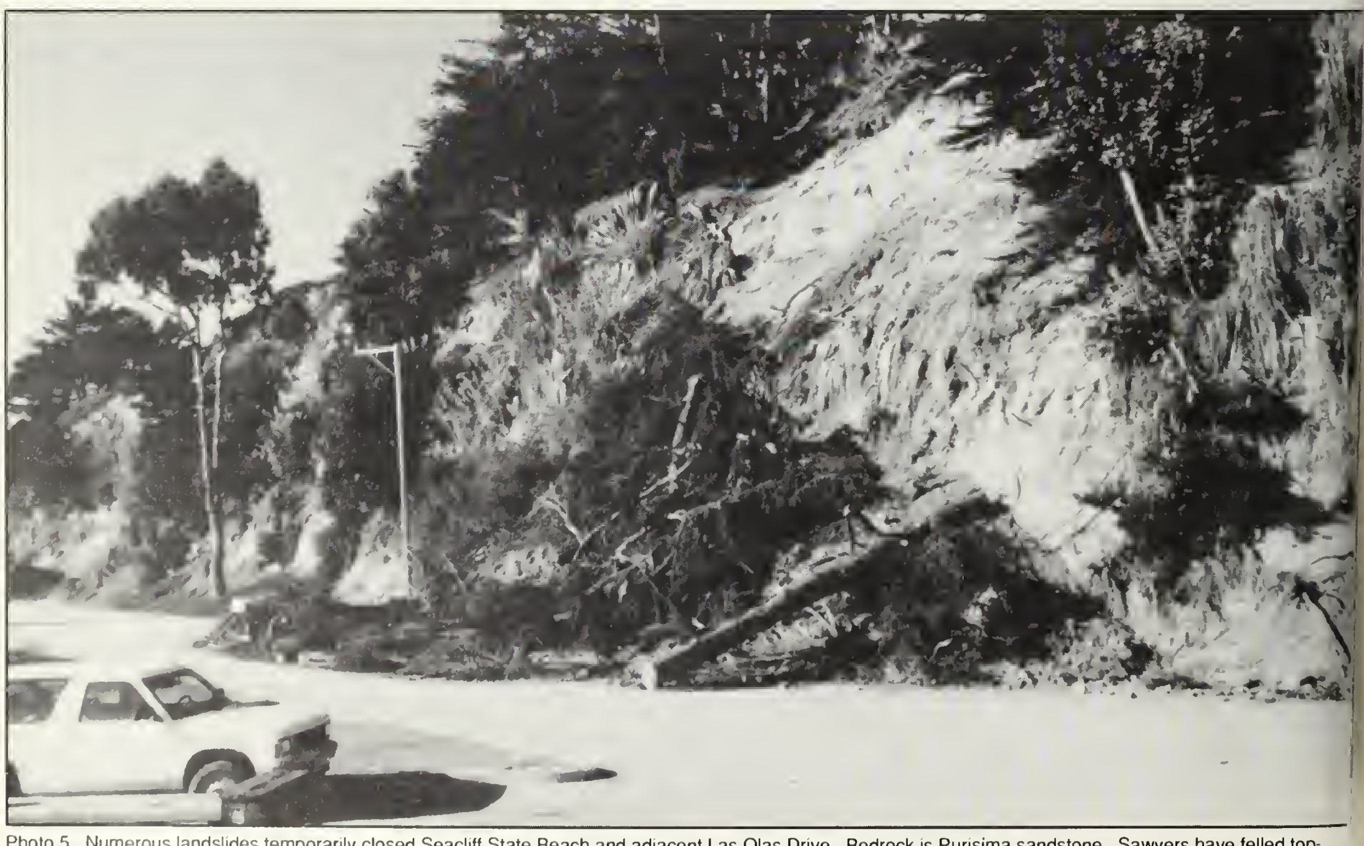


Photo 5. Numerous landslides temporarily closed Seacliff State Beach and adjacent Las Olas Drive. Bedrock is Purisima sandstone. Sawyers have felled top-heavy eucalyptus and cypress trees to make access for crane-supported dragline and track-mounted backhoe. Utility lines were relocated underground during cliff repair. (Photo by Robert H. Sydnor, October 20, 1989)

hin A-B soil horizon is formed on the terrace surface (Plant and riggs, 1990).

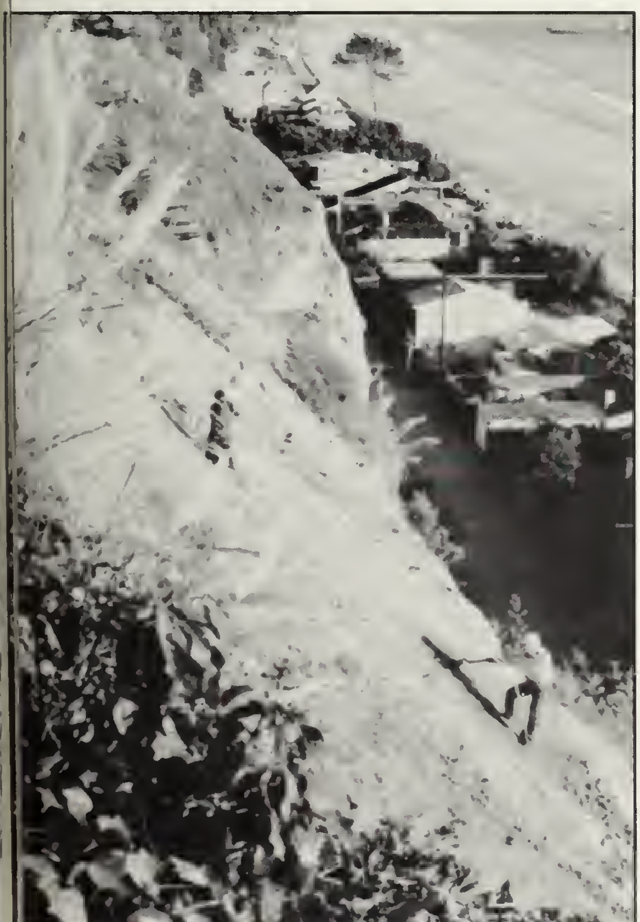
The base of the cliff is protected from marine erosion by a timber eawall and a revetment (Griggs and Savoy, 1985). A new $1.5 illion timber bulkhead at Seacliff State Beach was partly deroyed in the January 1983 storms by wave impact; it cost an dditional $740,000 to rebuild the six-week old structure (Griggs nd Fulton-Bennett, 1987). Despite acute erosional problems, the alifornia Department of Parks and Recreation endeavors to keep e park open and available for large recreational vehicles and ailers. The state park was temporarily closed during repair of ndslides following the 1989 Loma Prieta Earthquake.

Several dozen coalescing landslides occurred along this 1.1 km-ng segment of the coastline (Photo 5). The eastern portion of ndslides was within Seacliff State Park and the western portion cluded 23 private homes along Las Olas Drive. The landslides ere principally blockfalls within the Quaternary terrace deposits d in the underlying Purisima sandstone. Subvertical joints comned with near-horizontal bedding planes caused an orthogonal, ocky mode of failure. Bluff-top homes were threatened by dermining and tension cracks were common adjacent to cliff ests. The beach-level homes lost driveway access, but sustained ly minor damage because most sandstone blocks disaggregated they fell.

In some cases, strong seismic shaking of tall trees evidently transmitted overturning moments to the root structure causing the entire mass (fractured sandstone, roots, and trees) to fail as an intact landslide block. Tall, unpruned, top-heavy trees on steep slopes appear to be susceptible to overturning during strong seismic shaking. Overturning trees also snagged adjacent telephone and electrical power lines, which then overturned the power poles.

Remedial grading and removal of landslide blocks on these steep cliffs proved difficult because of restricted access from either above or below. Access problems were exacerbated by several private gazebos and decks which encroached onto state park land at the brink of the cliff. Most of the remedial grading was performed by a crane-supported dragline. The field work was inspected by an engineering geologist belayed by mountaineering ropes on the cliff face (Photos 6 and 7).

In summary, rock and soil falls were the most prevalent type of slope failure and they caused the most destruction to property. Most failures occurred in the Purisima Formation, especially where the siltstone and sandstone were closely jointed, or where the sandstone lacked a cohesive matrix. The coastal segment closest to the epicenter received the strongest shaking, and rockfalls were therefore more prevalent than farther north.



oto 6. Engineering geologist and worker belayed on cliff above Las Olas e. Bedrock is Purisima sandstone. (Photo by Gerald E. Weber)

Photo 7. Crane-supported dragline and belayed worker remove loose landslide blocks above Las Olas Drive near Seacliff State Beach. No equipment access was available from above. (Photo by Gerald E. Weber)

TRANSLATIONAL LANDSLIDES

Geologic Setting

The second type of seismically-induced failures were larger translational landslides (Figure 4). These were several meters in thickness, up to 30 m wide, and occurred in the upper 10 to 15 m of the cliff face where near-vertical more cohesive cliff tops existed before the earthquake. A 1 to 3 m-vertical scarp cut through the more cohesive material that was undermined by downslope failure of underlying, less cohesive soils. Large intact blocks (1 to 2 m thick) and loose sand from the upper portion of the cliff cascaded down the slope to form an apron of talus. Tension cracks (up to 10 m long) formed several meters landward of the scarps (Plant and Griggs, 1990). Translational landslides occurred principally in the Rio Del Mar area. They were not as widespread as rock falls, but locally caused acute damage.

Sea View Drive Landslide

An example of this type of coastal landslide is the Harts property on Sea View Drive, Rio Del Mar (Photo 8). A steep canyon is obliquely cut into the coastal bluff, forming a narrow promontory with steep relief (≈40°) on three sides. Bedrock is friable sands of the Purisima Formation, capped by about 2 m of cohesive terrace deposits. Intense seismic shaking (estimated MMI VIII) evidently occurred, based on widespread ground cracks on the promontory. These cracks did not occur elsewhere on the terrace surface, but were confined to the promontory. After the earthquake the severely damaged house was dismantled and the slope reduced to a lower elevation and slope. A row of homes is situated at the base of the sea cliffs and was impacted by the slope failure during the earthquake. To protect these homes from further inundation by the slide mass, sandy debris was removed from the seaward cliff face and placed as engineered fill in the steep side canyon. This remedial grading increased future stability of the remaining property.

Backward-rotated intact blocks were found in the upper portion of the Sea View Drive landslide, indicating loss of support from below. It appears that a shallow translational landslide first occurred in mid-slope, followed by a progression of failure upslope towards the more cohesive terrace deposits. These more cohesive blocks then failed along vertical ped-like joints and rotated backward as they slid downslope. This steep three-sided promontory was evidently very vulnerable to intense ground shaking.

Photo 8. Remedial grading at the Sea View Drive landslide in Rio Del Mar. Loose friable sands are being removed and the slope angle reduced. The former residence was located directly upslope from where the bulldozer is working; only the separate guest house remains. (Photo by Robert H. Sydnor, May 2, 1990)

Photo 9. Very large dry sand flow above Place de Mer development in Rio Del Mar. Houses at the top and base of this failure were at risk (Airphoto by Gary B. Griggs, November 1, 1989).

SAND FLOWS

Geologic Setting

South from Rio Del Mar to La Selva Beach and Manresa State Beach, the coastal bluffs consist of the Pleistocene Aromas Sand, a friable, semi-consolidated formation consisting of eolian and fluvial sands (Brabb, 1989; Dupré, 1975; Dupré and Tinsley, 1980; Alexander, 1953). The coastal bluffs are about 25 to 40 m high. The bluff faces are unusually steep (30°- 40°) for a friable sandy unit. The reason is that the bluffs are normally protected from wave erosion by a wide beach. Sand flows occurred on these steep Pleistocene dune faces (Figure 5) and were limited in geographic distribution to the coast between Rio Del Mar and Sunset Beach.

Place de Mer

An example of sand flow occurred above the Place de Mer condominium development in La Selva Beach. Refer to Photo 9. This sand-flow was 2 to 3 m thick and about 100 m wide. The flow detached from the upper 10 to 15 m of the cliff, just below the near-vertical cliff in the terrace sands. Hundreds of old automobile tires had been stacked on the lower half of this sandy slope for slope protection. These tires proved to be ineffective for either surficial erosion control or as a retaining device for landsliding.

At the headscarp area vertical tension cracks developed in the more cohesive terrace deposits. With loss of support from below, large blocks (1-2 m^3) of terrace soil toppled and rolled downslope, some crossing Oceanview Avenue and nearly reaching the row of condominiums built at the base of the cliff.

A home on the crest of the hill above the condominiums was undermined by the landsliding. Its wooden deck and caisson support were left overhanging by loss of support from below (Photo 10). This home had to be razed. The hilltop building pad was then lowered in elevation by grading and the seaward-facing slope was reduced to a safer angle.

Pleistocene Dunes

At Sunset State Beach in the southern-most portion of Santa Cruz County, the coastal bluffs consist of weakly consolidated Pleistocene dunes of Wisconsin age (Dupré, 1975). The bluffs are about 40-55 m high and the seaward dune face has a slope of about 35°. These bluffs have been partly stabilized by vegetation. Homes have been built on the edge of this ancient dune complex. Slope failure in this area occurred when shallow slabs of sand up to 1 m thick were detached and translated short distances downslope. One home is scheduled to be relocated due to this type of dry sand flow (Plant and Griggs, 1990).

Photo 10. Coastal landslide in unconsolidated sands of the Aromas formation, above Place de Mer development (Photo by Robert H. Sydnor, October 20, 1989).

Sand flow or failure in Pleistocene dunes should be an anticipated event during a strong earthquake. Sand lends itself readily to geotechnical analysis and application of geotextiles for remedial repair. Fortunately, the sand dunes are limited in geographic distribution and much of the coast is already protected within the state park system.

SUMMARY

Coastal landslides due to seismic shaking were most abundant within 9-20 km of the 17 October 1989 epicenter where MMI VII to VIII shaking occurred. Episodic earthquakes are part of one dynamic geomorphic process which shapes the coastline, along with wave erosion and storms. New strong-motion records provide an opportunity for quantitative analysis of coastal landsliding. The bracketed duration of significant shaking was on the order of 17 to 23 seconds. Had the duration of shaking continued as long as typically expected, then coastal landsliding might have been even more widespread. Ground cracking at the crest of coastal bluffs and promontories indicates that these areas are vulnerable to the effects of strong shaking. Prevailing drought conditions apparently minimized the severity and extent of coastal landsliding.

Three types of seismically-induced landslides occurred: rock falls, translational landslides, and sand flows. Geologic units most affected were the Purisima Formation, the Aromas Sand, and Pleistocene terrace deposits and sand dunes. The mode of failure depended on several factors, including thickness of overlying terrace deposits, joint spacing, joint orientation, relative cohesiveness of the unit, and cliff morphology. One fatality and several million dollars in damage resulted from coastal landslides, which primarily affected private residences and state parks. Many tall trees overturned from intense seismic shaking.

Given the 7.1 magnitude of the Loma Prieta earthquake and the proximity of the epicenter, coastal landsliding was not as serious as it might have been; the difference is attributed to lack of antecedent rainfall and a short duration of shaking.

INSIGHTS GAINED FOR LAND-USE PLANNING

The 1989 Loma Prieta Earthquake was a learning experience for the geologic community (government, academia, consulting, and regulatory). Landslides on coastal bluffs provide new insights into the larger picture of land-use planning and environmental geology.

1. Governments should both anticipate and plan for seismically-induced landslides along the coastline. They are natural events. Geomorphic agents of earthquakes, marine wave action, and rainstorms, all affect the occurrence of coastal landslides.

2. Encroachment of manmade structures (homes, roads, utilities, etc.) into the coastal zone requires a complete geologic investigation. A full understanding of coastal processes, marine erosion, regional seismicity, and Quaternary geomorphology is necessary.

3. Wise land-use planning decisions along the California coastline are best addressed by the Geohazards Element of a Local Coastal Program (LCP) which incorporates detailed geologic information into the planning process. The California Coastal Commission reviews and approves the LCP for adequacy. Most of the permitting process is then released to local government agencies. The Geohazards Element of most LCPs needs systematic update to include 1989 Loma Prieta earthquake ground-motion information and consideration of seismically-induced coastal landslides.

4. Systematic geologic mapping is needed at a detailed scale for those coastal cliff areas where development is anticipated. The map scale should be sufficiently large (such as 1:1,200 or larger) so that landslide data can be plotted. Prudent site-specific planning decisions can then be made along the coastline.

5. Depending upon the relative exposure to coastal landslides, local building officials may wish to encourage homeowners with unsafe conditions to remedy geologic hazards by corrective grading and/or structural repairs. The building official also has the power under Section 203 of the Uniform Building Code to convene hearings for hazard abatement.

6. Older flight lines of low-level stereoscopic aerial photographs are available for much of the California coastline. They are a valuable research tool for semi-quantitatively estimating erosion rates and locating areas of previous landsliding activity. Several aerial photograph libraries which have imagery of coastal landslides are listed in the Appendix.

7. Efficient reconnaissance of coastal bluffs can be performed shortly after an earthquake by use of a hand-held video camera from a low-flying aircraft. Aerial oblique photographs are also very useful.

8. Trees which are both tall and top-heavy, such as eucalyptus and cypress, apparently do not perform well on coastal bluffs during earthquakes. Native shrubs and native dwarf trees appear to be optimum for four reasons: (1) good root strength for erosion control, (2) adequate natural growth without need for artificial watering, (3) lower susceptibility to intense seismic shaking and overturning, (4) minimal snagging hazard to adjacent aerial utility lines along coastal cliffs.

ACKNOWLEDGMENTS

We appreciate drafting of several figures by Joy Sullivan and Frances Rubish, and the layout by Ross Martin. Thanks are also due to Jeffrey K. Howard, Stephen R. McNutt, John P. Schlosser, and Timothy P. McCrink for critical review. William R. Cotton, Patrick O. Shires, and Mark G. Smelser kindly provided information about the Sea View Drive landslide in Rio Del Mar.

APPENDIX

Special Aerial Photograph Libraries of the California Coastline

Fairchild Airphoto Library
Geology Department
Whittier College, Whittier, California 90608
telephone (213) 693-0771, ext. 419
1,222 separate flights, beginning in 1928.

Airphoto Library
U.S. Geological Survey, Mail Stop 955, Building 5
345 Middlefield Road, Menlo Park, California 94025
telephone (415) 329-5009

California Coastal Commission
631 Howard Street,
San Francisco, California 94105
telephone (415) 543-8555
Imagery begins in the early 1970s, with new coastal flights every four years.

The libraries of several campuses of the University of California (particularly Santa Cruz, Santa Barbara, Los Angeles, and San Diego) also contain special libraries of older stereoscopic aerial photographs taken along the California coastline. Many private photogrammetry firms also have an inventory of older aerial photographs.

REFERENCES

Aki, K., 1988, Local site effects on strong ground motion: American Society of Civil Engineers, Geotechnical Division, Proceedings of Earthquake Engineering & Soil Dynamics II, Park City, Utah ASCE Conference, p. 103-155.

Alexander, C.S., 1953, The marine and stream terraces of the Capitola - Watsonville area: University of California Publications in Geography, v. 10, p. 1-44.

Anderson, R.S., 1990, Evolution of the Santa Cruz Mountains by advection of crust past a restraining bend on the San Andreas fault: a conceptual model stimulated by the Loma Prieta Earthquake: EOS, Transactions of the American Geophysical Union, v. 71, no. 8, p. 287 (abstract).

Atwater, B., 1978, Land-use controls arising from erosion of seacliffs, landsliding, and fault movement - central San Mateo County, California, *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. 11-19.

Brabb, E.E., 1989, Geologic map of Santa Cruz County, California: U.S. Geological Survey Miscellaneous Investigations Series Map I-1905, scale 1:62,500.

Bradley, W.C., 1957, Origin of marine-terrace deposits in the Santa Cruz area, California: Geological Society of America Bulletin, v. 68, p. 421-444.

Bradley, W.C., and Griggs, G.B., 1976, Form, genesis, and deformation of central California wave-cut platforms: Geological Society of America Bulletin, v. 87, p. 433-449.

Bullen, K.E., and Bolt, B.A., 1985, An introduction to the theory of seismology (4th edition): New York, Cambridge University Press, 499 p.

Clark, J.C., 1981, Stratigraphy, paleontology, and geology of the central Santa Cruz Mountains, California Coast Ranges: U.S. Geological Survey Professional Paper 1168, 51 p.

Cleveland, G.B., 1975, Landsliding in marine terrace terrain, California: Calif. Division of Mines and Geology, Special Report 119, 24 p.

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.

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.

Griggs, G.B., 1973, Earthquake activity between Monterey and Half Moon Bay, California: California Geology, v. 26, no. 5, p. 103-110.

Griggs, G.B., 1982, Flooding and slope failure during the January 1982 storm, Santa cruz County, California: California Geology, v. 35, no. 7, p. 158-163.

Griggs, G.B., 1986, Relocation or reconstruction - viable approaches for structures in areas of high coastal erosion: Shore and Beach, v. 54, p. 8-16.

Griggs, G.B., and Fulton-Bennett, K.W., 1987, Failure of coastal protection at Seacliff State Beach, Santa Cruz County, California: Environmental Management, v. 11, p. 175-182.

Griggs, G.B., and Fulton-Bennett, K.W., 1987, Rip-rap revetments and seawalls and their effectiveness along the central coast of California: Shore and Beach, v. 56, p. 3-11.

Griggs, G.B., and Johnson, R.E., 1979, Coastline erosion: Santa Cruz County, California: California Geology, v. 32, no. 4, p. 67-76.

Griggs, G.B., and Savoy, L.E., 1985, Living with the California coast: Duke University Press, Durham, N.C., 393 p.

Habel, J.S., and Armstrong, G.A., 1977, Assessment and atlas of shoreline erosion along the California coast: California Department of Boating and Waterways, 277 p., map scale 1:50,000.

Joyner, W.B., and Boore, D.B., 1988, Measurement, characterization, and prediction of strong ground motion: American Society of Civil Engineers, Geotechnical Division, Proceedings of Earthquake Engineering and Soil Dynamics II, Park City, Utah ASCE conference, p. 43-102.

Kuhn, G.C., and Shepard, F.P., 1984, Sea cliffs, beaches, and coastal valleys of San Diego County: University of California Press, 193 p.

Murphy, J. R. and O'Brien, L. J., 1977, The correlation of peak ground acceleration amplitude with seismic intensity and other physical parameters: Bulletin of the Seismological Society of America, v. 67, no. 3, p. 877-915.

Plafker, G., and Galloway, J.P., eds., 1989, Lessons learned from the Loma Prieta, California, earthquake of October 17, 1989: U.S. Geological Survey Circular 1045, 48 p.

Plant, N., and Griggs, G.B., 1990, Coastal landslides caused by the October 17, 1989, Santa Cruz County, California: California Geology, v. 43, no. 4, p. 75-84.

Reasenberg, P.A., and Jones, L.M., 1989, Earthquake hazard after a mainshock in California: Science, v. 243, March 3, 1989, p. 1173-1176. Also see Comment: Rydelek, P.A., 1990, California aftershock model uncertainties: Science, v. 247, 19 January 1990, p. 343; and Response: Reasenberg, P.A., and Matthews, M.V., ibid, p. 343-345; and Reasenberg, P.A., and Jones, L.M., 1990, California aftershock hazard forecasts: ibid, p. 345-346.

Reichle, M.S., Darragh, R.B., Huang, M-J., Cao, T., Shakal, A.F., and Vetter, U. R., 1990, Preliminary analysis of processed strong-motion data from the Loma Prieta earthquake: this volume, p. 47-57.

Shakal, A.F., Huang, M-J., Reichle, M.S., Ventura, C., Cao, T., Sherburne, R.W., Savage, M., Darragh, R.B., and Petersen, C., 1989, CSMIP strong-motion records from the Santa Cruz Mountains (Loma Prieta), California earthquake of 17 October 1989: California Division of Mines and Geology, Report No. OSMS 89-06, 196 p.

Spittler, T.E., and Sydnor, R.H., 1990, Landslides and ridge-top failures associated with the epicentral area of the Loma Prieta earthquake of October 17, 1989: EOS, Transactions of the American Geophysical Union, v. 71, no. 8, p. 290 (abstract).

Spittler, T.E., Sydnor, R.H., Manson, M.W., Levine, P., and McKittrick, M.A., 1990, Large-scale mapping of landslides in the epicentral area of the Loma Prieta earthquake of October 17, 1989, Santa Cruz County, California: EOS, Transactions of the American Geophysical Union, v. 71, no. 8, p. 290, (abstract).

Stover, C.W., Reagor, B.G., Baldwin, F.W., and Brewer, L.R., 1990, Preliminary isoseismal map for the Santa Cruz (Loma Prieta), California earthquake of October 18, 1989 (UTC): U.S. Geological Survey Open-File Report 90-18, 24 p.

U.S. Geological Survey Staff, 1990, The Loma Prieta, California, Earthquake: an anticipated event: Science, v. 247, p. 286-293.

Weber, G.E, Lajoie, K.R., and Griggs, G.B., 1979, Coastal tectonics and coastal hazards in Santa Cruz and San Mateo counties, California: field trip guide: Geological Society of America, Cordilleran Section, 75th annual meeting, 1979, Guidebook No. 8, 187 p., 3 plates.

Weber, G.E., and Griggs, G.B., 1990, Coastal geologic hazards and coastal tectonics: Northern Monterey Bay and Santa Cruz/San Mateo County coastline: Association of Engineering Geologists, San Francisco Section, field trip guidebook, March 3, 1990, 156 p.

THE SEARCH FOR FAULT RUPTURE AND SIGNIFICANCE OF RIDGETOP FISSURES, SANTA CRUZ MOUNTAINS, CALIFORNIA

by

Earl W. Hart[1], William A. Bryant[1], Christopher J. Wills[1], and Jerome A. Treiman[1]

ABSTRACT

Investigations following the 1989 Loma Prieta earthquake revealed no convincing evidence that primary surface faulting occurred on the San Andreas or other faults in the epicentral area. However, triggered slip did occur on the Calaveras fault in Hollister. In contrast, extensive fault-like fissures developed on several ridges near and southwest of the San Andreas fault.

Some of these fissures, many of which are large, follow pre-existing scarps and depressions, indicating previous displacements. These features are clearly hazardous and avoidable, similar to active faults. Other fissures, however, do not correspond with specific geomorphic features and to some extent are distributive. The latter constitute a less predictable hazard that needs to be addressed, possibly by the use of specially reinforced foundations or other means. This is a dilemma for zoning provisions of local government.

The fissures also are a dilemma for implementation of the Alquist-Priolo Special Studies Zones Act, which is intended to mitigate the hazard of surface faulting by means of avoidance. Our concern relates to the facts that the fissures (1) are largely caused by shaking and are more likely to be related to landsliding than faulting, and (2) are partly distributive and therefore difficult to avoid.

INTRODUCTION

Immediately after the 17 October 1989 earthquake the entire staff ıf the Fault Evaluation and Zoning Project was dispatched to search 'or fault rupture. The purposes of our response were to: (1) map any urface faulting, and (2) evaluate the accuracy and effectiveness of xisting Special Studies Zones (SSZs) established under the Alquist-'riolo Special Studies Zones (APSSZ) Act.

Our response plan was to first determine the distribution and nature ıf surface faulting and then map the ruptures in greater detail. After hree days of field work, it was evident that significant primary surface upture did not occur in the epicentral area along the San Andreas fault ır on adjacent parts of the Sargent and Zayante faults. However, ıinor coseismic slip was triggered on the Calaveras fault in and north ıf Hollister and possibly on the San Andreas fault in and south of San uan Bautista.

More impressive were the many large fissures that developed on idgetops and damaged a number of buildings and other structures. ılthough many of the fissures were within existing Special Studies :ones, it was decided that detailed fissure mapping would be left to thers — including the U. S. Geological Survey, Santa Cruz County :ooperative mapping with DMG), and various consulting geologists — to avoid duplicated mapping field work. Much of that preliminary work is now available and it is apparent that some geologists consider the fissures to be secondary faults probably related to tectonic uplift of the ridge (e.g., Wells and others, 1989; Plafker and Galloway, 1989; USGS, 1990; Cotton and others, this volume). Other geologists (e.g., Baumann and others, 1990; Hempen, 1990; this paper) believe that the fissures are largely due to intense shaking effects. The question of origin may be difficult to prove, but there is no doubt that some of the fissures are fault-like, having significant vertical and/or lateral components of slip. As such, they are a threat to buildings and other structures. Because some of these fissures are fault-like in character and tend to occur along known geomorphic features (linear scarps and depressions) near active faults these features are problematic in terms of their identification and cause.

Under California law, the State Geologist is required to establish Special Studies Zones around active faults in order to mitigate the hazard of surface faulting to structures for human occupancy (Hart, 1988). Cities and counties must regulate most projects within the SSZs by requiring geologic site-investigations prior to issuing development permits. Structures for human occupancy must not be constructed over an active fault trace.

[1]California Department of Conservation, Division of Mines and Geology, Geologic Hazards Assessment Program

FAULT RUPTURE INVESTIGATION

Two teams of DMG geologists from the Fault Evaluation and Zoning Project were sent into the epicentral area early the following morning (within 15 hours) after the main shock of the Loma Prieta earthquake. Efforts during several days of field investigations (October 18-20 and 27) were concentrated along previously mapped and zoned traces of the San Andreas fault between Alma College (locality D, Figure 1) and the Cienega Winery (locality H, Figure 1). Selected traces of the Calaveras, Sargent, and Zayante faults were also checked. Only sparse and equivocal evidence of surface fault rupture was observed along the San Andreas fault. Based on the worldwide data base of Bonilla and others (1984), primary surface rupture with at least 1 m of displacement would be expected for a M_S7.1 earthquake. Triggered slip occurred along the Calaveras fault and possibly along strands of the San Andreas fault in and south of San Juan Bautista (localities G - J, Figure 1). No evidence of surface fault rupture was observed along traces of the southern Sargent and Zayante faults that had been zoned by the State Geologist (Figure 1).

Equivocal evidence of surface fault rupture along the San Andreas fault was found at Mt. Madonna Road, which was right-laterally offset 2.7 cm (locality D, Figure 1). These cracks were followed northwest into colluvium exposed in a roadcut that also was right-laterally offset. Although extensional cracks were traced discontinuously for about 1 km northwest of Mt. Madonna Road along a northeast-facing scarp, evidence of systematic right-lateral offset was not observed.

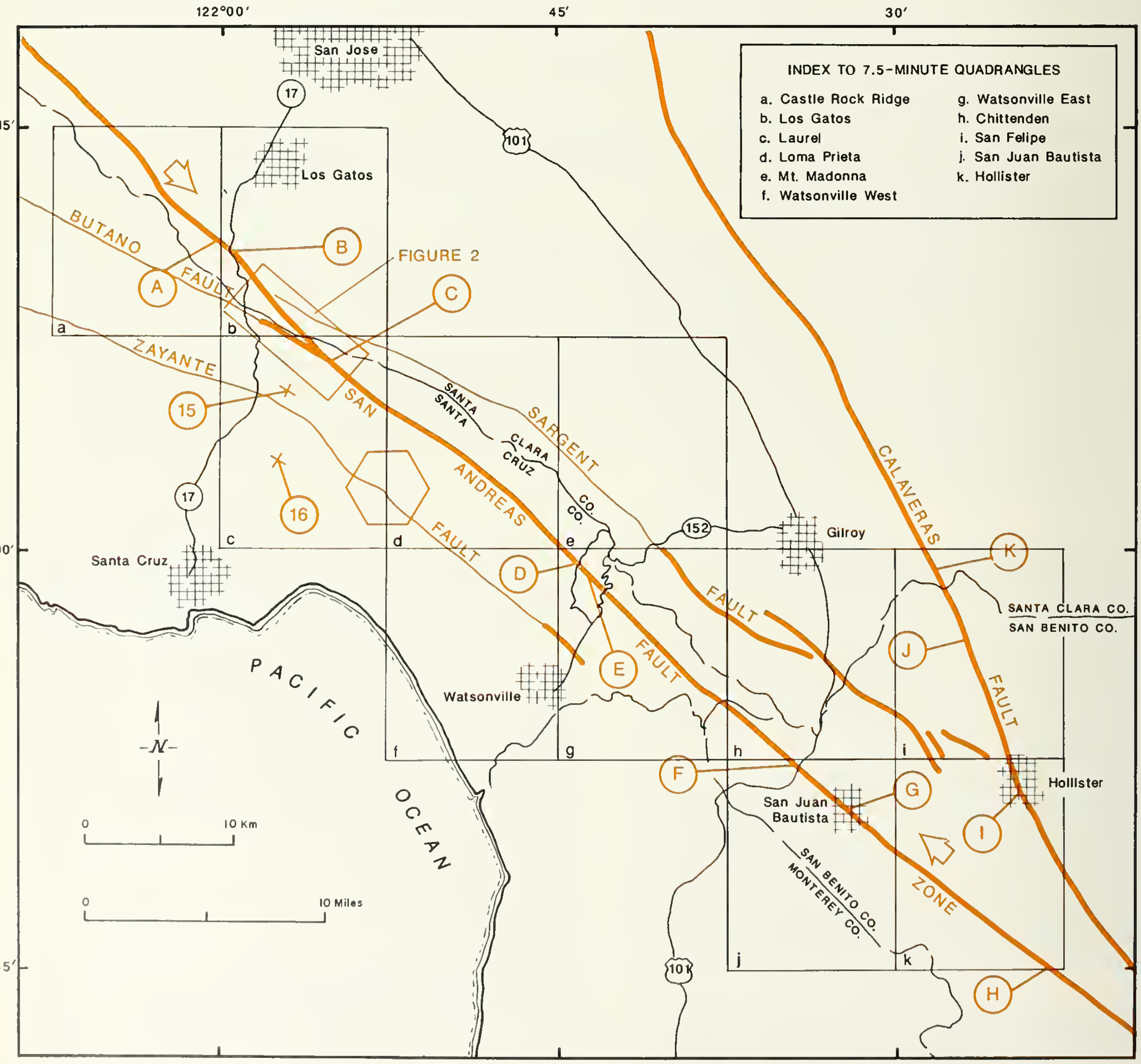


Figure 1. Location of the San Andreas and related faults in the epicentral area of the M_S7.1 Loma Prieta earthquake. Quadrangle boundaries indicate areas of Special Studies Zones Maps that were checked for evidence of surface fault rupture after the earthquake. Heavy lines indicate faults previously zoned for Special Studies under the Alquist-Priolo Special Studies Zones Act of 1972; light lines indicate faults not zoned. Location of the M_S7.1 epicenter is shown by the hexagon; arrows indicate the approximate extent of the mainshock subsurface rupture zone. Letters A-K indicate specific localities referred to in text; localities 15 and 16 are described in Table 1.

It is not certain if the observed right-lateral offset at Mt. Madonna Road is meaningful because shaking and downslope movement may have produced the observed right-lateral offset. It is also not clear f any afterslip occurred at this site. Measurements of displacement rom a USGS quadrilateral array installed two days after the earth-uake are no larger than the resolution of the survey methods (J.D. ims, personal communication, February 28, 1990).

Evidence of surface fault rupture along the San Andreas fault to he northwest and southeast of locality D (Figure 1) is even more un-ertain and equivocal. For example, 13 to 14 cm of right-lateral ffset and compression occurred in the northbound lanes of High-ay 17 (locality B, Figure 1), but the rupture did not continue north-estward across the southbound lanes. As the road at this locality largely on fill, the ruptures are believed to be due to shaking. ompressional fractures also occurred in pavement of San Jose oad along the San Andreas fault (locality C, Figure 1), but these ccur over a road fill prism and are considered to be caused by haking. About 5 cm of right-slip was observed along a 15- to 20-n-wide fissure at locality E (Figure 1). Because this locality is 300 northeast of the mapped trace of the San Andreas fault (Bryant and hers, 1981) and because it occurs on a naturally benched slope, we elieve this feature is a reactivation of a landslide. Several other acture zones along the San Andreas fault revealed minor right-teral extension, but all are considered most likely to be due to aking effects. However, minor discontinuous faulting could sily be obscured by the numerous shaking cracks and fissures.

In contrast to the surprising absence of primary surface faulting on e San Andreas fault, triggered slip occurred as expected along the eeping segment of the Calaveras fault in the Hollister area. Left-epping, *en echelon* cracks were observed in an unpaved baseball amond just south of 7th Street in Hollister (locality I, Figure 1). ght-lateral offset along this N5°W-trending zone of cracks was out 4 mm. Because this observation was made less than 24 hours ter the earthquake, these cracks apparently formed coseismically.

Additional evidence of triggered slip along the Calaveras fault cludes a minor fracture in soil and a freshly cracked concrete curb 5th Street in Hollister (locality 1, Figure 1) and fresh hairline acks in Shore Road (locality J, Figure 1). About 5 mm of triggered p was recorded by a creepmeter at Shore Road (McClellan and ay, 1989). Triggered slip also was observed at Shore Road after 1984 M6.2 Morgan Hill earthquake and the 1979 Coyote Lake rthquake (Schultz, 1984). About 5 mm of right-lateral offset was served by McClellan and Hay (1989) 90 hours after the earth-ake at Highway 152 north of San Felipe Lake (locality K, Figure Hairline cracks suggestive of triggered slip also formed along ep-active traces of the San Andreas fault near San Juan Bautista d south of Hollister (localities F-H, Figure 1).

The lack of primary surface rupture on the San Andreas fault ring the Loma Prieta earthquake is not fully understood. Prior rldwide earthquake data provide an expectation that a M_S7.1 thquake would be associated with 1 to 2 m of right-lateral placement (Bonilla and others, 1984). The 18 km focal depth, the SW dip of the fault, and the reverse oblique sense of displacement 6 m right-lateral; 1.2 m vertical, southwest side up; Lisowski and ers, 1990) are unusual for the San Andreas fault and may have ntributed to the lack of surface fault rupture. It is also significant t the aftershock distribution did not extend to the surface (Plafker l Galloway, 1989).

The lack of discrete surface fault rupture along the San Andreas fault in the area may not be unique. No through-going surface fault rupture in this area was reported after the 1906 earthquake (E.P. Carey, *in* Lawson, 1908), although detailed geologic surface mapping was not undertaken. Approximately 1.4 m of right slip occurred in the old South Pacific Coast Railroad Company tunnel near Wrights Station in 1906 (Figure 2), but this displacement apparently did not extend to the surface.

Geomorphic expression of the San Andreas fault in the Los Gatos, Laurel, and northwestern Loma Prieta quadrangles, as viewed on stereoscopic aerial photographs (National Archives, 1939; USGS, 1966), is only weakly developed and largely concealed by massive landslides and heavy vegetation. Sarna-Wojcicki and others (1975) have portrayed the fault zone in this area as a wide zone (up to 2 km) of discontinuous traces that are partly obscured by landslides. They also show the fault zone as having a more westerly trend than adjacent segments of the San Andreas fault zone. It is not clear if the lack of a well-defined surface trace is due to distributive deformation along this compressional bend or to the obscuring effects of massive landsliding.

RIDGETOP FISSURES

A large number of fault-like fissures and associated fractures developed in the epicentral region during the Loma Prieta earthquake. Most of the fissures occurred along the ridge of Summit Road and on Skyland Ridge to the southeast (Figure 2). Similar fissures were noted on ridgetops to the southwest at localities 15 and 16 (Figure 1). These fissures are notable because of their size and continuity, association with existing linear depressions and scarps, and almost exclusive location on the uplifted southwestern block of the San Andreas fault. Some geologists believe these extensional features are tectonic (Cotton and others, this volume; Plafker and Galloway, 1989; Wells and others, 1989; USGS, 1990) but recognize that lateral spreading of ridges due to shaking may have enhanced them. In contrast, we believe that intense shaking is the dominant factor in forming the fissures. (Refer to Shakal and others, this volume, who document a significant 0.50 g to 0.60 g horizontal and vertical peak acceleration in the near-field.) Regardless of origin, it is clear that the larger fissures and fractures are hazardous to buildings and other structures.

By far the largest concentration of fissures occurs in the Summit Road-Skyland Ridge area (Figure 2). This area was mapped in detail by the USGS (Wells and others, 1989) to identify those fissures[1] and associated fractures thought to be tectonic in origin (i.e., regional uplift). The identification of tectonic fractures by the USGS apparently was based on linearity, continuity along trend, relatively large vertical or lateral displacements, and general coincidence with linear topographic features (USGS, 1990). Although extensional displacement was dominant, vertical and left-lateral components of slip suggested flexural-slip (i.e. secondary) faulting. Many additional fissures were mapped in the Summit Road-Skyland Ridge area without regard to origin by DMG in cooperation with Santa Cruz County, the USGS, and various consulting geologists (Spittler and Harp, 1990). Most of these features appear to us to be landslide related, but selected linear traces that are parallel to the traces of Wells and others (1989) are shown on Figure 2.

[1]The USGS has used the term "fractures" and "cracks" to identify the large extensional features discussed here as fissures. We prefer the term "fissure" which identifies the dominantly extensional character of these fracture zones.

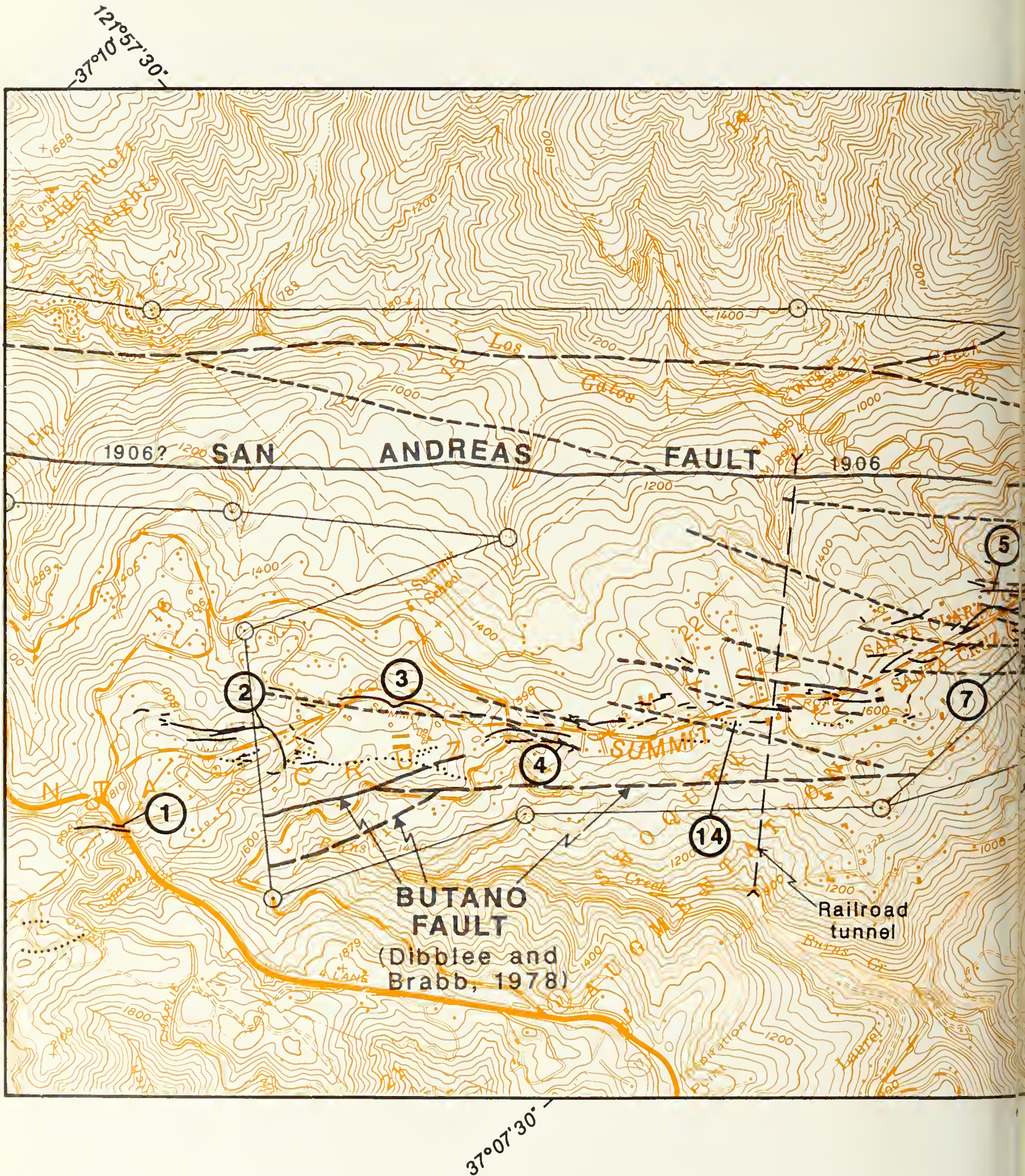


Figure 2. Preliminary map showing the distribution of fissures developed during the 17 October 1989 earthquake. Fissures shown by heavy solid lines are generalized in Wells and others (1989). Selected linear fissures from Spittler and Harp (1990) are shown by dotted line. Base map shows fault traces and Special Studies Zones established under the Alquist-Priolo Act (California Division of Mines and Geology, 1976). Numbers identify localities discussed in Table 1 (overleaf) and in the text.

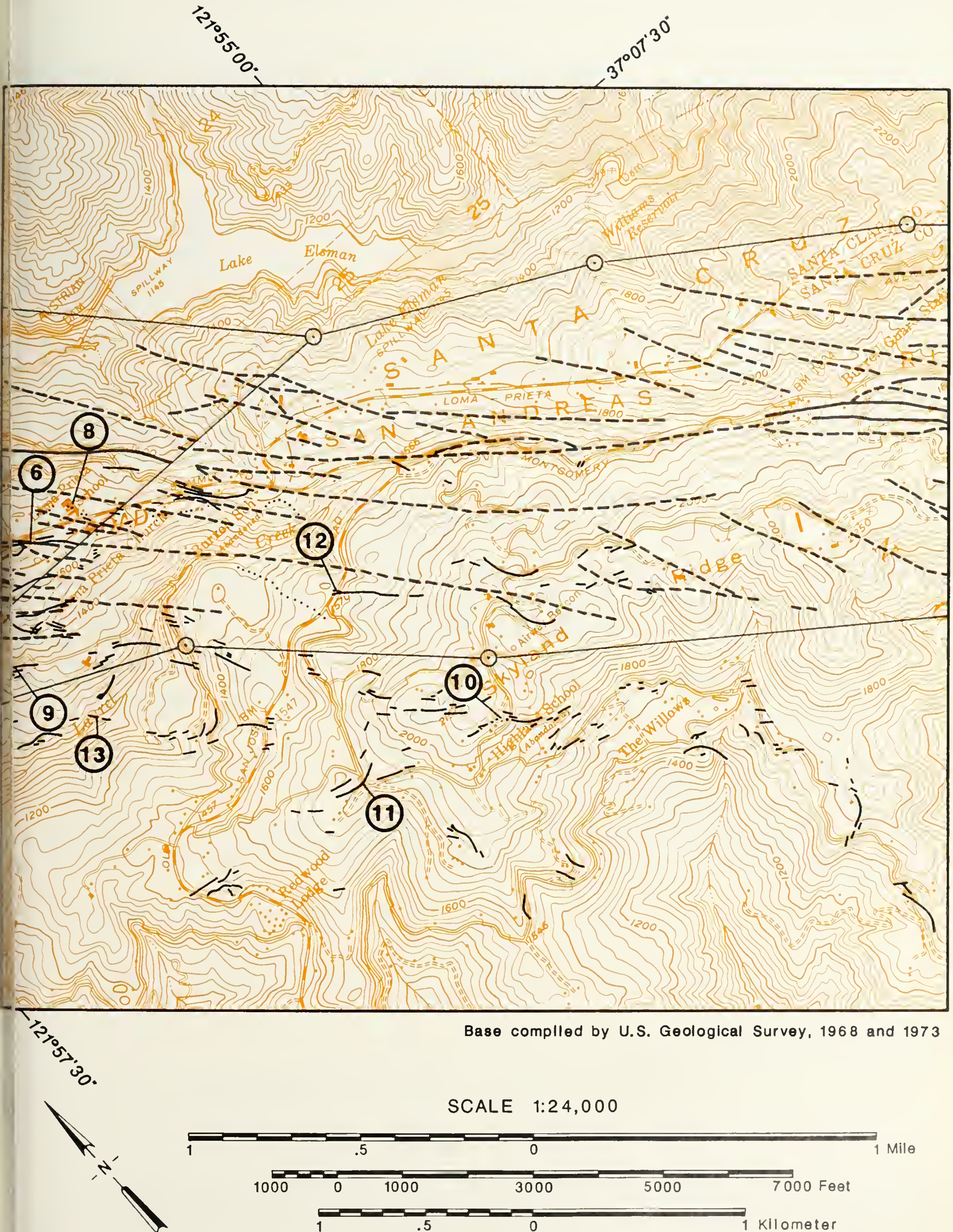

121°55'00"
37°07'30"
121°57'30"
Lake Elsman
Lake Elsman Spillway
Williams Reservoir
S A N T A C R U Z
SAN ANDREAS
LOMA PRIETA
MONTGOMERY
Ridge
SANTA CLARA CO
SANTA CRUZ CO
Skyland
The Willows
Highland School (Abandoned)
Redwood Lodge
Laurel
Loma Prieta School
Loma Prieta Church
6
8
9
10
11
12
13
Base compiled by U.S. Geological Survey, 1968 and 1973
SCALE 1:24,000
1 .5 0 1 Mile
1000 0 1000 3000 5000 7000 Feet
1 .5 0 1 Kilometer
N

Table 1

Locality descriptions of significant fissures and fracture zones developed on or near ridgetops during the 17 October 1989 Loma Prieta Earthquake (see Figure 2 for localities 1-14 and Figure 1 for localities 15-16).

1. Highway 17 pavement offset 40 cm vertically (south side up); bedding-plane fractures in steeply dipping mudstone unit of Vaqueros Sandstone are exposed in high road cuts; attributed to coseismic secondary faulting (flexural slip) by Cotton and others (this volume). Two narrow fissure zones each with up to a few centimeters of extension and minor down-to-the-north offset in paved road to northwest. Not obviously associated with a geomorphic feature, but faulted colluvial wedge exposed in east highway cut indicates previous down-to-the-north displacements along fracture zone.

2. Large ridgetop fissure with as much as 79 cm net displacement - mostly extensional with significant vertical (down to south) and left-lateral components of displacement; mostly a narrow, well-defined fissure zone, but partly branching and diffuse; follows pre-existing, somewhat sinuous drainage swale (subtle in part). Severely damaged local water supply system and offset Summit Road. Fissures are in Vaqueros Sandstone (Dibblee and Brabb, 1978).

3. Somewhat sinuous fissure with as much as 40 cm total displacement—extensional and vertical (down to southwest); follows base of existing southwest-facing scarp and drainage swale. Fissure zone is in Vaqueros Sandstone (Dibblee and Brabb, 1978).

4. Linear fissure zone with up to 19 cm of net extension and down-to-northeast offset; follows well-defined north-facing scarp along margin of linear depression. Southeast end of zone at damaged house had estimated 5 to 7 cm extension and minor subsidence. In Vaqueros Sandstone (Dibblee and Brabb, 1978).

5. 600 m-long fissure zone. Northwestern part had 22 cm of left-lateral extension at Morrill Road in same location where at least 1m of left-lateral offset occurred in 1906 (Wells and others, 1989; Lawson, 1908); segment is well-defined by prominent northeast-facing scarp. Southeast segment is weakly defined by swale. Complexly interconnects with other fissure zones which are not as well-defined geomorphically. Fissure partly follows Butano fault of Dibblee and Brabb (1978).

6. Ground surface around a water-well pad and within a 5 m- wide fissure zone subsided 20 cm; indicates shallow subsidence caused by shaking and not tectonic subsidence; fissures occur in broad swale. In Butano sandstone near Butano fault.

7. Two zones of fissures/fractures pass under and damage two buildings and paving of C.T. English Middle School; total extension across building site is 23 cm (J. Cottingham, 1990, personal communication). Trenches excavated in January 1990 indicate about 2.5 m previous vertical offset of Butano Formation against soil/colluvium (northeast side down). Also, one fissure filled with soft soil may represent a 1906 fissure or other recent event (Cleary Consultants, 1990). In Butano sandsone and siltstone (Dibblee and Brabb, 1978).

8. Minor to moderate extensional cracking and differential settlement of Loma Prieta School buildings and pavement. Fissures and cracks are somewhat distributive, but partly correspond to "faults" previously identified in trenches by Johnson (1989), which caused this public school to be closed prior to earthquake; report identifies offset colluvium as young as 2,180 ybp, soil-filled fissures, and several faults. In Vaqueros Sandstone and near Butano fault of Dibblee and Brabb (1978).

9. Large extensional fissures with northeast-facing scarps developed on hillslope; fissures turn downslope to the west in benched topography; to east fissures connect landslide fissures and related features upslope. Fissures are gradational with those at C.T. English School farther upslope, all of which suggest toppling associated with landsliding. In landslide deposits in San Lorenzo Formation (Clark and others, 1989).

10. Zone of northwest-trending fissures and southwest-facing scarplets becoming arcuate to west; coincides with existing arcuate scarp and associated bench in large landslide deposit and in Butano sandstone of Dibblee and others (1978). Based on ground inspection and aerial photos, other fractures mapped near the hamlet called The Willows and to the southeast also occur on hummocky and benched topography and probably are landslide related.

11. Fissures with 21 cm of extension at road coincide with a broad trough and closed depression to the west which, along with arcuate pattern of fissure zone, indicate a landslide feature; slope to the northwest is benched and hummocky. San Lorenzo Formation of Clark and others (1989).

12. Large fissure zone extends diagonally uphill; 33 cm extension at road; crudely follows weak swale, bench, and scarps; left-lateral slip in eastern segment (Wells and others, 1989) appears to represent the left flank of a large landslide as do other crack zones to the northwest and southeast. Hillslope is benched and hummocky. Butano shale and sandstone of Clark and others (1989).

13. Extensional cracks in sandstone outcrop in Laurel Creek suggest expansion (bulging) of slopes outward; bedrock is pervasively sheared and bedding attitudes erratic, suggesting landslide deformation. San Lorenzo Formation of Clark and others (1989).

14. Faults, soil-filled fissures, and possible landslide slip plane identified in trench logs of consultant's report (Foxx, Nielson and Associates, 1988). Fissures mapped at this locality by Spittler and Harp (1990) closely align with trench features, suggesting repeated activity.

15. Ridgetop fissures parallel to northwest-trending ridge over distance of nearly 0.8 km mapped by Spittler and Harp (1990). Fissures are in steeply dipping Purisima Formation and Lambert Shale (Clark and others, 1989).

16. Discontinuous fissures noted along both sides and the narrow crest of N20°W-trending ridge; fissures to 25 cm wide are linear and resemble fissures along Summit Road; Spittler and Harp (1990) show this fissure zone to be 0.6 km long. Two houses and a studio were severely damaged (now torn down) and at least two had fissures under foundations. Trenching showed at least one fissure to flatten out at depth of about 1m; another fissure extended into bedrock and was at least 4 m deep. Bedrock is soft sandstone and siltstone of Purisima Formation with nearly horizontal dip (Clark and others, 1989).

Photo 1. Portion of sinuous fissure zone in Summit Road at locality 3 (Figure 2) showing significant extensional and vertical offset. (Photo by E.W. Hart, 10/18/89)

Photo 2. A near miss: fissure in front of Tranbarger house (near locality 2, Figure 2) had significant extensional opening as well as vertical displacement seen here. Note offset of walkway to front door. (Photo by C.J. Wills, 10/25/89)

Description of Fissures

Most of the fissures in the Summit Road-Skyland Ridge area have N50°W to N60°W trend, which is generally parallel to the regional strike of Tertiary strata (Dibblee and Brabb, 1978; Clark and others, 1989) as well as the ridgelines. Other fissure zones trend more westerly or northerly and also tend to parallel ridge spurs. Individual fissures tend to be relatively straight, apparently controlled by bedrock structures (bedding, faults or joints). However, some zones of fissures are curved, sinuous or irregular (Photo 1) (localities 2, 3, and 9, Figure 2), as well as complexly branching and anastomosing (localities 2 and 6, Figure 2). Selected fissure localities, field-checked by us from October 1989 to January 1990, are identified on Figure 2 and described in Table 1.

Fissure zones are as long as 700 m and individual fissures are open as wide as 0.8 m (Photo 2). Although extension dominates the sense of displacement, many fissures have vertical components of displacement to 0.4 m and uphill-facing scarps are common. Left-lateral components of offset are also common and approach 0.4 m at localities 2 and 5. Right-lateral slip components are less abundant and smaller (Wells and others, 1989).

The depth of the fissures generally could not be determined because thick colluvial soil from the walls would tend to collapse into the fissures. However, depths to 4 to 5 m were observed (Baumann and others, 1990). Presumably, the larger fissures extended even deeper into bedrock. The general linearity of fissures and the fact that they followed existing geomorphic features (linear depressions, ridgelets, and scarps) indicate that they are anchored in bedrock and probably follow bedding planes, faults, and joints. Exposures at localities 1, 7, and 8 further verify this relationship.

Photo 3. Fissure formed along the base of a pre-existing scarp at locality 4 (Figure 2). House at southeastern end of this fissure (left of photo) was damaged by extension. Linear scarp defines margin of depression and provides good evidence of previous fissuring. (Photo by E.W. Hart, 10/25/89)

Many fissures are clearly associated with geomorphic features indicative of past extension and vertical displacement (Photo 3). However, the individual depressions, swales and scarps seldom exceed 200 to 300 m in length and most lack the degree of linearity and continuity normally associated with recent faulting. Recurrence of displacement has been documented in a road cut at Highway 17 (locality 1, Table 1; Cotton and others, this volume), in trenches at two school sites (localities 7 and 8), and at a residential site (locality 14). Recurrence also has been documented at Morrill Road (locality 5) which was offset left-laterally as much as 0.4 m in 1989 at the same location where 1.1 m of left-lateral offset was recorded in 1906 (Lawson, 1908, plate 64B; USGS, 1990, p. 290). Other fissures and landslides reported by Lawson (1908, p. 109-113 and 275-278) in the Summit Road-Skyland Ridge area also appeared to have greater displacements in 1906. For example, Los Gatos Creek near Wright Station was dammed by a large landslide in 1906 (Lawson, p. 110), but no comparable sliding occurred in 1989.

Origin of Ridgetop Fissures

Many of the fissures in the Summit Road-Skyland Ridge area are considered to be tectonic in origin by some geologists, based on the fault-like characteristics and general linearity (e.g. USGS, 1990). The fracture zone and offset highway pavement at locality 1 (Figure 2) were mapped as a bedding-plane fault in both of the 20 m high road cuts of Highway 17 by Cotton and others (this volume). The fractures parallel bedding in a shale unit of the Vaqueros Formation and offset a colluvial/soil wedge in the same sense (north side down) as the pavement of Highway 17 and the closely associated fissure zone just west of the highway.

The evidence for a tectonic origin of other fissures is indirect, however, being based on the assumed 1.3-0.4 m of uplift and presumed extension across the southwestern block of the San Andreas fault (USGS, 1990). Furthermore, some of the fissures follow linear depressions, scarps and other small-scale geomorphic features often associated with active faulting. Some of these same geomorphic features were used by Hall and others (1974) and Sarna-Wojcicki and others (1975) to map left-stepping *en echelon* faults in the Summit Road-Skyland Ridge area. Yet the fissure and fracture zones mapped by Wells and others (1989) only coincide to a limited extent with traces of Hall and others (see Figure 2), which is similar to Sarna-Wojcicki and others. This suggests that the fault traces shown in the 1974 and 1975 publications are rather interpretive and inadequately predicted the 1989 fissure locations.

Based on our own interpretations of aerial photographs (National Archives, 1939; USGS, 1966; Air Flight Service, 1989), we were unable to verify the northwest set of left-stepping faults mapped by the USGS in 1974 and 1975. What we see in unforested areas is a rather complex set of short, linear to curved depressions, swales, scarps, and hummocks that generally parallel the ridgecrest along Summit Road. There is no question that these features are youthful. The only question is their origin. Features observed on Skyland Ridge are less parallel to the ridgetop and associated spurs, being a mosaic of young hummocks, swales, and benches punctuated with round to elongate depressions. These ridgetop features are clearly gradational with the hummocky and benched landslides of the steep slopes of Skyland Ridge.

Most of the linear, fault-like fissures were concentrated within a relatively small area on or near ridgecrests. Therefore, it seems unlikely that the fissures could be caused by tectonic uplift that extended over a much larger area (USGS, 1990). More likely, the fissures in the Summit Road-Skyland Ridge area were caused by intense shaking that caused the ridges to spread laterally and the tops to settle. The fact that the fissures tend to parallel the ridgecrests and spurs suggests this is so, and the association of the 1989 fissures and scarps with existing depressions and scarps demonstrates a repetition of events. The gradational relations with landslide fissures developed on the flanks of the ridges (Spittler and Harp, 1990) further indicate a common cause for both types of fissures.

Ridgetop depressions and fissures, and uphill-facing scarps are relatively common in mountainous terrain in glaciated regions of the world (Beck, 1968; Tabor, 1971; Radbruch-Hall and others, 1977; Bovis, 1982; Savage and Varnes, 1987; Thorsen, 1989; Varnes and others, 1989). These features have been largely attributed to lateral spreading involving gravity and rock creep. Toppling, translation, and rotational phenomena also contribute to such features.

Models for ridgetop features have been proposed or summarized by Varnes (1978), Bovis (1982), Savage and Varnes (1987), Thorsen (1989), and Varnes and others (1989). Ridgetop features and uphill-facing scarps also can result from seismic shaking and may involve hills and ridges, as well as high mountains. Beck (1968) thought that uphill-facing scarps in New Zealand were caused by earthquakes. Radbruch-Hall (1978) associated the 1899 and 1958 earthquakes on the Fairweather fault, Alaska, and the 1971 San Fernando earthquake with lateral spreading of ridges and uphill-facing scarps. We have noted ridgetop depressions and uphill-facing scarps within a few kilometers of active faults in the Coast Ranges, Transverse Ranges, and elsewhere in California and believe that many of the features are caused by intense seismic shaking.

The relatively weak rocks that underlie the Summit Road- Skyland Ridge area undoubtedly have contributed to the ridgetop failures and the landslides observed on these relatively low (200 m-high) ridges. Figure 3 is a schematic cross section through the ridge along Summit Road showing how lateral spreading and ridgetop settling might occur. However, the spreading/settling phenomenon probably is very complex and no doubt is significantly controlled by bedding planes, faults, and joints.

The abundant left-lateral fractures reported by Wells and others (1989) have been cited as evidence of tectonic deformation (USGS, 1990). It seems to us that most left-lateral and right-lateral displacements can be explained by shaking-induced lateral movement of ridgetop blocks towards a free-face. Also, afterslip, which frequently is observed after normal and strike-slip faulting events, has not been measured across any of the fracture zones surveyed by the USGS (M.M. Clark, personal communication, 1990).

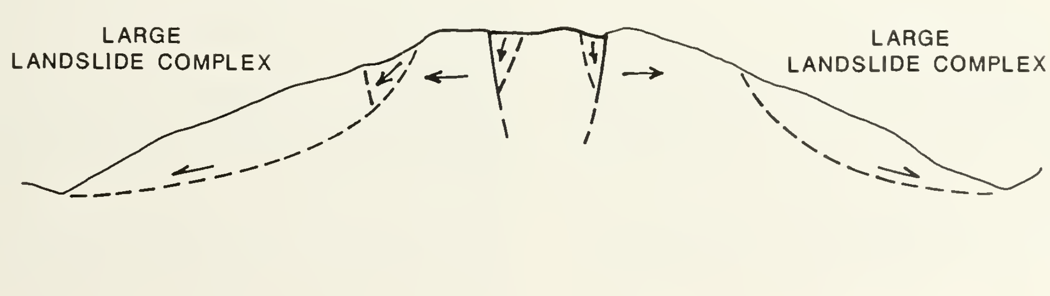
Although we are reasonably confident that shaking and associated lateral-spreading caused most of the ridgetop fissures, as well as the fissures associated with landslides on the flanks of ridges, we cannot rule out a tectonic contribution that may have occurred during the Loma Prieta earthquake. However, we doubt that a shaking versus tectonic origin can be consistently demonstrated by trenching or other normal investigative techniques.

RELATIONSHIP OF FISSURES TO ALQUIST-PRIOLO SPECIAL STUDIES ZONES

Subsurface rupture on the San Andreas fault during the Loma Prieta earthquake extended over a distance of 45 km beneath nine quadrangles covered by Special Studies Zones maps (Figure 1). These SSZ maps were issued in 1974, 1976, and 1982 under the Alquist-Priolo Special Studies Zones Act (Hart, 1988). We fully expected to have the opportunity to determine the efficacy of these zones, some of which were based on the work of others (1974 and 1976 maps) and some based mainly on our own mapping (1982 maps). But as discussed above, there was little evidence that any primary fault rupture propagated to the ground surface. So, in terms of primary surface rupture, the SSZ maps have not really been tested.

The numerous fissures developed during the Loma Prieta earthquake raise a different set of questions. Are these features actually secondary faults? How widely distributed are these fissures? What is the likelihood that fissuring will recur? Although many of these features formed within the SSZs of the Los Gatos and Laurel quadrangles, several formed outside the SSZs (Figure 2).

We feel that the ridgetop fissures are caused largely by intense shaking, although we recognize that the uplifted southwestern block of the San Andreas fault probably was associated with some tectonic stretching. Being unable to prove the absence of faulting, it is difficult to recommend against zoning the fissures, particularly when some are clearly related to geomorphic features indicative of repeated events. In addition, these fault-like features are certainly hazardous to structures and are best mitigated by avoidance. One possible course of



ıure 3. Schematic cross section through ridge of Summit Road showing seismically-induced lateral-spreading of ridge. Outward movement of ridge induces erential settlement forming back-facing scarps and linear depressions on top of ridge. Large landslide complexes, which generally flank ridges, also are activated d move downslope coseismically. Displacements on ridgetop tend to follow pre-existing faults, bedding planes, or other rock structures, which are not detailed in s model.

Photo 4. Looking southeast at uphill-facing scarp and associated fissures along sidehill bench at locality 9 (Figure 2); note knife for scale. Features are similar to fault-like fissures on ridgecrest above but appear to interconnect with landslide features to northwest and southeast. Presence of bench indicates previous rupture events. (Photo by W. A. Bryant, 1/11/90)

action would be to treat the features like faults and to zone them under the APSSZ Act. This would precipitate the need for a consulting geologist to evaluate sites proposed for new construction on a case-by-case basis.

The problem with this course of action is that the fault-like fissures are very similar to fissures that develop on landslides which are not zonable under the APSSZ Act (Photo 4). Elsewhere in California we have made a conscious effort in the past not to zone lateral spreading or landslide features.

The 1989 fault-like fissures also are associated with lesser fissures that are distributed over the entire Summit Road-Skyland Ridge area. These minor fissures create a dilemma for those who propose new building in the epicentral area. Although these fissures may be somewhat less damaging than larger ones, they are more difficult to avoid due to their abundance. It may be possible to mitigate potential damage to structures by design of a specially reinforced foundation for a structure. We observed that smaller fissures and fractures were at least partly diverted around the foundations of several structures. As an alternative to avoiding all possible future ruptures, it may be appropriate to avoid the more obvious fault-like fissures and to design structures to resist or otherwise accommodate displacement by minor fissures.

In order to decide which fissures are landslide-related and which are not, more needs to be known about the various fissures. These features are still being evaluated by DMG and others.

CONCLUSIONS

In spite of the large size of the M_S7.1 Loma Prieta earthquake, there as no through-going primary surface rupture in the epicentral area ong the San Andreas fault. If surface faulting occurred, it was minor, scontinuous, and generally obscured by extensional cracks and ssures caused by shaking. The best evidence of surface faulting was Mt. Madonna Road (locality D) where 2.7 cm of right-lateral splacement was observed shortly after the earthquake. Because this rface rupture is minor and discontinuous, it seems unlikely to be imary. No evidence of fault rupture was observed on the Sargent or iyante faults in the epicentral area. The general absence of primary rface rupture on the San Andreas fault came as a complete surprise geologists, even though the subsurface rupture was abnormally ep and contained a large component of reverse slip (compression).

Triggered slip occurred 36-46 km from the epicenter along the ılaveras fault from the town of Hollister to San Felipe Lake ighway 152) with maximum right-lateral slip of about 5 mm. Some this slip was coseismic. Additional minor triggered slip may have curred near San Juan Bautista and to the southeast on the San ıdreas fault. Triggered slip also may have occurred within the icentral area to the northwest (such as at locality D, Figure 1), but ›uld be difficult to distinguish from other shaking cracks.

The extensive fissuring that developed on the uplifted southwestern ›ck of the San Andreas fault was perhaps as surprising as the lack surface faulting. The most abundant fissures developed in the mmit Road-Skyland Ridge area (Figure 2), where some fissure ıes attained lengths of 0.7 km and net displacements to 0.8 m ostly extensional but commonly including vertical and left-lateral nponents). Some geologists believe that fissures at or near the getops are caused by tectonic uplift and secondary faulting. We believe that secondary faulting may be a causative factor, but that lateral spreading of the ridges caused by shaking is the dominant cause of fissuring. The fact that many of the fissures follow existing geomorphic features (depression boundaries, swales, scarps) and have displacements with a similar sense indicates that some of the displacements are repeatable over time. Other fissures are distributive or otherwise do not follow existing geomorphic features. Moreover, similar fissures occur on the flanks of ridges within known landslides that also were reactivated by the Loma Prieta earthquake. The ridgetop fissures and landslide fissures appear to have a gradational relationship.

The ridgetop fissures contributed to the damage of a number of school buildings, residences, and other structures — mainly by extensional and vertical displacement. Future construction should be preceded by a detailed geologic investigation to avoid these larger, fault-like fissures. Where fissures are distributive or difficult to identify, specially reinforced foundations and other engineering techniques may be appropriate.

Although a broad zone of fissures on the Summit Road ridge generally lies within regulatory zones established under the Alquist-Priolo Special Studies Zones Act, some fault-like features extend farther to the northwest (Figure 2). Other fissures on Skyland Ridge largely lie outside established SSZs. As a result, the SSZ s in the Los Gatos and Laurel quadrangles are being reevaluated.

ACKNOWLEDGMENTS

We would like to acknowledge David L. Wagner and Robert H. Sydnor of DMG for reviewing this paper and providing suggestions for improvement. Thanks also goes to Malcolm M. Clark and Daniel J. Ponti of the USGS, Thomas E. Spittler and Michael W. Manson of DMG, William R. Cotton, and J.M. Cleary for providing preliminary fracture/fissure data in a timely way. Finally, we acknowledge the many useful discussions with these geologists, as well as many others too numerous to mention here.

REFERENCES

Baumann, M.F., Connelly, S.F., Falls, J.N., Haley, L.A., McKee, M.W., and Upp, R.R., 1990, Finding fissures from the Loma Prieta earthquake: Association of Engineering Geologists, AEG News, v. 33, no. 1, p. 31-32.

Beck, A.C., 1968, Gravity faulting as a mechanism of topographic adjustment: New Zealand Journal of Geology and Geophysics, v. 11, p. 191-199.

Bonilla, M. G., Mark, R. K., and Lienkaemper, J. J., 1984, Statistical relations among earthquake magnitude, surface rupture length, and surface fault displacement: Seismological Society of America Bulletin, v. 76, no. 6, p. 2379-2411.

Bovis, M.J., 1982, Uphill-facing (antislope) scarps in the Coast Mountains, southwest British Columbia: Geological Society of America Bulletin, v. 93, p. 804-812.

Bryant, W.A., Smith, D.P., and Hart, E.W., 1981, Sargent, San Andreas and Calaveras fault zones: evidence for recency in the Watsonville East, Chittenden and San Felipe quadrangles, California: California Division of Mines and Geology Open File Report 81-7SF, 3 plates, scale 1:24,000.

California Division of Mines and Geology, 1976, Revised Official Maps of Special Studies Zones, Laurel and Los Gatos quadrangles, scale 1:24,000.

Clark, J. C., Brabb, E. E., and McLaughlin, R. J., 1989, Geologic map and structure sections of the Laurel 7.5-minute quadrangle, Santa Clara and Santa Cruz counties, California: U. S. Geological Survey Open-File Report 89-676, 30 p., 2 plates, scale 1:24,000.

Cleary Consultants, 1990, Post-earthquake geotechnical evaluation, C. T. English Middle School, 23800 Summit Road, Santa Cruz County, California: Los Altos, California, Cleary Consultants, Inc., unpublished consulting report, January 31, 1990, 19 p., 22 drawings.

Cotton, W. R., Fowler, W. L., and J. E. Van Velsor, 1990, Coseismic bedding plane faults and ground fissures associated with the Loma Prieta earthquake of 17 October 1989: this volume, p. 95-104.

Dibblee, T.W. Jr., and Brabb, E.E., 1978, Preliminary geologic map of the Los Gatos quadrangle, Santa Cruz and Santa Clara counties, California: U.S. Geological Survey Open-File Report 78-453, 1 plate, scale 1:24,000.

Dibblee, T.W. Jr., and Brabb, E.E., 1980, Preliminary geologic map of the Loma Prieta quadrangle, Santa Cruz and Santa Clara counties, California: U.S. Geological Survey Open-File Report 80-994, 1 plate, scale 1:24,000.

Foxx, Nielson and Associates, 1988, Geologic fault investigation, Lands of Donna Hines (APN 96-131-22), Summit Road, Santa Cruz County, California: Unpublished consulting report dated 10 August 1988, 29 p., 4 plates.

Hall, N.T., Sarna-Wojcicki, A., and Dupre, W.R., 1974, Faults and their potential hazards in Santa Cruz County, California: U.S. Geological Survey Miscellaneous Field Studies Map MF- 626, scale 1:62,500.

Hart, E.W., 1988, Fault-rupture hazard zones in California: California Department of Conservation, Division of Mines and Geology Special Publication 42 (revised edition), 24 p.

Hempen, G.L., 1990, Notes on the Loma Prieta earthquake: Association of Engineering Geologists, AEG News, v. 33, p. 29- 30.

Johnson, R.E., & Associates, 1989, Fault investigation, Loma Prieta Elementary School, 23845 Summit Road, Santa Clara County, California (Phases 1 and 2): Unpublished consulting report dated 23 March 1989, 45 p., 1 appendix, 9 plates.

Lawson, A.C., ed., 1908, The California Earthquake of April 18, 1906: Report of the California State Earthquake Investigation Commission: Carnegie Institution of Washington, Publication 87, v. 1, 451 p.

Lisowski, M., Prescott, W.H., Savage, J.C., and Svarc, J.L., 1990, A possible geodetic anomaly observed prior to the Loma Prieta, California, earthquake: Geophysical Research Letters, v. 17, p. 1211-1214.

Mahr, T., 1977, Deep-reaching gravitational deformations of high mountain slopes: International Association of Engineering Geology Bulletin, no. 16, p. 121-127.

McClellan, P.H., and Hay, E.A., 1989, Geologic evidence for triggered slip on the Calaveras fault during the magnitude 7.1 Loma Prieta earthquake of October 17, 1989: U.S. Geological Survey Open File Report 89-641, 37 p.

Plafker, G., and Galloway, J.P., eds., 1989, Lessons learned from the Loma Prieta, California, earthquake of October 17, 1989: U.S. Geological Survey Circular 1045, 48 p.

Radbruch-Hall, D.H., 1978, Gravitational creep of rock masses on slopes, *in* B. Voight, ed., Rockslides and avalanches, 1— Natural phenomena: Elsevier Scientific Publishing Company, Developments in Geotechnical Engineering 14A, p. 607-657.

Radbruch-Hall, D.H., Varnes, D.J., and Colton, R.B., 1977, Gravitational spreading of steep-sided ridges ("sackung") in Colorado: U.S. Geological Survey Journal of Research, v. 5, no. 3, p. 359-363.

Sarna-Wojcicki, A.M., Pampeyan, E.H., and Hall, N.T., 1975, Map showing recently 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, W.Z., and Varnes, D.J., 1987, Mechanics of gravitational spreading of steep-sided ridges ("sackung"): International Association of Engineering Geology Bulletin, no. 35, p. 31- 36.

Schulz, S.S., 1984, Triggered creep near Hollister after the April 24, 1984, Morgan Hill, California, earthquake, *in* J.H. Bennett and R.W. Sherburne, eds., The 1984 Morgan Hill, California, earthquake: California Division of Mines and Geology Special Publication 68, p. 175-182.

Shakal, A. F., DeLisle, M. J., Reichle, M. S., and Darragh, R. B., 1990, Strong ground shaking from the Loma Prieta earthquake of 17 October 1989 and its relation to near surface geology in the Oakland area: this volume, p. 29-46.

Spittler, T.E., and Harp, E.L., 1990, Preliminary map of landslide features and coseismic fissures triggered by the Loma Prieta, California, earthquake of October 17, 1989: California Division of Mines and Geology, Open-File Report 90-6, map scale 1:4,800.

Tabor, R.W., 1971, Origin of ridge-top depressions by large-scale creep in the Olympic Mountains, Washington: Geological Society of America Bulletin, v. 82, p. 1811-1822.

Thorsen, G.W., 1989, Splitting and sagging mountains: Washington Geologic Newsletter, v. 17, no. 4, p. 3-13.

U.S. Geological Survey Staff, 1990, The Loma Prieta, California, earthquake: an anticipated event: Science, v. 247, p. 286- 293.

Varnes, D.J., 1978, Slope movement types and processes, *in* R.L. Schuster and R.J. Krizek, eds., Landslides—analysis and control: National Academy of Sciences, Washington, D.C.,Transportation Research Board, Special Publication 176, p. 11-33 and Figure 2.1.

Varnes, D.J., Radbruch-Hall, D.H., and Savage, W.Z., 1989, Topographic and structural control in areas of gravitational spreading of ridges in the western United States: U.S. Geological Survey Professional Paper 1496, 28 p.

Wells, R.E., Ponti, D.J., Clark, M.M., Bucknam, R.C., Budding, K.E., Fumal, T.E., Harwood, D.S., Lajoie, K.R., Lienkaemper, J.J., Machette, M.N., Prentice, C.S., and Schwartz, D.P., 1989, Preliminary map of fractures formed in the Summit Road-Skyland Ridge area during the Loma Prieta, California, earthquake of October 17, 1989: U.S. Geological Survey Open-File Report 89-686, 1 plate, scale 1:12,000.

COSEISMIC BEDDING PLANE FAULTS AND GROUND FISSURES ASSOCIATED WITH THE LOMA PRIETA EARTHQUAKE OF 17 OCTOBER 1989

by

William R. Cotton[1], William L. Fowler[1],
and Joan E. Van Velsor[2]

ABSTRACT

Coseismic bedding plane faulting of approximately 40 cm slip has been documented in two 20 m-high road cuts and highway pavement located just south of the intersection of the state Highway 17 and Summit Road at the crest of the Santa Cruz Mountains. The site is situated near the north end of the earthquake rupture zone and approximately 2 km south of the mapped trace of the San Andreas fault.

Ground rupture in the form of high-angle normal faulting is characterized by ground cracking and uplifted highway pavement. The faulting is preferentially confined to the weak shale interbeds of a thick section of massive Vaqueros Sandstone which is exposed in the two facing cutslopes. The primary zone of active faulting is defined by a 15 cm-wide zone of clay gouge which parallels bedding (N55°W,d82°N) and has been mapped through the road cuts on both sides of the faulted road section. Near the top of one cut slope, the fault cuts an 8 m thick, charcoal-rich deposit of surficial materials.

The exposed stratigraphic relationships indicate that the fault has a well-established paleoseismic history of repeated episodes of normal fault displacement. The surficial materials are interpreted to have formed as infill deposits of a fault-bounded, ridgetop depression. The origin and significance of the depressions and associated topographic furrows and scarps that characterize the crest of the Summit Ridge area have been a topic of geologic debate for several decades.

Bedding plane faulting with normal slip is presented as a likely geologic model to explain the origin, orientation, and distribution of both the ridgetop depressions and many of the ground fissures that developed along the crest of the ridge as a result of the Loma Prieta earthquake. The bedding plane faults are, in turn, structurally controlled by the strike and dip of the bedrock and the location of the weak shale intervals. Ground fissures that appear to cut across strike of the underlying bedrock are interpreted to be the result of slip along other bedrock structures such as faults or fracture zones that are discordant to bedding.

We propose that the bedding plane faults and the secondary faults represent second-order, bending-moment faults which result from lengthening (i.e., tension) of the ridgecrest as a result of large magnitude earthquake events on the San Andreas fault.

INTRODUCTION

wide variety of ground fissuring developed in the Summit Ridge a of the Santa Cruz Mountains, Santa Cruz and Santa Clara c nties, as a result of the M_S7.1 Loma Prieta earthquake (Figure 1). ny of the fissures are on steep mountain flanks and are clearly ted to landslide processes. Many others, however, are located a g the crest of the ridge and are closely related to pre-existing g morphic features such as ridgetop depressions, linear topographic f ows, and subdued scarps. Their area-wide pattern suggests that t are controlled by the underlying bedrock structure and lithology (tton and others, 1990 and U. S. Geological Survey Staff, 1990).

It is generally recognized that the zone of ground fissuring ranges from 1 to 2 km wide and extends southeast from Highway 17 along the axis of the ridge for a distance of 8 km (Wells and others, 1989). The tectonic relationship between the distribution and nature of the ground fissuring and the lack of primary ground rupture along the southern Santa Cruz Mountains segment of the San Andreas fault is presently uncertain. Detailed paleoseismic studies of the extensive record of second-order deformation that accompanied the earthquake should enable the development of a tectonic model that will explain regional deformational patterns and provide some insights into the return period of large earthquakes along this segment of the San Andreas fault.

[1] iam Cotton and Associates, Inc., Los Gatos
[2] fornia Department of Transportation, District 4, San Francisco

COSEISMIC SECOND-ORDER SURFACE FAULTING

Coseismic bedding plane faulting with approximately 40 cm of vertical throw has been documented cutting across two 20 m-high roadcuts and adjacent highway pavement for State Highway 17 (Figure 1). The previously unmapped fault buckled both the northbound and southbound lanes of the highway as well as the intervening reinforced concrete divider (Photo 1). Ground cracks mapped to the west and east of the highway roadcut, at or near the original ground surface along frontage roads, are characterized by deformation of the asphalt pavement as well as fissuring of the natural ground. The cracks and fissures are like those found elsewhere in the Summit Ridge area that developed as a result of the 1989 Loma Prieta earthquake.

The distribution and nature of these fissures, and the apparent lack of a well-defined zone of primary, right-lateral ground rupture along the mapped trace of the San Andreas fault, have prompted several geologic models to explain their origin (Cotton and others, 1990; Hardin and others, 1990; U. S. Geological Survey Staff, 1990; Spittler and Sydnor, 1990; Plafker and Galloway, 1989; Spittler and Harp, 1990; Horns, 1990; and Hart and others, this volume).

The Highway 17 site is located approximately 1.5 km to the southwest of the mapped trace of the San Andreas fault and approximately 300 m to the northeast of the Butano fault (Brabb, 1989; Dibblee and Brabb, 1978; Hall and others, 1974). The bedding plane faulting is confined to near-vertical shale interbeds of a thick section of massive Vaqueros Sandstone that strikes nearly perpendicular to the highway alignment (Photo 2). The primary zone of recent faulting is defined by a 15 cm-wide zone of clay gouge that parallels bedding (N55°W,d82°N) and has been mapped through the roadcuts on both sides of the road. Because of the fault's location entirely within the Vaqueros section, and its concordant relationship to the bedrock stratification, the faulting is not considered to be related to the nearby Butano fault.

Near the top of the eastern cutslope, the fault cuts an 8 m thick, charcoal-rich deposit of surficial materials (Photo 3 and Figure 2). The lowermost 2 m of the deposit is cut by several subsidiary faults, indicating that the primary bedding plane fault has experienced multiple episodes of normal fault displacement. Our preliminary geologic logging of the fault relationships indicates that buried paleosols and colluvial wedges may exist within the surficial deposit that will provide further evidence for multiple faulting events. Charcoal samples for radiometric dating have been obtained. Because the observed 1989 displacement of this fault was clearly coseismic, we believe that investigation of these features will provide important data on the timing and magnitude of paleoseismic events on the Santa Cruz Mountains segment of the San Andreas fault.

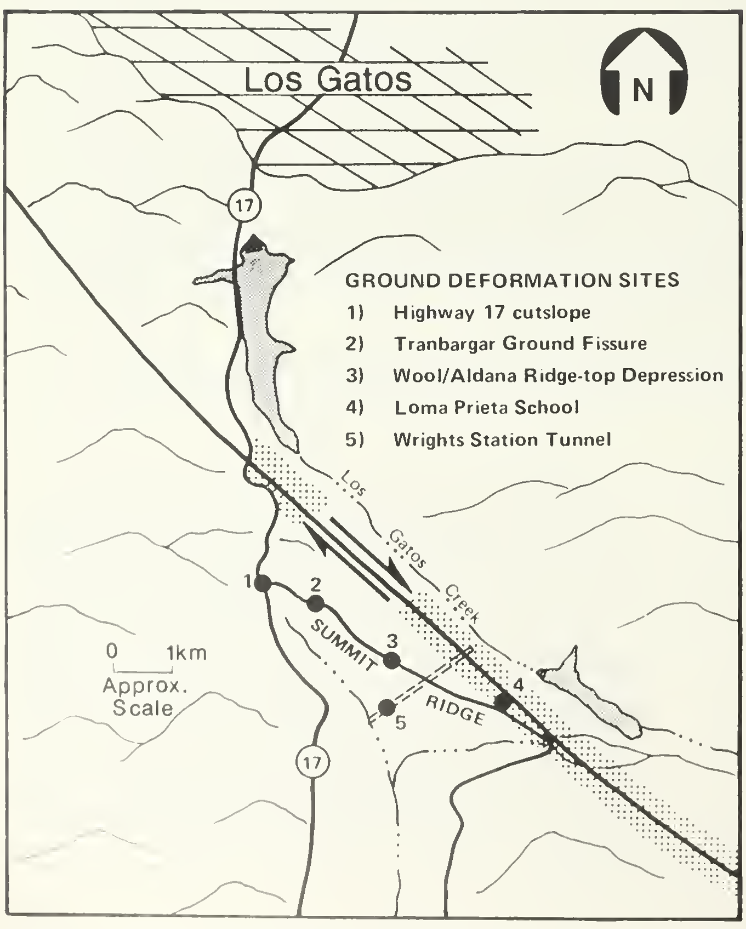


Figure 1. Index map of the Summit Ridge area, the fault rupture zone of the Loma Prieta earthquake, and the ground deformation sites described in the text.

The surficial materials cut by the fault are interpreted to have formed as infill deposits of a fault-bounded, ridgetop depression. Similar topographic depressions are present along the ridgecrest to the east and have been mapped previously by others (Hall and others, 1974; and Sarna-Wojcicki and others, 1975). The origin of the depressions and associated topographic furrows and scarps that characterize the Summit Ridge area is believed to be the result of repeated second-order faulting of the underlying bedrock.

We have identified several locations where active bedding plane faulting was associated with the earthquake event, and that in at least two sites, such faults have a clear geologic record of repeated slip events. This discovery is especially significant because little or no paleoseismic information exists for this segment of the San Andreas fault. Such information is necessary to evaluate the relative activity of the fault segment and for judging the potential seismic hazard in the southern San Francisco Bay region with its population of three million.

GROUND FISSURE CHARACTERISTICS

Ground fissures in the Summit Ridge area are characterized predominantly by a general northwest strike that is subparallel to the axis of the ridge and the alignment of Summit Road. They display primarily extensional openings; however, both strike slip and compressional displacement have been documented (Wells and others, 1989). As a first approximation, those segments that parallel the strike of the underlying bedrock display extensional displacements. Predominantly left-lateral strike-slip displacement is characteristic of fissures that have trends that are more northerly of the bedrock

Photo 1. Bedding plane, normal faulting expressed as a 40 cm heave in Highway 17. View looking south toward Santa Cruz County.

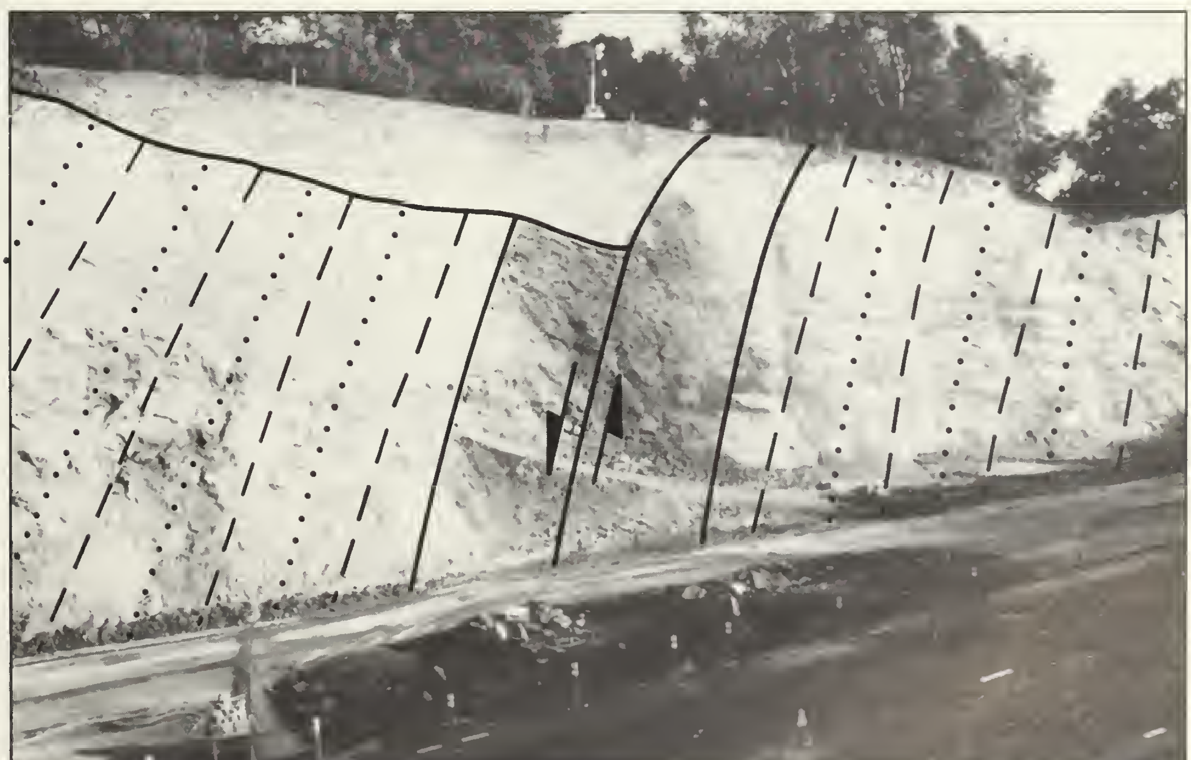


Photo 2. Southeast view of the bedding plane, normal fault relationships in the Highway 17 roadcut. Faulting bisects a thick shale unit in the Vaqueros Sandstone and can be traced to within one meter of the ground surface. An 8 meter thick cover of surficial materials, believed to be the infilling of a ridgetop depression, is cut by the fault.

Photo 3. Close-up view of the surficial material (light color) faulted against shale bedrock (dark color).

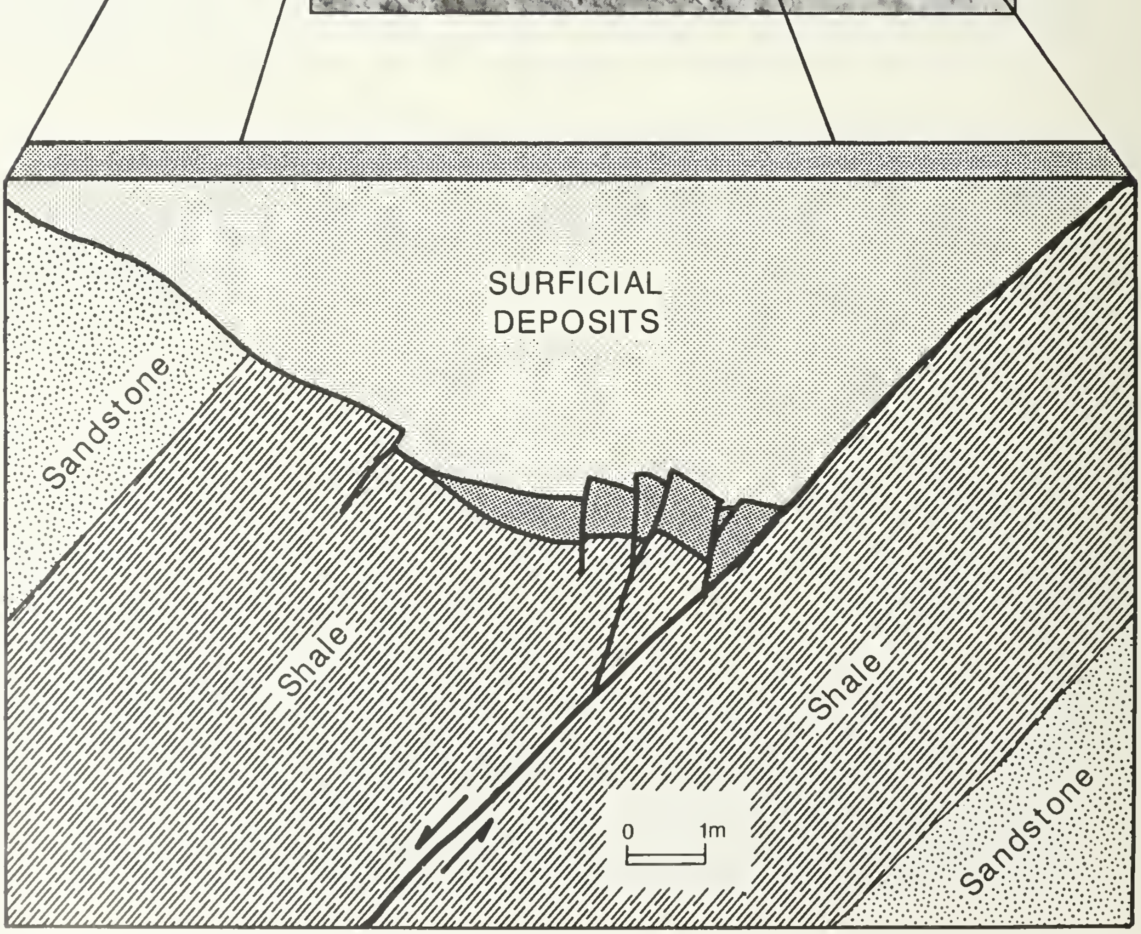


Figure 2. Preliminary geologic log of the fault relationships in the bottom 2 m of surficial deposits.

structure and the northwest trend of the crest of Summit Ridge. Ground fissures that exhibit compression are rare and are characterized by trends that are generally perpendicular (i.e., trend more northeast) to the strike of the bedrock.

The ground fissures are confined for the most part to the surficial earth materials that mantle the Summit Ridge area. Generally, the cohesive surficial deposits that host the ground fissures perform in a brittle manner and are capable of supporting high, near-vertical scarps and open fissures for a considerable length of time, especially during seasonal drought conditions. The most common ground fissures are those that represent extension of the ground surface. These are considered to be the result of normal slip along bedding planes or other weak bedrock structures (i.e., faults, fractures, etc.) which propagate up through the overlying surficial deposits (Figure 3). Other styles of ground fissuring such as strike slip (i.e., left lateral) and compression can be explained by such a model as well.

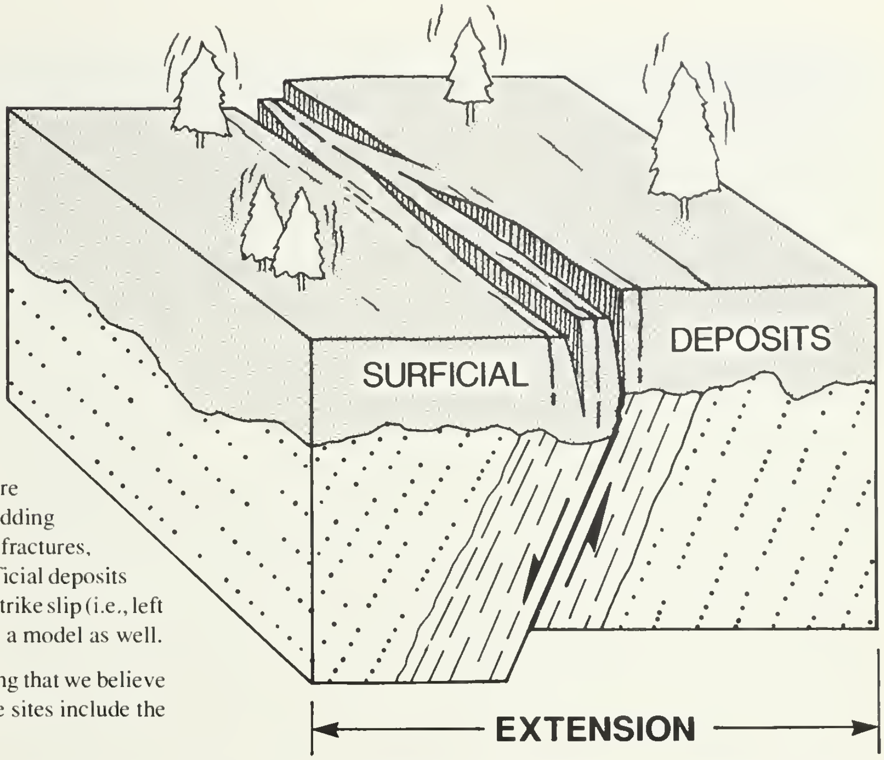


Figure 3. Development of extensional ground fissures in surficial deposits due to coseismic normal slip along a bedding plane within shale bedrock.

We have identified several sites of ground fissuring that we believe can be attributed to faulting within bedrock. These sites include the following:

Tranbarger Ground Fissure - A spectacular system of ground fissures is located along the crest of Summit Ridge at the Tranbarger property, approximately 3 km southeast of Highway 17 (Figure 1). Detailed geologic mapping (scale 1:240 and 1:120) has documented a 335 m-long by 76 m-wide zone of ground fissures that crosses the axis of Summit Ridge. Extensional ground fissures up to 1 m-wide and 2 m-deep (Photo 4), compressional mole tracks up to 15 m long, and a pronounced left-lateral displacement of Summit Road of up to 90 cm horizontal and 40 cm vertical (Figure 7), make this feature one of the largest and certainly most highly publicized of the Loma Prieta earthquake (Hardin and others, 1990). The Tranbarger fissure was pictured in dozens of local and national newspapers and news magazines immediately following the October 17, 1989 event.

Through much of its length, the Tranbarger fissure is associated with geomorphic features such as topographic furrows and sidehill benches that are the result of repeated episodes of deformation. Geometric analysis of the fissure where it crosses a drainage swale near its western end indicates that the fissure strikes N40°W and dips 59°SW. This attitude conforms with the regional bedrock attitudes of the Vaqueros Sandstone (generally N40-65°W, d50-60°S) and strongly suggests that the fissure is related to fault rupture along bedding.

Wool/Aldana Ridgetop Depression - This site is located along Summit Road 6 km southeast from Highway 17 (Figure 1) and is within the Wool and Aldana properties. It is characterized by a very pronounced northwest-trending, elongate ridgetop depression that measures approximately 500 m long and 200 m wide and has a topographic closure of nearly 3 m (Photo 5). Two extensional ground fissures developed along the southwestern and northeastern flanks of the depression as a result of the earthquake. Displacement along the fissures indicates a relative downward displacement of the depression in relation to the flanks.

We interpret the depression to be a graben structure that has resulted from displacement along normal faults that form the flanks of the depression. The youthful, undrained aspect of the depression indi-

Photo 4. Northwest view of the dramatic extensional ground fissure that passed within several meters of the front door of the Tranbarger home.

Photo 5. Northwest view across the left lateral displacement of Summit Road near the Tranbarger property. In this area, the extensional ground fissure near the Tranbarger home (driveway at upper right corner) changes to a north-trending zone of shear.

cates that this site is a zone of repeated Late Quaternary fault displacements, that such displacements are rooted in the underlying bedrock, and are most probably controlled by the structure of the underlying bedrock.

Loma Prieta School - The school site is located at the southeast end of Summit Ridge approximately 4 km from Highway 17 (Figure 1). The school was closed in the spring of 1989 because geologic studies mandated by the State Alquist-Priolo Special Studies Zones Act found that active faults associated with the San Andreas fault system passed underneath several of the school buildings (Johnson, 1989).

As a result of the Loma Prieta earthquake, it is apparent that at least one of the faults identified in the exploratory trenches experienced displacement that resulted in a broad zone of ground warping and fissuring. The zone of distress extended under two school buildings and caused considerable structural damage. Other earthquake-generated cracks were noted in the asphalt school yard and to a lesser degree in the natural ground. These cracks, however, did not display any measurable slip and could not be correlated to any bedding planes or fault surfaces that were logged in the exploratory trenches.

It was clear from the engineering geologic investigation that several of the faults that passed through the school site were zones of repeated faulting and that in an event like the 1989 Loma Prieta earthquake, damaging ground rupture could recur. To our knowledge, this is the only case where a school site was abandoned due to high risk of surface faulting and where this did indeed occur essentially as predicted.

Wrights Station Tunnel - An abandoned narrow-gauge railroad tunnel passes through Summit Ridge nearly perpendicular to the structural trend of the bedrock (Figure 1). The tunnel for the old South Pacific Coast Railroad was built by Chinese labor in 1877-1880 (MacGregor and Truesdale, 1982, p. 186-203). The tunnel is 1,898 m long, and is located about 210 m beneath the ridgecrest. During the 1906 earthquake, the tunnel was deformed over much of its length and was offset approximately 1.4 m near the north ("Wrights") portal along what was described as a discrete "fissure" (Lawson, 1908, p. 111). Observations of the deformation of the tunnel were made by E.P. Carey and included the following:

> *A fissure crost (sic) the tunnel 400 feet from the northeast portal, along which there was a lateral displacement of 4.5 feet. The movement on the southwest side was northerly with reference to the northeast side. ... The strike of this fissure is N25° W, making an angle of 80° with the trend of the tunnel, and it dips at an angle of about 75° to the west.*

Several other "fissure lines" were found to be generally parallel to the main zone of offset but were located between 427 m and 670 m from the Wrights Station portal. E.P. Carey states further:

> *According to the evidence, so far as it went, the whole of the top of the mountains was fissured thruout in such a way that a large movement could be distributed among several fissures and thus account for a relatively slight motion along any one fissure.* (Carey, *in* Lawson, 1908, p. 111.)

The sharp displacement on the "fissure" near the north end of the tunnel which was attributed to primary fault rupture along the trace of the San Andreas fault in 1906 may well have been secondary faulting parallel to bedding. Likewise, fault displacement that was described at two other discrete localities within the tunnel (that is, 427 m and 670

Photo 6. Northwest-trending ridgetop depression near the crest of Summit Ridge. Linear zones of ground fissures developed along both the north and south edges of the depression.

1), as well as the overall deformation of the tunnel alignment, can also e best accounted for by a combination of broad uplifting of Summit idge and fault rupture along weak bedding plane intervals.

Although the tunnel was closed with dynamite in 1944 for military ecurity reasons, approximately 190 m of the south portal (at Laurel) still accessible for geologic inspection. As a result of the Loma rieta earthquake, this portion of the tunnel experienced compresonal deformation. The width of the tunnel was shortened by approxiiately 15 cm to 23 cm and the floor was heaved upward nearly 30 cm. V.F. Cole, 1989, personal communication). A continuous, 15 cmide tension crack opened along the crest of the heaved floor and xtended nearly the entire length of the exposed alignment. This style deformation is very similar to that recorded in 1906. Observations the damage to the tunnel as described by E.P. Carey (Carey, *in* awson, 1908, p. 111) include the following passage:

> *The damage to the tunnel itself consisted in the caving in of overhead rock; the crushing in toward the center of the tunnel of the lateral upright timbers, and the heaving upward of the rails, due to the upward displacement of the underlying ties. In some instances, these ties were broken in the middle. In general, the top of the tunnel was carried north or northeast with reference to the bottom.*

The strike of the tunnel is N48°E which is roughly coincident with e stress axis that would experience compression in an earthquake if e hanging-wall block were thrust obliquely to the northwest along e San Andreas fault.

TECTONIC MODEL

Bedding plane faulting characterized by predominantly normal slip is presented as the best working hypothesis to explain the origin, orientation, and distribution of both the pre-existing ridgetop depressions and the many ground fissures that developed along the crest of the Summit Ridge area as a result of the 1989 Loma Prieta earthquake (Photo 6). The orientation and distribution of the bedding plane faults are, in turn, controlled by the lithology and structure of the bedrock and, specifically, the location of the weak shale interbeds. It is our working model that faults like the bedding plane fault identified at Highway 17 are analogous to second-order, bending-moment faults related to coseismic, active folding processes as described by Yeats (1986, fig. 4.6).

Bending-moment faults result from lengthening (i.e., tensional-normal faults) of the convex side of a folded layer and corresponding shortening (i.e., compressional-thrust faults) of the concave side of the fold. An example of this model is the 1980 Algerian earthquake on the El Asnam fault where displacement on the main seismogenic thrust was accompanied by active anticlinal folding, which was, in turn, accompanied by graben development along the anticlinal crest (Yeats, 1986, p. 67).

In the Summit Ridge area, it is our hypothesis that the ridgecrest was lengthened and normal faulting occurred along pre-existing planes of weakness in the bedrock such as bedding planes, faults and fractures. The extension of the ridgecrest was due to tectonic arching of this portion of the Santa Cruz Mountains that occurred in association with the earthquake.

In our model, the 1.2 m reverse-slip and 1.6 m right-lateral oblique strike-slip that occurred at depth did not extend into the upper 5 km of the crust (Lisowski and others, 1990), but was accommodated at the ground surface by extensional faulting along bedding planes and other weak bedrock structures on the southwest side of the fault zone (i.e., hanging-wall block), and possibly by compressional tectonics along the rangefront to the northeast (i.e., foot-wall block). The vertical deformation of 1.2 m at depth translated into approximately 36 cm of uplift at the ground surface (Plafker and Galloway, 1989). The uplift was not concentrated along the trace of the San Andreas fault as primary ground rupture and, therefore, must have been partially accommodated by slip along weak discontinuities within the bedrock.

With regard to compressional tectonics, evidence for shortening as a result of the Loma Prieta earthquake has been documented in the Los Gatos area situated north of the fault (Haugerud and Ellen, 1990) and is well-expressed in the geologic record by the Sargent-Berrocal, Shannon, and Monta Vista faults that define a zone of range-front faulting along the north side of the Santa Cruz Mountains (McLaughlin, 1974; McLaughlin and others, 1988; Dibblee and Brabb, 1978; Sarna-Wojcicki and others, 1975). The Santa Cruz Mountains have attained their present elevation by thrusting Franciscan bedrock to the north over Quaternary alluvial deposits of the Santa Clara Valley.

We propose that a model incorporating bending-moment faults characterized by extensional tectonics in the hanging wall block and compressional tectonics in the footwall block can account for: (1) the ground fissures in the Summit Ridge area, (2) the geomorphology of the Summit Ridge area, (3) the compressional ground deformation documented along the Santa Cruz Mountains rangefront, (4) the system of range-front faults along this segment of the fault, and (5) the lack of primary right-lateral ground rupture along the trace of the San Andreas fault.

We further propose that the bending-moment faults themselves are the result of the geometry of the San Andreas fault zone in this region. The 70 km-long segment of the San Andreas fault that lies between Hollister and Saratoga, including all of the Loma Prieta rupture zone, represents a restraining bend in the fault. Along most of this segment, the fault strikes nearly 10° more northwesterly than the general N40°W strikes that characterize the fault zone to the south and the north. The Summit Ridge terrain and the other mountainous topography that are found along the fault in this region are the tectonic products of convergence between the Pacific Plate and the North American Plate where soft Tertiary marine sediments to the southwest are abutted against strong Mesozoic sedimentary and volcanic rocks to the north of the fault.

PALEOSEISMIC CONSIDERATIONS

It seems clear that the ground effects of the Loma Prieta earthquake were to a lesser extent a repeat performance of the great San Francisco earthquake of 1906. Field descriptions of the ground behavior along the crest of the Summit Ridge area in 1906 included the following observation by L.E. Davidson who was camping in the Santa Cruz Mountains during the earthquake:

The ridge on which we camped was full of cracks, ranging up to 2 and 3 feet in width and in length from a few rods to 0.25 miles, all trending west of north to northwest. . . The canyon south of us was filled with landslides. In this canyon the stratification of the rocks is plainly shown. The strike is northwest-southeast and the dip is almost vertical. The cracks coincide in direction with the strike of the strata. (Davidson, *in* Lawson, 1908, p. 278.)

These and other descriptions confirm the notion that the "characteristic" behavior of the Summit Ridge area to large earthquakes is the development of widespread landsliding on the steep flanks of the ridge and the production of ground fissures along the crest of the ridge. This segment of the San Andreas fault has had two large, well documented, historic earthquakes which have created field conditions (i.e., open fissures and closed depressions) which are ideal for the collection and preservation of seismic data. Therefore the ridge area should be considered as a primary target for paleoseismic research.

We believe that the timing of large-magnitude earthquake events on the San Andreas fault can be approximated by paleoseismic studies of second-order, ridgetop faults. This is especially true where normal faulting has provided topographic depressions which are capable of trapping sediments and thus recording earthquakes. Preservation of strata within such depressions is typically related to surface faulting events, and the timing of these events can be interpreted based on radiocarbon dating and soil stratigraphy. Because soil development reflects some degree of stability of a geomorphic surface, buried soils within a tectonic depression suggest intermittent stability separated by discrete rupture events. A package of buried soils would provide data on the number of rupture events and, because soil development is time-dependent, the relative amounts of time between faulting events.

If the seismotectonic behavior of the southern Santa Cruz Mountains segment of the San Andreas fault is characterized mainly by coseismic faulting in the bedrock of the upper plate of the rift zone, then studies of these second-order faults may be the only source of paleoseismic data available to define the return period of major earthquakes. It is important to emphasize that such studies would, at best, provide a *minimum* seismic record for earthquakes along this segment of the San Andreas fault.

The argument can be made, however, that the Late Quaternary behavior of the fault may be characterized by events like the 1989 Loma Prieta earthquake. This segment of the fault did not experience primary fault rupture within the upper 6 km of the crust in 1989 and may not have done so in 1906. Since the development of the restraining bend, the northwest migration of the Pacific Plate may never have been characterized by through-going rupture that reaches the earth's surface. Rather, the plate motion is manifested by a broad zone of deformation which is accommodated by arching and internal faulting of the hanging-wall block. Consequently, under the present tectonic setting, it may be reasonable to assume that primary ground rupture is not necessary along this segment of the San Andreas fault in order to reduce the seismic potential of the fault to lower levels.

ACKNOWLEDGMENTS

We would like to thank Bill Cole and Heidi Mack for their helpful discussions, review of our paper, and many valuable suggestions for its improvement. A special debt of thanks goes to Bob Sydnor of DMG for his encouragement, critical editorial comments, and constant prodding to complete our work. We thank Bill Cole for sharing with us his preliminary measurements of the deformation of the Wrights tunnel. Finally, we thank all of those geologists that we have had fruitful discussions with since October 17, 1989.

REFERENCES

rabb, E.E., 1989, Geologic map of Santa Cruz County, California: U. S. Geological Survey Miscellaneous Investigations Series Map I-1905, scale 1:62,500.

lark, J.C., 1981, Stratigraphy, paleontology, and geology of the central Santa Cruz Mountains, California Coast Ranges: U.S. Geological Survey Professional Paper 1168, 51 p.

lark, J.C., Brabb, E.E., and McLaughlin, R.J., 1989, Geologic map of the Laurel 7.5-minute Quadrangle, Santa Cruz and Santa Clara counties, California: U. S. Geological Survey Open-File Report 89-676, scale 1:24,000.

otton, W.R., Fowler, W.L., and Van Velsor, J.E., 1990, Coseismic bedding plane faulting associated with the Loma Prieta earthquake of October 17, 1989: EOS, Transactions of the American Geophysical Union, v. 71, no. 8, p. 287, (abstract).

bblee, T.W., Jr., and Brabb, E.E., 1978, Preliminary geologic map of the Los Gatos quadrangle, Santa Cruz and Santa Clara counties, California: U. S. Geological Survey Open-File Report 78-453, 1 plate, scale 1:24,000.

bblee, T.W., Jr., and Brabb, E.E., 1978, Preliminary geologic maps of the Chittenden, Los Gatos, and Watsonville East quadrangles, California: U. S. Geological Survey Open-File Report 78-453, 3 sheets, scale 1:24,000.

ibblee, T.W., Jr., and Brabb, E.E., 1980, Preliminary geologic map of the Loma Prieta quadrangle, Santa Cruz and Santa Clara counties, California: U. S. Geological Survey Open-File Report 80-994, 1 plate, scale 1:24,000.

bblee, T.W., Jr., Brabb, E.E., and Clark, J.C., 1978, Preliminary geologic map of the Laurel quadrangle, Santa Cruz and Santa Clara counties, California: U. S. Geological Survey Open-File Report 78-84, 1 plate, scale 1:24,000.

ill, N.T., Sarna-Wojcicki, A.M., and Dupré, W.R., 1974, Faults and their potential hazards in Santa Cruz County, California: U. S. Geological Survey Miscellaneous Field Studies Map MF-626, scale 1:62,500.

ırdin, B.C., O'Regan, G.T., and Cotton, W.R., 1990, Large-scale mapping of extensional ground cracks associated with the Loma Prieta earthquake of October 17, 1989: EOS, Transactions of the American Geophysical Union, v. 71, no. 8, p. 288, (abstract).

ıugerud, R.A., and Ellen, S.D., 1990, Deformation along the northeast foot of the Santa Cruz Mountains during the Loma Prieta earthquake: EOS, Transactions of the American Geophysical Union, v. 71, no. 8, p. 288, (abstract).

ırt, E. W., Bryant, W. A. Wills, C. J. and Tremain, J. A., 1990, The search for fault rupture and significance of ridgetop fissures, Santa Cruz Mountains, California: this volume, p. 83-94.

rns, D., 1990, Surface fractures from the Loma Prieta earthquake: evidence for tectonic extension?: EOS, Transactions of the American Geophysical Union, v. 71, no. 8, p. 288, (abstract).

Johnson, R.E., 1989, Fault investigation report, Loma Prieta Elementary School, Santa Clara County, California: Santa Cruz, CA, Rogers E. Johnson and Associates, unpublished consultant report.

Lawson, A.C., ed., 1908, The California Earthquake of April 18, 1906, Report of the State Earthquake Investigation Committee: Carnegie Institution of Washington, Publication no. 87, v. I, 451 p.

Lisowski, M., Prescott, W.H., Savage, J.C., and Svarc, J.L., 1990, A possible geodetic anomaly observed prior to the Loma Prieta, California, earthquake: Geophysical Research Letters, v. 17, p. 1211-1214.

MacGregor, B.A., and Truesdale, R., 1982, South Pacific Coast [Railroad] - a centennial: Boulder, Colorado, Pruett Publishing Company, 351 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.

McLaughlin, R.J., Clark, J.C., and Brabb, E.E., 1988, Geologic map and structure sections of the Loma Prieta 7.5-minute Quadrangle, Santa Clara and Santa Cruz counties, California: U. S. Geological Survey, Open-File Report 88-752, 32 p., scale 1:24,000.

Plafker, G., and Galloway, J.P., eds., 1989, Lessons learned from the Loma Prieta, California, earthquake of October 17, 1989: U. S. Geological Survey Circular 1045, 48 p.

Sarna-Wojcicki, A.M., Pampeyan, E.H., and Hall, N.T., 1975, Recently active breaks, San Andreas fault, Santa Cruz Mountains to Gabilan Range, California: U. S. Geological Survey Miscellaneous Field Studies, Map MF-650, 1:24,000.

Spittler, T.E., and Harp, E.L., 1990, Preliminary map of landslide features and coseismic fissures triggered by the Loma Prieta, California, earthquake of October 17, 1989: California Division of Mines and Geology Open-File Report 90-6, map scale 1:4,800.

Spittler, T.E., and Sydnor, R.H., 1990, Landslides and ridge-top failures associated with the epicentral area of the Loma Prieta earthquake of October 17, 1989: EOS, Transactions of the American Geophysical Union, v. 71, no. 8, p. 290, (abstract).

U.S. Geological Survey Staff, 1990, Apparent lithologic and structural control of surface fracturing during the Loma Prieta earthquake of October 17, 1989: EOS, Transactions of the American Geophysical Union, v. 71, no. 8, p. 290, (abstract).

Wells, R.E., Ponti, D.J., Clark, M.M., Bucknam, R.C., Budding, K.E., Fumal, T.E., Harwood, D.S., Lajoie, K.R., Lienkaemper, J.J., Machette M.N., Prentice, C.S., and Schwartz, D.P., 1989, Preliminary map of fractures formed in the Summit Road-Skyland Ridge area during the Loma Prieta, California, earthquake of October 17, 1989: U. S. Geological Survey Open-File Report 89-686, 1 plate, scale 1:12,000.

Yeats, R.S., 1986, Active faults related to folding, *in* Active Tectonics: National Academy Press, Washington, D.C., p. 63- 79.

EARTHQUAKE DAMAGE IN SOQUEL DEMONSTRATION STATE FOREST, SANTA CRUZ COUNTY

by

Trinda L. Bedrossian[1] and Julie A. Sowma[1]

ABSTRACT

A geologic reconnaissance of earthquake damage resulting from the 1989 Loma Prieta earthquake was conducted in Soquel Demonstration State Forest, Santa Cruz County. Particular emphasis was placed on road and stream channel failures that could pose potential slope stability and flooding hazards within and downstream from the state forest. New and reactivated landslides and other types of earthquake-related ground rupture were identified within the East Branch of Soquel Creek and the Amaya Creek drainages as areas that could cause blockage of the stream channels and result in future flooding along Soquel Creek. Numerous snapped tree trunks within the state forest indicate that the intensity of shaking was VIII or greater on the Modified Mercalli Scale.

More detailed geologic mapping is recommended to identify site-specific slope stability problems that could be encountered during road construction and other types of development associated with management of the forest.

BACKGROUND

Soquel Demonstration State Forest comprises about 1,200 hectares (ha) in the East Branch of Soquel Creek watershed, approximately 5 to 11 km north of the earthquake epicenter (Figure 1). At the request of California Department of Forestry and Fire Protection (CDF), geologists from the Division of Mines and Geology evaluated the earthquake damage to the state forest in the weeks following the Loma Prieta Earthquake (Bedrossian, 1990). The state forest is located in the Santa Cruz Mountains about 19 km northeast of the City of Santa Cruz and less than 16 km upstream from the town of Soquel. Soquel has suffered severe flood damage at least eight times since 1890 (Singer and Swanson, 1983). During the past 25 years, major land-use activities in the Soquel Creek watershed have been rural residential development and timber harvesting. The watershed currently supplies domestic water for approximately 40,000 customers.

The Soquel Creek watershed drains 109 km^2 on the southern flank of the Santa Cruz Mountains into the northern end of Monterey Bay; the main creek is about 18 km long. According to Singer and Swanson (1983), the mean annual precipitation in the upper watershed is over 102 cm and the recurrence interval for significant flooding is seven years. Flood hazards are increased throughout the watershed by: (1) the concentration and movement of logs and other large woody debris, and (2) landslides which move directly into the stream channels.

GEOLOGIC CONDITIONS

Soquel Demonstration State Forest is underlain primarily by a sequence of early- to mid-Tertiary marine sedimentary rocks that is highly folded and faulted with some units overturned (refer to Figure 2; and Wagner, this volume). The regional geology has been well mapped by Brabb (1989), Clark (1981), McLaughlin and others (1988), and Clark and others (1989).

The eastern third of the forest contains thin- to very thick-bedded arkosic sandstone with thin interbeds of siltstone of the Eocene-age Butano Sandstone formation. These rocks lie within the active San Andreas fault zone and have been subjected to both large- and small-scale downslope movement related in part to movement along the fault.

Rocks in the central portion of the forest are comprised of mudstone, shale, sandstone of the San Lorenzo Formation (Oligocene and Eocene), and Vaqueros Sandstone (lower Miocene and Oligocene).

The western portion of the forest is underlain primarily by mudstone of the lower Miocene-age Lambert Shale and very thick-bedded tuffaceous siltstone interbedded with andesitic sandstone of the Pliocene- and upper Miocene-age Purisima Formation. The conglomerate unit of the Butano Sandstone is present in the southwestern corner of the forest. The conglomerate is in contact with the Purisima Formation along the Zayante fault.

---

[1]California Department of Conservation, Division of Mines and Geology, Environmental Protection Program

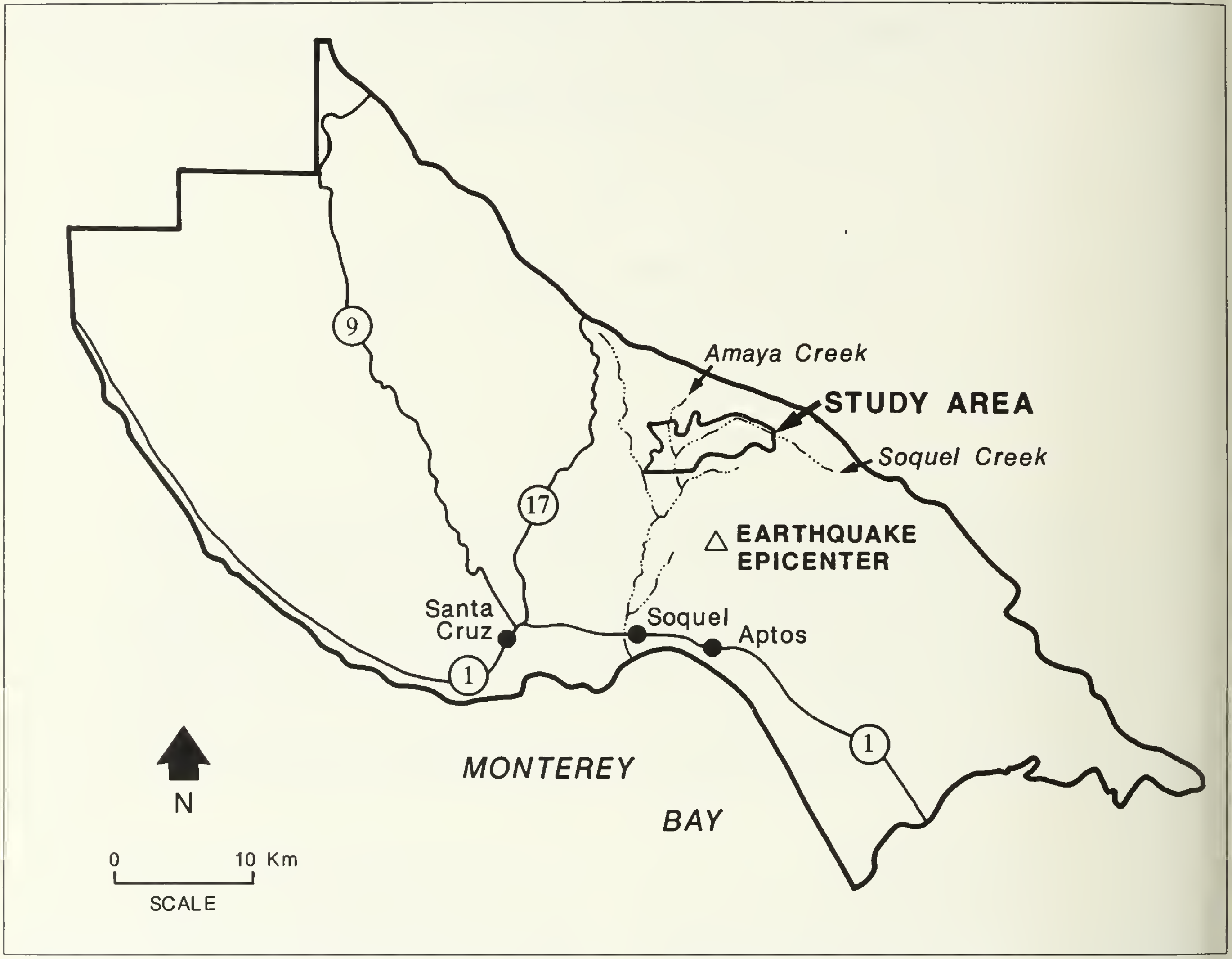


Figure 1. Location of study area in Santa Cruz County.

LANDSLIDES

Large, deep-seated translational/rotational landslides are present throughout the forest (Cooper Clark and Associates, 1975; Clark and others, 1989; McLaughlin and others, 1988). These large failures generally originate near or just below ridgetops and continue downslope to the stream channels. Although well-vegetated, these slides are characterized by steep slopes in the scarp areas and more gently sloped terrain broken by numerous benches within the landslide mass. Stream channels and tributary draws within these large landslides are often deeply incised and show evidence of smaller-scale, shallow-seated debris sliding where steep slopes have been undercut. The frequent benches and depressions within the more gently sloped portions of the slides may impair water drainage as indicated by numerous springs, wet areas, and sag ponds. Large-scale landsliding is enhanced by deeply weathered bedrock, steep slopes, and earthquake activity coupled with heavy, prolonged rainfall, according to Singer and Swanson (1983).

Many large landslides were generated during major earthquakes such as the April 1906 event (Lawson, 1908) and portions of many were reactivated during the October 1989 event. Slopes on which the underlying sedimentary bedding planes dip in the same direction as the slope are particularly prone to large-scale, deep-seated movement.

Smaller-scale slope failures are also present within the forest in the form of debris slides, debris flows, rockfalls, and localized rotational slumps. Many of the recent failures originated during or immediately after high intensity rainfall of January 3-5, 1982 (Blodgett and Poeschel, 1988). The October 17, 1989 earthquake reactivated some of these small-scale slides and generated many new ones (Spittler and Sydnor, 1990; Spittler and Harp, 1990). In general, the shallow-seated failures are located on steep slopes within the inner gorge of the stream channels and along steep road cuts. While some of the failures support scattered vegetation, many are characterized by unvegetated scars that are likely to ravel.

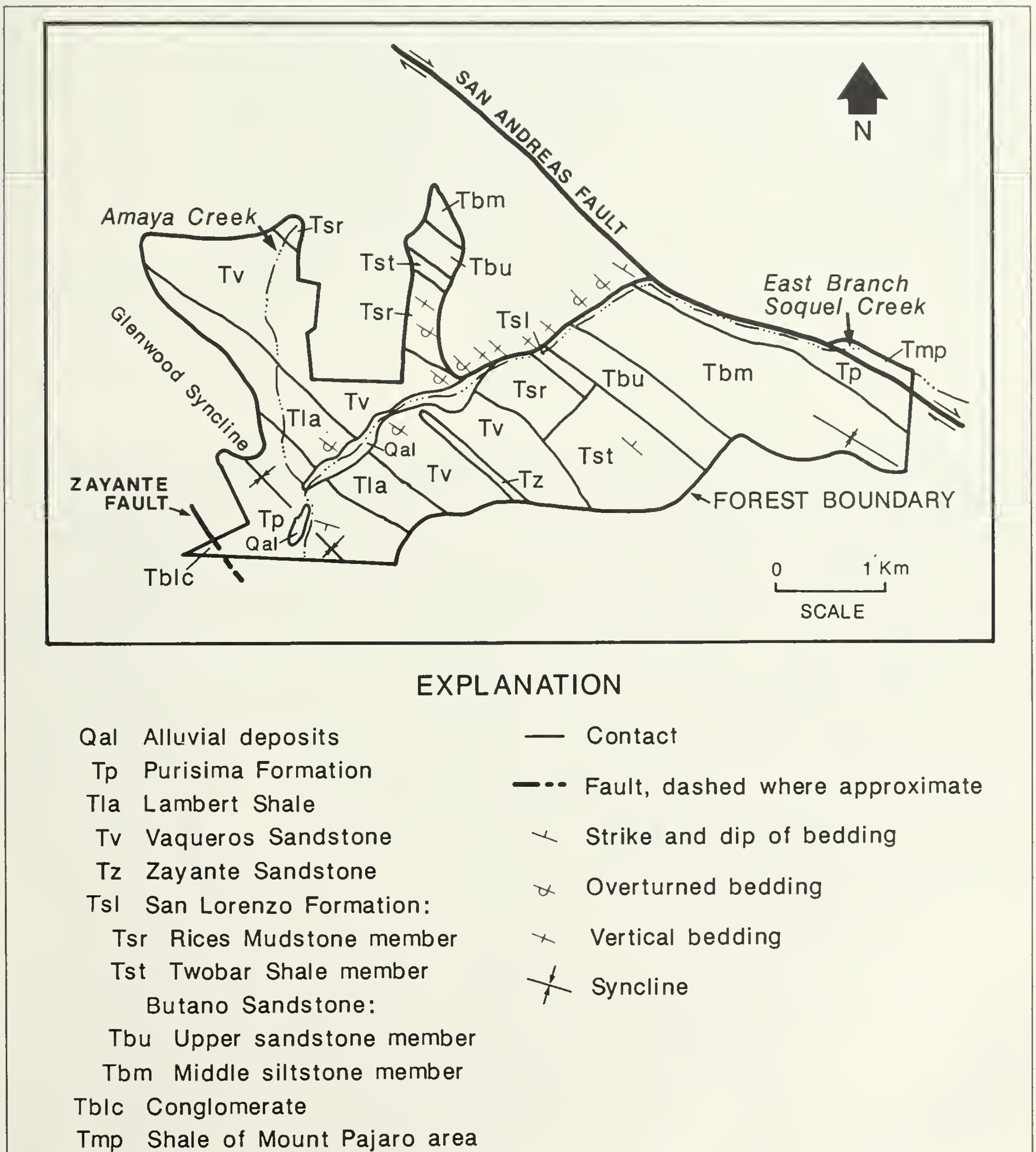


Figure 2. General geology of Soquel Demonstration State Forest (after Brabb, 1989).

EARTHQUAKE DAMAGE

Recent ground rupture resulting from the earthquake was associated primarily with the shaking of underlying soils and rock materials on steep slopes where there is a break in slope, whether natural or manmade, and where the soils are not buttressed from below. Many of the cracks followed previous landslide scarps and benches; some followed bedding planes across spur ridges; and others were associated with road cut and fill failures and stream bank failures resulting from shaking.

San Andreas Fault Zone

Magnitude 7 earthquakes along the San Andreas fault and other strike-slip faults worldwide commonly produce through-going surface faulting with a displacement of 1 to 2 m (USGS Staff, 1990, p. 290; Bonilla and others, 1984). However, the expected through-going surface faulting was not observed in preliminary reconnaissance of the epicentral region (Hart and others, this volume). Cotton and others (this volume) did find conclusive evidence of coseismic surface faulting along Highway 17 and in several other localities.

During this reconnaissance in Soquel Demonstration State Forest, many cracks were found over several discontinuous and indistinct zones. Reasons for the apparent lack of through-going surface-rupture include: (1) the unusual focal depth (18 km) apparently made it difficult for bedrock rupture to propagate to the ground surface; and (2) the complex rock and soil structures, the steep rugged topography of the Santa Cruz Mountains, the thick soil and the dense forest cover resulted in a multitude of landslides, cracks and fissures which may conceal evidence of surface fault rupture.

Numerous cracks and fissures were observed in the eastern third of the Soquel Demonstration State Forest, along inferred traces of the San Andreas fault mapped by the Division of Mines and Geology (1976). Where the main forest access road crossed the mapped fault trace in the eastern portion of the forest, a series of N50°W-trending, left-stepping cracks occurred within a 15-meter wide zone. The cracks were 0.6 to 1.5 m deep, 2.5 to 7.5 cm wide, and showed 2.5 to 7.5 cm of right-lateral offset with 2.5 to 7.5 cm of down-drop to the northeast. The cracks were traced laterally approximately 600 m to the northwest where numerous fissures with up to 1.5 m of vertical displacement were observed along the scarp of a large translational/ rotational landslide adjacent to Soquel Creek.

Numerous snapped tree tops 1.8 to 3.6 m in length were observed along the zone of cracks (Photo 1). This is an indication of Intensity VIII (or greater) on the Modified Mercalli Scale. The California Division of Mines and Geology's Strong Motion Instrumentation Program data from three nearby strong motion stations indicate that the near-field epicentral region (including all of Soquel Demonstration State Forest) experienced *horizontal* ground motion on the range of 0.44 g to 0.64 g and *vertical* ground motion in the range of 0.40 g to 0.60 g (Shakal and others, 1989; Shakal and others, this volume).

Although this series of cracks follows a mapped inferred trace of the San Andreas fault, many of the cracks and fissures probably are associated with the intense shaking and downslope movement of unstable soils along the fault trace rather than actual surface fault rupture (see Hart and others, this volume).

Photo 1 Ground rupture and snapped tree tops along the inferred trace of San Andreas fault zone adjacent to Soquel Creek. (Photo by Trinda L. Bedrossian)

Additional slope failures, including lebris slides, rock falls, and cracks asso-iated with landsliding, occurred along nferred and approximately located fault races throughout the forest. Sulfurous umes and associated rock-coating min-rals not previously reported were also oticed near earthquake-induced frac-ures and springs within the fault zone at wo locations.

Photo 2. Translational/rotational landslide blocking road at eastern edge of forest. (Photo by David Soho)

orest Roads

Most of the roadbeds within the Soquel emonstration State Forest suffered rela-vely minor damage as a result of the arthquake. Failures along secondary for-st roads observed in this reconnaissance onsisted primarily of cutslope failures the form of small debris slides, rock lls, boulder topples, and translational/ otational slumping resulting from shak-g.

One relatively large translational/rota-onal slide completely blocked the road the eastern edge of the forest for a stance of about 15 m (Photo 2). Addi-onal damage to the roadbeds occurred as a result of cracking along eep downslope free-faces and the failure of fill slopes. Many of the nall cracks and fill failures were located near or above steep scarps pre-existing landslides. Snapped tree tops resulting from the severe aking (MMI≥VIII) in these areas were commonly found in the cinity of the cracks.

Roadbed damage within the forest was most severe along the ridge ad on the eastern side of Amaya Ridge. Cracks 15 to 60 cm wide d up to 2.4 m deep were observed for a total distance of about 0 m near a pre-existing slide. On the north side of the slide, the adbed had dropped 0.6 to 1.5 m and loosely consolidated road and de materials were perched above 70 to 80% slopes. Cracks and all cutbank failures continued to the north along the road for about m. Additional large-scale landslide failure was reactivated farther wnslope where the existing mid-slope roadbed dropped 0.6 m or re and a rockfall covered a portion of the road. A series of N10°W-N45°W-trending cracks were traced southward from the road to a ctivated translational/rotational landslide scarp approximately 60 wide and 3 to 6 m high above 80 to 90% slopes. Trees below the rp were uprooted and/or tilted, and large boulders were exposed r the head of a debris torrent track located south of the large nslational/rotational slide. Large-scale reactivated translational/ ational landslide scarps were also observed below the mid-slope d adjacent to Amaya Creek (described below).

eam Channels

he stream channels of the East Branch of Soquel Creek and Amaya ek were heavily impacted during the storms of January 1982 and rch 1983. Numerous log jams and landslides along the inner gorge es of these drainages were mapped by Santa Cruz County (1986) their impacts described by Singer and Swanson (1983). Portions he East Branch of Soquel Creek and Amaya Creek located within state forest were re-examined after the earthquake.

East Branch of Soquel Creek - Within the state forest, the East Branch of Soquel Creek is generally characterized by two distinct types of morphology. Steep inner-gorge slopes immediately adjacent to the channel on the northern side of the drainage are prone primarily to debris sliding. In contrast, the southern side of the drainage, characterized by more gentle sloping, large-scale landslide terrain, is prone to translational/rotational slumping near the toes of the large slides and debris sliding on steeper slopes where the toes of the slides have been over-steepened and undercut by the stream.

Landsliding resulting from earthquake shaking along the East Branch of Soquel Creek consisted of reactivation of portions of the existing debris slides on the northern side of the channel. On the southern side of the drainage, earthquake shaking initiated several new but smaller-scale debris slides and rockfalls and downslope movement of loosely consolidated slide deposits along pre-existing landslide scarps. Although no new log jams were observed along the upper reaches of the East Branch of Soquel Creek, earthquake shaking caused small-scale sliding that resulted in the uprooting of trees and/ or the deposition of small amounts of rock and talus debris into the creek in several places. Along the narrows of the creek, numerous large cracks were observed along the steep rock face.

Amaya Creek - Failures within the Amaya Creek drainage appear to be related to, and partially controlled by, the geologic structure of the underlying bedrock units. This same type of structural control was noted in the Summit Ridge area by USGS Staff (1990) and Plafker and Galloway (1989). Steep slopes on both sides of the drainage are underlain by highly folded, faulted, and overturned beds that, in many places, dip in the same direction as the slope. In addition, the underlying rocks and soils are highly shattered and weathered, making them highly susceptible to translational/rotational slumping, earthflows, and debris slides. According to Singer and Swanson (1983), Amaya Creek was the second most severely impacted watershed in the Soquel Creek drainage during the 1982-83 storms. Most

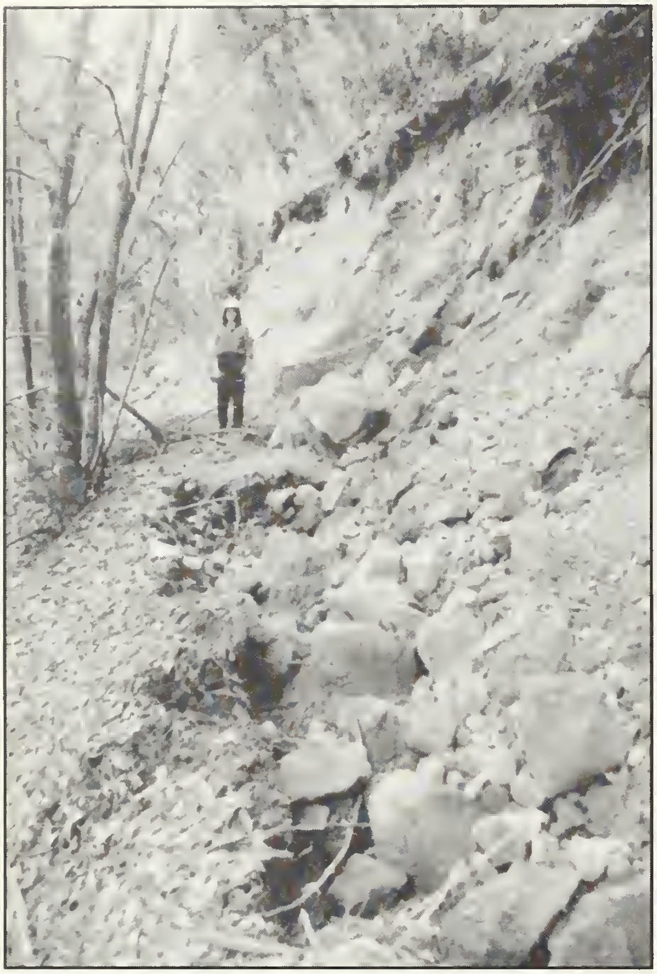


Photo 3. Landslide scarp on the west side of Amaya Creek. (Photo by David Soho)

Photo 4. Fresh cracks resulting from earthquake shaking upslope from Amaya Creek along the southeast side of the stream channel. (Photo by Trinda L. Bedrossian)

of the channel is characterized by continuous landsliding along both banks, which has deposited large quantities of woody debris, soil, and rock into the channel. In addition, the generally straight channel, which lies within over-steepened inner-gorge slopes undercut by channel scouring, has a high capacity to move large logs.

Landsliding resulting from earthquake shaking along Amaya Creek consisted of reactivation of existing slides on both sides of the stream channel and initiation of new failures on steep, unbuttressed slopes adjacent to the inner gorge. Renewed failure that resulted in the uprooting of trees and/or the deposition of small amounts of rock and talus debris into the creek occurred midway up the channel. Snapped tree tops associated with severe shaking (MMI≥VIII) were prevalent along the upslope scarps of these failures, particularly on the east side of the drainage. New and reactivated failures that resulted in partial blockage of the creek also occurred farther upstream. Small amounts of water were ponded behind two of the failures but appeared to be eroding small channels around them.

On the west side of the channel, earthquake shaking caused large-scale translational/rotational sliding and debris sliding approximately 75 m wide and 45 m long on 80 to 90% slopes adjacent to the channel. North of the slide, failure along inner-gorge banks resulted in a 3 m-high scarp, with failed materials remaining perched above the channel (Photo 3). On the southeast side of Amaya Creek, multiple sets of fresh cracks up to 1 m wide and 2.4 m deep were observed for a distance of about 150 m on 80% slopes, 30 to 45 m upslope from the stream channel (Photo 4).

CONCLUSIONS

Two primary hazards to public safety resulting from earthquake damage within Soquel Demonstration State Forest consist of: (1) cutslope failures along existing roads and horse trails in the form of small debris slides, rock falls, boulder topples, and translational/rotational slumping; and (2) areas of potential landsliding along the East Branch of Soquel Creek and Amaya Creek drainages that could result in blockage of the stream channels, flooding of the alluvial flats within the forest, and subsequent movement of logs and other large woody debris farther downstream during high water flows. The construction of roads and hiking/horse trails on slopes with high landslide potential resulting from earthquake shaking could also pose a hazard to public safety should these slopes fail in the future.

Areas of high landslide potential were identified where cracks occurred on or above steep slopes, particularly where the soils and underlying rock materials are not buttressed from below. Many of the cracks followed previous landslide scarps and benches; some followed bedding planes across spur ridges; and others were associated with road cut and fill failures and downslope movement along stream banks. Three areas of particular geologic concern include: (1) the east side of Amaya Ridge, (2) both sides of the entire Amaya Creek channel, and (3) selected slopes along Soquel Creek. A high landslide potential may also exist where steep slopes and the toes of landslides are undercut by streams and/or existing and proposed roads.

Areas that could result in flood-related hazards within and downstream from the forest include existing and potential slope failures located primarily in the Amaya Creek drainage. The downstream movement of debris into existing log jams within the East Branch of Soquel and Amaya creeks drainages could also result in future flooding problems.

As a result of this reconnaissance geologic field work, the California Department of Forestry and Fire Protection is taking measures to periodically monitor these potential hazard areas to assess the degree and urgency of remedial work needed within the drainage. In addition, more detailed geologic mapping of the forest will be conducted at an appropriate scale to identify site-specific slope stability problems that could be encountered during road construction, timber harvesting, and other types of development associated with management of the forest. These specialized geologic mapping methods are outlined in six Division of Mines and Geology publications by Huffman (1977), Huffman and Bedrossian (1979), Bedrossian (1983), Bedrossian (1986a and 1986b), and CDMG Note 54 entitled "Guidelines for Geologic Reports Prepared for Timber Harvesting Plans."

ACKNOWLEDGMENTS

Assistance in the field was provided by Richard Boylan (DMG), Nancy Drinkard (CDF), and David Soho (CDF). The authors also express their appreciation to Joy Sullivan and Ross Martin for completion of drafting and layout design, and to Robert H. Sydnor for his editorial comments.

REFERENCES

Bedrossian, T.L., 1983, Watersheds mapping in northern California: California Geology, v. 36, no. 7, p. 140-147.

Bedrossian, T.L., 1986a, An update [on] watersheds mapping in northern California: California Geology, v. 39, no. 2, p. 34-38.

Bedrossian, T.L., 1986b, Geologic recommendations for timber harvesting: California Geology, v. 39, no. 6, p. 134-138.

Bedrossian, T.L., 1990, Reconnaissance geologic review of earthquake damage in Soquel Demonstration State Forest resulting from the October 17, 1989 Loma Prieta earthquake, Santa Cruz: California Department of Conservation, Division of Mines and Geology, Open-File Report 90-03, 26 p., map scale 1:1,000.

Blodgett, J.C., and Poeschel, K.R., 1988, Peak discharge, volume, and frequency of the January 1982 flood in the Santa Cruz Mountains and vicinity, *in* Ellen, S.D., and Wieczorek, G.F., eds., 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, p. 229-243.

Bonilla, M.G, Mark, R.K., and Lienkaemper, J.J., 1984, Statistical relations among earthquake magnitude, surface rupture length, and surface fault displacement: Seismological Society of America Bulletin, v. 76, no. 6, p. 2379-2411.

Brabb, E.E., 1989, Geologic map of Santa Cruz County, California: U.S. Geological Survey Miscellaneous Investigations Series Map I-1905, scale 1:62,500.

Clark, J.C., 1981, Stratigraphy, paleontology, and geology of the central Santa Cruz Mountains, California Coast Ranges: U.S. Geological Survey Professional Paper 1168, 51 p.

Clark, J.C., Brabb, E.E., and McLaughlin, R.J., 1989, Geologic map and structure sections of the Laurel 7.5-minute quadrangle, Santa Cruz and Santa Clara Counties, California: U.S. Geological Survey Open-File Report 89-676, scale 1:24,000.

Cooper Clark and Associates, 1974, Preliminary map of landslide deposits in Santa Cruz County, California: Santa Cruz County, Planning Department, Seismic Safety Element of the County General Plan, 1 sheet, scale 1:62,500.

Cotton, W. R., Fowler, W. S., and Van Velsor, J. E., 1990, Coseismic bedding plane faults and ground fissures associated with the Loma Prieta earthquake of 17 October 1990: this volume, p. 95-103.

County of Santa Cruz, 1986, Stream Survey: III Soquel System A to Z, Amaya Creek and East Soquel Creek: Unpublished report, map scale 1:24,000.

Division of Mines and Geology, 1976, Alquist-Priolo Special Studies Zones, Laurel and Loma Prieta quadrangles: California Division of Mines and Geology, scale 1:24,000.

Hart, E. W., Bryant, W. A., Wills, C. J., and Treiman, J. A., 1990, The search for fault rupture and significance of ridgetop fissures, Santa Cruz Mountains, California: this volume, p. 83-94.

Huffman, M.E., 1977, Geology for timber harvest planning, north coastal California: California Geology, v. 30, no. 9, p. 195-201.

Huffman, M.E., and Bedrossian, T.L., 1979, The role of the geologist in timber harvesting plan review: California Geology, v. 32, no. 6, p. 115-119.

Lawson, A.C., ed., 1908, The California Earthquake of April 18, 1906: Report of the California State Earthquake Investigation Commission: Carnegie Institution of Washington, Publication 87, v.1, 451 p.

McLaughlin, R.J., Clark, J.C., and Brabb, E.E., 1988, Geologic map and structure sections of the Loma Prieta 7.5-minute quadrangle, Santa Clara and Santa Cruz counties, California: U.S. Geological Survey, Open-File Report 88-752, 32 p., scale 1:24,000.

Plafker, G., and Galloway, J.P., eds., 1989, Lessons learned from the Loma Prieta, California, earthquake of October 17, 1989: U.S. Geological Survey Circular 1045, 48 p.

Shakal, A.F., Huang, M-J., Reichle, M.S., Ventura, C., Cao, T.,Sherburne, R.W., Savage, M., Darragh, R.B., and Petersen, C., 1989, CSMIP strong-motion records from the Santa Cruz Mountains (Loma Prieta), California earthquake of 17 October 1989: California Division of Mines and Geology, Report No. OSMS 89-06, 196 p.

Shakal, A. F., DeLisle, M. J., Reichle, M. S., and Darragh, R. B., 1990, Strong ground shaking from the Loma Prieta earthquake of 17 October 1989 and its relation to near surface geology in the Oakland area: this volume, p. 29-46.

Singer, S., and Swanson, M.L., 1983, Soquel Creek storm damage recovery plan: U.S. Soil Conservation Service, 71 p.

Spittler, T.E, and Harp, E.L., 1990, Preliminary map of landslide features and coseismic fissures triggered by the Loma Prieta, California, earthquake of October 17, 1989: California Division of Mines and Geology Open-File Report 90-6, map scale 1:4,800.

Spittler, T.E., and Sydnor, R.H., 1990, Landslides and ridge-top failures associated with the epicentral area of the Loma Prieta earthquake of October 17, 1989: EOS, Transactions of the American Geophysical Union, v. 71, no. 8, p. 290, (abstract).

U.S. Geological Survey Staff, 1990, The Loma Prieta, California, earthquake: an anticipated event: Science, v. 247, p. 286-293.

Wagner, D. L., 1990, Geologic and tectonic setting of the epicentral area of the Loma Prieta earthquake, Santa Cruz Mountains, Central California: this volume, p. 1-10.

REPRESENTATIVE DAMAGE PHOTOGRAPHS FROM THE LOMA PRIETA EARTHQUAKE

by

David R. Montgomery[1]

ABSTRACT

The types and distribution of damage from the Loma Prieta earthquake reflected both the earthquake magnitude and the influence of distance, local geology, and building design and materials. In steep terrain near the epicenter high peak accelerations, localized ground surface rupture, and massive landsliding caused considerable damage. In other less steep areas near the epicenter, structural damage was severe in many unreinforced masonry buildings and older residences underlain by unconsolidated alluvium. Liquefaction was widespread in sandy alluvial deposits throughout the Monterey Bay area. Farther from the epicenter, damage was concentrated in areas underlain by alluvium, bay mud, and sandy artificial fill and preferentially impacted building types generally considered susceptible to damage during earthquakes.

INTRODUCTION

The Loma Prieta earthquake lasted only 15 seconds but had wide- :aching effects. The magnitude 7.1 earthquake was felt throughout ıost of California. Sixty-three people were killed, 3,757 injured, and ıany thousands rendered homeless (Plafker and Galloway, 1989; ES, 1989). Total public and private property damage exceeded $6 llion, emergency response services cost millions, and millions more commerce were lost due to economic disruption. The general types ıd distribution of damage, however, varied as a function of distance om the earthquake epicenter and local geologic conditions. The ırposes of this article are to describe the broad damage patterns and show representative photographs of different types of damage.

The Modified Mercalli (MM) intensity scale (Table 1) provides a ıalitative method for describing the intensity of ground shaking .sed on relative effects on people, buildings, and the ground surface. gure 1 shows the generalized distribution of MM intensities for the ›ma Prieta Earthquake (Stover and others, 1990). Ground shaking ıs generally most destructive near the earthquake epicenter, its ıpact diminishing with increasing distance. However, amplifica- ·n of ground shaking due to local surficial deposits (Borcherdt, 70) resulted in areas of anomalously high MM intensity at great ıtances from the epicenter.

DAMAGE NEAR THE EPICENTER

Damage from severe ground shaking was extensive in the Santa Cruz Mountains. Peak horizontal accelerations of 0.64 g were measured near the earthquake epicenter (Shakal and others, 1989; Shakal and others, this volume) and local peak accelerations may have approached 1.0 g (McNally and others, 1989). Eyewitness reports of household items flying across rooms and evidence for water tanks becoming temporarily airborne also suggest extreme peak vertical accelerations on narrow ridge tops in the Santa Cruz Mountains. To date, some 4,875 residences in unincorporated areas of Santa Cruz County have been inspected for earthquake-related damage (D. Houghton, personal communication, 1990). Some houses were thrown from their foundations (Photo 1) and many residences were damaged by extensive ground cracking and landsliding. One massive slope failure closed the northbound lanes of Highway 17 for 33 days. Large slumps initiated by the earthquake severely damaged dozens of homes in the Redwood Estates and Villa del Monte subdivisions. These and many other similar landslides which initially moved relatively little may become chronically unstable during heavy winter rains. The potential for future deformation of these massive landslides during large-magnitude earthquakes is undoubtedly large.

ɘpartment of Geology and Geophysics, University of California, Berkeley

Table 1
Modified Mercalli intensity scale.

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 or 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.

(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 above.)

In flatter terrain on the margins of the Santa Cruz Mountains ground shaking also caused extensive damage, especially in the communities of Los Gatos, Santa Cruz, and Watsonville. Discontinuous northwest trending zones of deformed sidewalks and curbs extended from Los Gatos to Palo Alto and may reflect secondary movement on thrust faults that parallel the trend of the San Andreas fault (Plafker and Galloway, 1989). In the town of Los Gatos approximately 31 commercial buildings and 318 residences experienced damage totalling an estimated $240 million (D. Figone, personal communication, 1990). Much of this damage was highly localized and involved masonry structures or older residences (EQE,1989). On the Stanford University campus near Palo Alto, 25 out of the 60 damaged buildings require structural reinforcement or repair, with a total damage estimate of $160 million (McKnight and others, 1990; J. Shirkin, personal communication, 1990).

In Santa Cruz damage to commercial properties was on the order of $51 million, residential structures sustained damage estimated at $50 million, and damage to municipal properties totaled $12 million (C. Schmitt, personal communication, 1990; D. Stuendorf, personal communication, 1990). The nearby University of California campus suffered roughly $5.8 million in total damage, $4.8 million of which was from structural damage (T. O'Leary, personal communication, 1990). The greatest impact was concentrated in the downtown Pacific Garden Mall and several residential blocks of mostly older homes. Both of these areas are underlain by recent alluvium deposited by the San Lorenzo River (Clark, 1981), and ground shaking in these areas was probably more severe than in neighboring areas underlain by older, more consolidated marine terrace deposits. Damage to the downtown mall was extensive in older

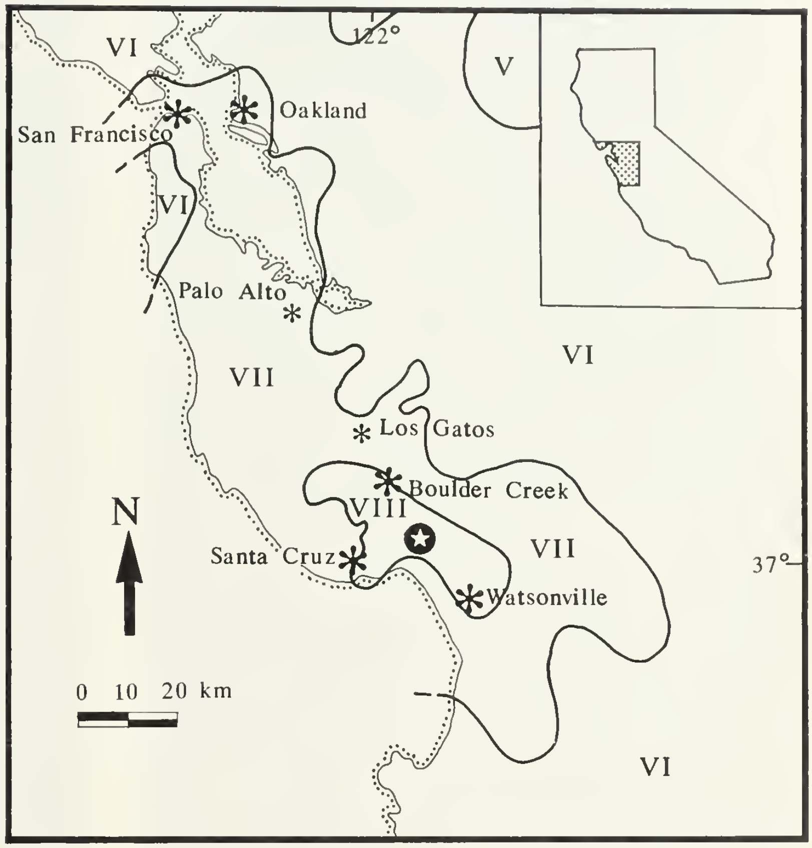


Figure 1. Map showing distribution of Modified Mercalli ground shaking intensities from the Loma Prieta earthquake (modified from Stover and others, 1990). Ground shaking of MM intensity VIII was estimated for the epicentral region. Localized ground shaking of MM intensity IX occurred in parts of San Francisco and Oakland underlain by artificial fill and bay mud. White star within black circle represents location of earthquake epicenter. Large asterisks represent general locations of photographs presented in this article. Smaller asterisks are other locations mentioned in the text.

Photo 1. House thrown from its foundation near Summit Road in the Santa Cruz Mountains.

Photo 2. Partially collapsed masonry building in the Pacific Garden Mall, Santa Cruz.

Photo 3. Collapsed chimney in the heavily damaged residential area of Santa Cruz (from Montgomery, 1990).

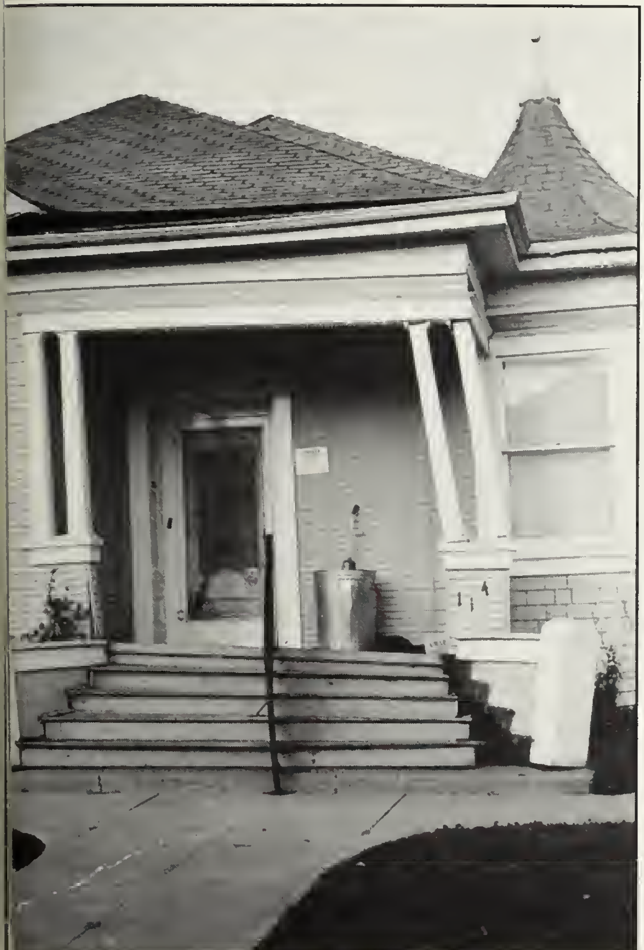
brick buildings (EQE, 1989) (Photo 2) and several people were killed when they were buried under rubble. Roughly 375,000 square feet of commercial space in 23 buildings have already been demolished. Extensive damage in the residential area near Myrtle and Laurel streets primarily involved collapsed chimneys and porches, and various foundation failures (Photo 3). One building in this neighborhood burned to the ground, apparently as a result of a gas line rupture. An example of the value of seismic retrofitting is provided by the relative impact on the houses in this neighborhood. Residences that had recently been structurally upgraded were essentially undamaged by the earthquake while many unretrofitted houses experienced severe damage (EQE Engineering, 1989).

Similar patterns of damage occurred in the town of Watsonville. Brick buildings were extensively damaged in the downtown area, and many older residential structures suffered partial collapse due to foundation failure (Photo 4). Liquefaction of unconsolidated, saturated, sandy deposits occurred throughout the alluvial plains and near the coast from Santa Cruz to near Salinas. Post-earthquake mapping indicates that the areas exhibiting evidence of liquefaction coincide with areas previously mapped as susceptible to liquefaction (Plafker and Galloway, 1989). Perhaps the most dramatic example of damage in this area was the collapse of a portion of Highway 1 spanning Struve Slough as a result of strong shaking that may have been enhanced by liquefaction (Photo 5).

DAMAGE FAR FROM THE EPICENTER

The intensity of ground shaking generally decreased with increasing distance from the epicenter for sites underlain by bedrock or relatively consolidated alluvium. In contrast, sites underlain by bay mud did not exhibit much attenuation of ground acceleration with distance from the epicenter (Plafker and Galloway, 1989). Not surprisingly, damage far from the earthquake epicenter was concentrated in areas underlain by soft soil artificial fill and bay mud, deposits prone to liquefaction or amplified ground surface accelerations.

Ground shaking in San Francisco was greatest in the poorly consolidated natural and manmade sediments on the margin of San Francisco Bay; and most of the roughly $2 billion in damage occurred in parts of the Marina, South of Market, and Mission districts mapped as being underlain by landfill (Schlocker, 1974). Throughout the city 22 buildings suffered damage sufficient to warrant their demolition, 363 were declared unsafe; and 1,250 designated as suitable only for limited access pending repairs (City of San Francisco, 1990; L. Kornfield, personal communication, 1990). The Marina District, one of the hardest hit areas of San Francisco, is located on an old lagoon that was filled to accommodate construction of the Panama-Pacific Exhibition, which celebrated the rebuilding of the city after the devastating 1906 earthquake and fire. Sand boils and evidence of lateral spreading



oto 4. Structural damage to a Victorian-style house in Watsonville.

Photo 5. Collapsed section of Highway 1 at Struve Slough near Watsonville. The young alluvium underlying the failed portion of the structure had been identified as having a high potential for liquefaction (Dupré, 1975).

s;gest that liquefaction of sandy fill c ıtributed to the extensive damage in t ; area. Many of the devastated struct :s were three-and four-story apartr'nt complexes with parking garages c the first floor (Photo 6). The limited s ar resistance offered by the open c ign of their lowest floor makes such t ldings particularly vulnerable to coll se during violent shaking or lateral s eading of the underlying ground ( )E, 1989; Plafker and Galloway, 1 ;9). Measurements of ground accele :ions during aftershocks indicate that p k accelerations at nearby, minimally i ›acted sites underlain by natural dune s ds were similar to those experienced i ıe heavily damaged area, suggesting tl a combination of ground deformat ı and susceptible building design c sed much of the damage (Plafker and C loway, 1989). Lateral spreading of f nay have also damaged water mains, h ıpering initial efforts to fight fires re s ing from the earthquake.

Photo 6. Collapsed apartment building in the Marina District of San Francisco.

Photo 7. Partially collapsed portion of Interstate 880 near 13th and 14th streets in west Oakland.

Many unreinforced masonry buildings in the South of Market District were severely damaged by ground shaking, and six fatalities resulted from the partial collapse of one brick structure (Plafker and Galloway, 1989). Strong ground shaking also damaged buildings located on the site of a filled lagoon in the Mission District.

Across the bay in Oakland, damage was concentrated in areas mapped as being underlain by manmade fill, bay mud, and sandy alluvium (Radbruch, 1957). The 1.5 mile-long collapsed portion of Interstate 880 (Cypress structure) was underlain by thin bay mud and artificial fill, whereas the portion of the structure that did not fail was underlain by older alluvium (Shakal and others, this volume). This correlation suggests that locally modified ground motion may have contributed to the disastrous pancaking of the freeway (Photo 7), although this issue is not yet completely resolved. Similar sections of Highway 280 and Highway 480 (Embarcadero Freeway) in San Francisco were closed as a result of earthquake-caused damage and may eventually be demolished. Liquefaction and lateral spreading caused damage in other areas underlain by sandy fill and bay mud on the eastern margins of the bay. Lateral spreading damaged the Port of Oakland (Photo 8), and liquefaction of sandy fill also caused damage on the approaches to the San Francisco-Oakland Bay Bridge, at Oakland International Airport, and at Alameda Naval Air Station.

Photo 8. Pavement disrupted by lateral spreading of sand fill in the Port of Oakland.

In the city of Oakland some 1,400 residential, 200 commercial, and 12 public buildings sustained damage estimated at $29 million, $750 million, and $250 million, respectively (City of Oakland, 1989). Thirteen commercial buildings were also destroyed at an estimated loss of $234 million, bringing the estimated damage total to almost $1.3 billion (excluding demolition and construction costs relating to the Cypress Structure). Much of the structural damage occurred in areas underlain by older alluvium where ground shaking should not have been as great as in the filled areas near the bay. The buildings in west Oakland that partially collapsed or were thrown off their foundations generally were either older Victorian-style or masonry structures that had not been seismically upgraded. Similarly, much of the damage in downtown Oakland, which is also underlain by older alluvium, was concentrated in masonry buildings (Photo 9).

hoto 9. Partially collapsed unreinforced masonry building in downtown Oakland.

CONCLUSIONS

The types and distribution of damage caused by the Loma Prieta earthquake illustrate that local geologic conditions profoundly influenced the particular types of damage likely to impact an area during seismic shaking (see Borcherdt, 1975, for a discussion of seismic zonation in land-use planning). The concentration of damage in areas underlain by sandy manmade fill graphically illustrates the increased seismic hazard associated with building on such deposits. Fatalities in San Francisco and Santa Cruz were concentrated in unreinforced masonry buildings. The highly localized nature of damage from the Loma Prieta earthquake may not, however, be representative of the hazard potential of all larger earthquakes. The DMG earthquake planning scenarios for large earthquakes on the San Andreas and Hayward faults outline areas of expected damage, especially in heavily urbanized areas (Davis and others, 1982; Steinbrugge and others, 1987). Unfortunately, knowing where earthquake-related damage will be greatest does not, in and of itself, reduce seismic hazards. The modification of land-use practices and reinforcement of existing potentially hazardous buildings are also required.

REFERENCES

Borcherdt, R.D., 1970, Effects of local geology on ground motion near San Francisco Bay: Bulletin of the Seismological Society of America , v. 60, p. 29-61.

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.

City of Oakland, 1989, Earthquake related issues fact sheet, 12-19-89, 5 p.

City of San Francisco, 1990, "Red Tag" buildings interim status report, January 24, 1990, City of San Francisco, Department of Public Works, Bureau of Building Inspection, 180 p.

Clark, J.C., 1981, Stratigraphy, paleontology, and geology of the central Santa Cruz Mountains, California Coast Ranges: U.S. Geological Survey Professional Paper 1168, 51 p.

Davis, J.F., Bennett, J.H., Borchardt, G.A., Kahle, J.E., Rice, S.J., and Silva, M.A., 1982, Earthquake planning scenario for a magnitude 8.3 earthquake on the San Andreas fault in the San Francisco Bay area: California Division of Mines and Geology Special Publication 61, 160 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.

EQE Engineering, 1989, The October 17, 1989, Loma Prieta earthquake, A quick look report: San Francisco, California, 40 p.

McKnight, C.L., Fehlhaber, K.L., Heubeck, C., and Sleep, N.H., 1990, Seismic damage at Stanford University from the October 17, 1989 Loma Prieta earthquake: EOS, Transactions of the American Geophysical Union, v. 71, no. 8, p. 289, (abstract).

McNally, K.C., Lay, T., Protti-Quesada, M., Valensise, G., Orange, D., and Anderson, R.S., 1989, Santa Cruz Mountains (Loma Prieta) earthquake: EOS, Transactions of the American Geophysical Union, v. 70, no. 45, p. 1463, 1467.

Montgomery, D.R., 1990, Effects of the Loma Prieta earthquake, October 17, 1989, San Francisco Bay Area: California Geology, v. 43, p. 8-13, 24.

OES (California Office of Emergency Services), 1989, executive summary, December 18, 1989, 4:00 p.m., 3 p.

Plafker, G., and Galloway, J.P., eds., 1989, Lessons learned from the Loma Prieta, California, earthquake of October 17, 1989: U.S. Geological Survey Circular 1045, 48 p.

Radbruch, D.H., 1957, Areal and engineering geology of the Oakland West Quadrangle, California: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-239.

Schlocker, J., 1974, Geology of the San Francisco North Quadrangle, California, U.S. Geological Survey Professional Paper 782, 109 p.

Shakal, A.F., DeLisle, M.J., Reichle, M.S., and Darragh, R.B., 1990, Strong ground shaking from the Loma Prieta earthquake of 17 October 1989 and its relation to near surface geology in the Oakland area: this volume, p.29-46.

Shakal, A.F., Huang, M.J., Reichle, M.S., Ventura, C., Cao, T., Sherburne, R.W., Savage, M., Darragh, R., and Petersen, C., 1989, CSMIP strong-motion records from the Santa Cruz Mountains (Loma Prieta), California earthquake of 17 October 1989: California Division of Mines and Geology, Report No. SMS 89-06, 196 p.

Steinbrugge, K.V., Bennett, J.H., Lagorio, H.J., Davis, J.F., Borchardt, G.A., and Toppozada, T.R., 1987, Earthquake planning scenario for a magnitude 7.5 earthquake on the Hayward fault in the San Francisco Bay area: California Division of Mines and Geology Special Publication 78, 243 p.

Stover, C.W., Reagor, G.R., Baldwin, F.W., and Brewer, L.R., 1990, Preliminary isoseismal map for the Santa Cruz (Loma Prieta), California, earthquake of October 18, 1989 UTC: U.S. Geological Survey, Open-File Report 90-18, 24 p.

U. S. Geological Survey Staff, 1990, The Loma Prieta, California, earthquake, An anticipated event: Science, v. 247, p. 286-293

ACKNOWLEDGMENTS

This paper is primarily based on a brief survey of damage during the days immediately after the earthquake, technical information on the earthquake subsequently published by the USGS, and interviews with local officials. A number of people were exceptionally helpful. In particular, I wish to thank Cheryl Schmitt and Dick Stubendorff (City of Santa Cruz), Linda Schroff (City of Oakland), Deborah Figone (City of Los Gatos), Darcy Houghton (Santa Cruz County), Lawrence Kornfield (City of San Francisco), Tom O'Leary (U.C. Santa Cruz), and Joel Shirkin (Stanford University). Many specific impacts of the earthquake are not covered to the extent that they deserve to be, and this broad overview should not be considered comprehensive. Any inadvertent errors of fact or interpretation are regretted and remain my responsibility. I also thank Joachim Hampel for technical assistance in preparing and printing photographs and Whole Earth Access for a timely donation of film the morning after the earthquake.

SECTION III
Earthquake Response

HIGH-ALTITUDE U-2 PHOTOGRAPHY FOR POST-EARTHQUAKE DISASTER ASSESSMENT

by

Charles R. Real[1], Robert E. Yoha[2], and Fumio Kaneko[3]

ABSTRACT

High-altitude U-2 photography was obtained of the San Francisco Bay region soon after the Loma Prieta earthquake, using an IRIS-II panoramic camera. The photographs were analyzed for evidence of structural damage and ground effects. The high resolution photography permitted ground viewing at scales up to 1:800 or about 1 inch equals 67 feet. Areas of liquefaction were readily identified on the imagery and later verified by field inspection. Although objects as small as 6 inches could be seen when contrast was high, only severe structural damage could be easily recognized. The imagery proved valuable for quickly assessing the regional scope of certain types of major structural damage.

INTRODUCTION

The morning following the Loma Prieta earthquake, the 9th Strategic Reconnaissance Wing (9th SRW) of Beale Air Force Base conducted an overflight of the San Francisco Bay region using U-2 aircraft to obtain photo coverage of the affected area in place of a routine training mission. This imagery was made available to Division of Mines and Geology (DMG) staff for post-earthquake assessment of damage and effects through the Governor's Office of Emergency Services. While the United States Air Force does not routinely provide such imagery for civilian use, this special circumstance presented a unique opportunity for government agencies to provide information of use in immediate disaster relief planning and also to evaluate the usefulness of unclassified U-2 photography for studying the effects of earthquakes on the land and engineered structures. Such unclassified high-altitude photography is also commercially available through other sources, so experience with this specific application would help provide a relative cost/benefit comparison as a basis for future considerations.

The Geologic Hazards Assessment Program of the Department of Conservation's Division of Mines and Geology collects, analyzes, interprets, and disseminates information on geologic hazards in California for the safety and welfare of the public. As a means of improving our ability to recognize hazardous areas well in advance of a disaster, program staff respond to damaging events by conducting field studies and making observations of their effects. Because the effects of earthquakes upon the land and engineered structures are short-lived, assessments must be made soon after the event. In many instances repairs in the San Francisco Bay region began almost immediately after shaking from the Loma Prieta earthquake ceased. Thus, from a regional damage assessment point of view, the scope of the disaster must be quickly determined, and a method of rapidly inventorying damage and shaking effects over a large geographic area must be used. With early reports of catastrophic collapse and widespread damage immediately following the Loma Prieta earthquake, aerial photography seemed to provide such a method.

Our purpose for investigating the use of U-2 photography is to determine the usefulness of the U-2 platform for making such assessments. Such photography can be used to rapidly assess the severity and geographic extent of damage, and to provide necessary imagery for a long-term study of the relationships between earthquake damage and effects, observed ground shaking, and near-surface geology. This paper discusses our preliminary conclusions on the utility of U-2 photography for post-earthquake disaster study. We first introduce the characteristics of the U-2 platform, and then provide some examples of its utility in the wake of the Loma Prieta earthquake.

---

[1]California Department of Conservation, Division of Mines and Geology, Geologic Hazards Assessment Program
[2]California Department of Conservation, Office of Land Conservation
[3]OYO Corporation, Japan

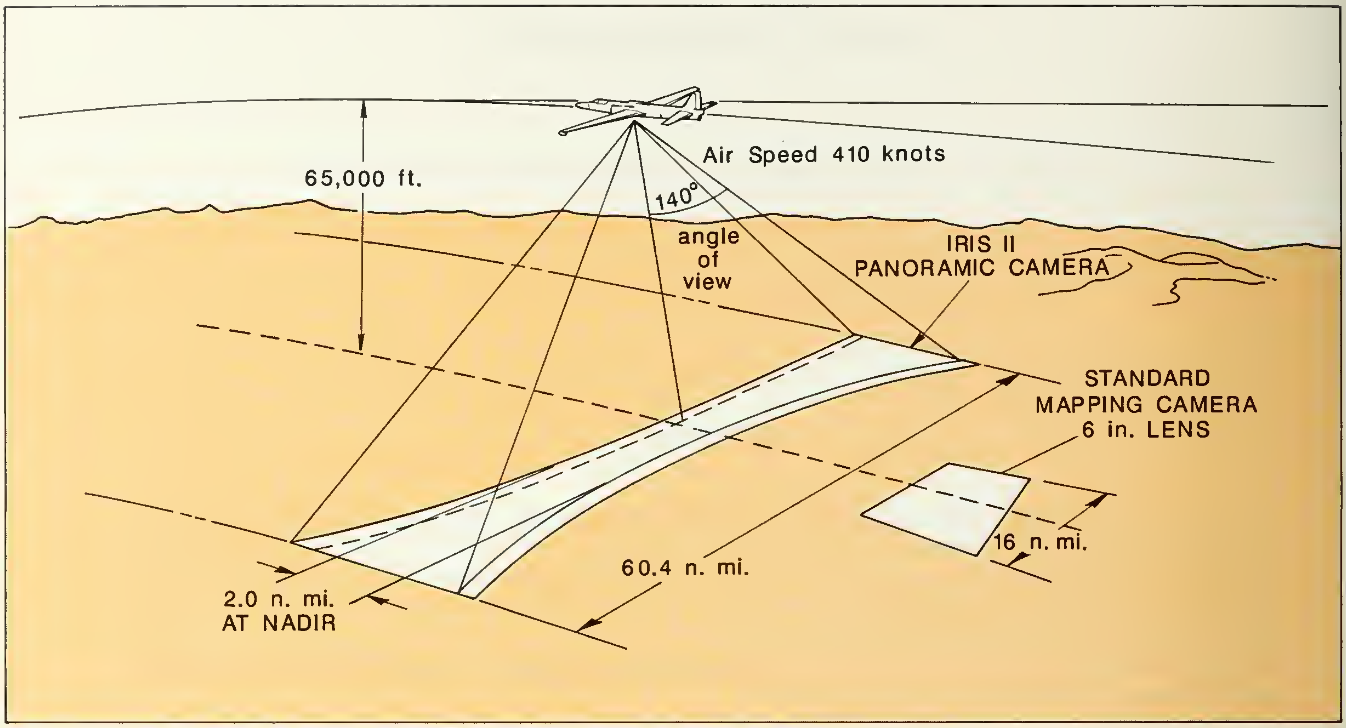


Figure 1. High Altitude Photographic Coverage. Diagram after NASA sketch, showing aircraft 65,000 feet above ground with panorama footprint directly below and to the side. Along the same flight path is the footprint of a 6-inch focal length mapping camera.

THE U-2 HIGH-ALTITUDE PHOTOGRAPHY PLATFORM

The U-2 aircraft is designed to operate above atmospheric turbulence at altitudes between 60,000 to 70,000 feet, thereby assuring a stable photographic platform. Its cruising speed of 410 knots (470 miles per hour) and duration of 8 hours aloft yield a range of 3,000 nautical miles (3,460 statute miles). An extensive array of photographic and electronic sensors can be mounted in two equipment bays in the fuselage and in two detachable wing pods. The 9th SRW used the U-2R, a recent variant of the U-2 aircraft series which has been operational since the late 1950's. Commercially available high altitude photography from NASA utilizes the ER-2 aircraft, an enhanced version of the U-2.

The 9th SRW equipped their U-2R aircraft with an IRIS-II panoramic camera manufactured by the Itek Corporation. The camera looks 70 degrees to the left and right of the aircraft's path, yielding a 140 degree panorama of the ground below. From 65,000 feet above the ground, the camera photographs a footprint of about 60.4 miles from left to right. Image width varies from approximately 2.3 miles directly under the aircraft and increases to approximately 6.7 miles wide at either side. At this height, image scale varies from 1:32,000 at the center of the negative directly below the aircraft (nadir), to approximately 1:94,000 off-nadir at the extreme oblique angle found at the far edges of the negative. Figure 1 illustrates the angle of view and compares the IRIS-II footprint with that of a standard 6-inch focal length mapping camera.

The IRIS II employs a folded optical system with an equivalent focal length of 24 inches. Image format is 5 inches by 60 inches. Film capacity of the camera is 10,000 linear feet with thin base film. The camera utilizes a continuously-rotating, folded optical system referred to as an optical bar. Both the lens and the film move in precise synchronization. The rate of film transport and lens rotation varies as a function of velocity and altitude. Single camera convergent stereographic coverage is accomplished by tilting the entire optical assembly forward or aft prior to each exposure.

The 9th SRW provided 16x20 inch black and white prints ranging from 5X to 40X enlargement. Military reconnaissance missions have shown that black and white format provides the most desirable contrast for structural damage assessment. Sophisticated computer controlled equipment and the high resolving power of the film emulsion makes it possible to obtain prints with extremely fine detail, even at enlargements as great as 40X. Print scale varies with the look angle and enlargement factor. Looking straight down a 40X enlargement yields a print with a scale of 1:800 or one inch equals 67 feet. At 70 degrees off-nadir, a 40X print has a scale of 1:2,352 or 1 inch equals 196 feet on the ground.

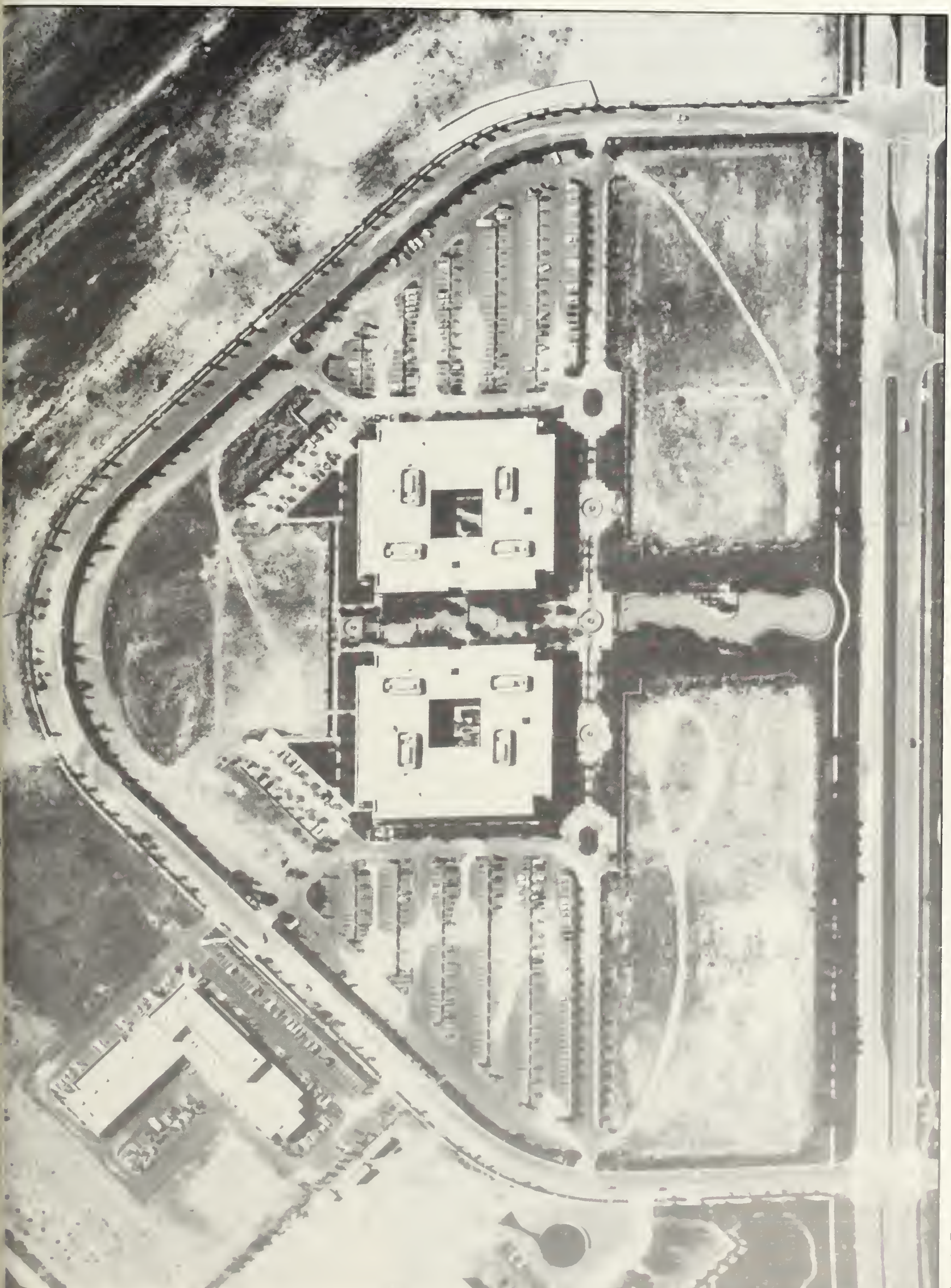


Photo 1 Twenty times enlargement of a portion of an IRIS-II panoramic camera aerial photograph showing liquefaction in a parking lot of an industrial park complex in Alameda. Notice white patches of sand against black asphalt in parking lots on both sides of complex.

Interpretation is best done using a second generation film positive, copied from the original negative, on a backlighted table equipped with viewing optics. The film positive image stands up well at magnifications of 50X and greater. Prints lose a certain amount of detail upon enlargement; however, it is still possible to observe objects as small as 6 inches across on a 20X vertical print.

Panoramic photography makes it possible to obtain both vertical and oblique views from the same camera and flight. The panoramic image provides the interpreter with three distinct views, vertical and oblique to either side of the flightline. If one side of the area/object of interest is in shadow or masked, it is a simple process to locate an adjoining flight line and choose a corresponding view looking from the other side, providing hills or mountains do not mask the area/object from the adjoining flightline. Having both a vertical and oblique print of the same scene is extremely useful because the amount of information that can be extracted from the pair is much greater than using one or the other alone. Oblique and vertical scenes make it possible to assess spatial information, without resorting to stereo interpretation, greatly facilitating the assessment of vertical objects such as buildings and other structures. Stereo interpretation is possible using IRIS-II images; however, this is best done with the film positive on a light table using stereo viewing equipment.

While the imagery used in this study is not available for public or private use, IRIS-II imagery and remote sensing services are commercially available from NASA's High Altitude Aircraft Program at NASA/AMES Research Center, Moffett Field, California.

ANALYSIS OF LOMA PRIETA EARTHQUAKE COVERAGE

Method of Analysis

The IRIS-II coverage was flown October 18, 1989 in the morning approximately 16 hours after the earthquake. We examined our first frames by noon, October 19, 1989, and began systematically evaluating the photography by about 3:00 p.m., about 48 hours after the earthquake. Our approach was to first identify sites of known reported damage to allow some level of "calibration" for photo-interpretive damage analysis. Analysis was done viewing a film positive with a motorized optical comparator, which allowed magnification to 30 times. Once a known damage site was evaluated, a reconnaissance of damage in the area immediately surrounding the site was made. Questionable observations were noted for subsequent field inspection and the next known damage site was then evaluated.

On-line reports from the Governor's Office of Emergency Services were used to select damage sites for analysis. Limited ground verification was available from media reports on television. After the first few hours of analysis, a discrepancy was apparent between the information given by the news media of the extent of regional damage, and what was beginning to unfold from air photo analysis. Damage was not uniformly high, nor even moderate, over the Bay region, but was instead very concentrated geographically. Information provided by the news media was not systematic throughout the region, but was focused instead on several severely damaged areas. In contrast, within 24 hours after the earthquake the high-altitude imagery showed the first clear indication of the regional extent of damage and thereby demonstrated the value of the imagery for such assessments.

Specific Examples of Damage and Effects

Three broad categories of structures were examined for damage detection: (1) Transportation, (2) Utilities, and (3) Buildings. In many instances where photo interpretation was questionable, the structures were later visited on-site to verify suspected damage or ground effects. The field inspection team consisted of DMG staff and geotechnical engineers with OYO Corporation of Japan, who were immediately dispatched to the affected area to gather information for a company reconnaissance report. DMG had already been cooperating with OYO Corporation in the exchange of hazard assessment technology, and the earthquake provided an opportunity to conduct joint field observations.

Transportation - Observed damage to highway bridges and overpasses included the collapsed Cypress segment of the Nimitz Freeway (Interstate 880) in Oakland, the failure of the San Francisco-Oakland Bay Bridge span and liquefaction along the toll plaza approach and the collapse of U.S. Route 1 in Watsonville. Less obvious damage was observed at bridge crossings over the San Lorenzo River in Santa Cruz, which field inspection proved to be the result of lateral spreads and abutment failure, and separation at the abutment of University Avenue overcrossing of U.S. 101 in Palo Alto. Fresh black asphalt patches about two feet wide on each abutment were readily visible on the imagery. Extensive liquefaction and runway damage were apparent at the Oakland International Airport and Alameda Naval Air Station. The latter revealed a lineation of liquefaction along seams between old hydraulic fill sea walls and newer bay fill supporting bayward expansions of the airport (Lee and Praszker, 1969).

Utilities - Leakage of gasoline storage tanks was observed at oil refineries located in Richmond, Pinole, and Rodeo. No structural damage was apparent, and leakage may have resulted from seiche-induced breaching. Damage to a switching yard at Moss Landing electric power generating station was observed. The partial collapse of KGO radio transmitting towers east of the Dumbarton Bridge was particularly evident on oblique images. Also observed were effects of buried water lines that ruptured. In most cases their effects could not be distinguished from liquefaction.

Buildings - Building damage proved difficult to verify on imagery unless very severe and accompanied by partial roof collapse, twisting, tilting, or wrenching of structures. Of many severely damaged structures in the Santa Cruz mall, only two clearly revealed partial roof collapse that was easily identified on the IRIS-II imagery. A school building at Santa Cruz High School having suspected damage was later proven to be undamaged. Practically none of the single family structures suffering foundation failure could be identified.

Foundation failure is usually accompanied by a downward settling of the structure one foot or so, which is not visible from overhead or oblique high-altitude photography. Of course, serious internal damage to buildings can go unnoticed from outside the building even at ground level. The more dramatic failures, such as in the Marina area of San Francisco where structures were severely tilted or twisted out of alignment with adjacent structures, were readily identified on the imagery.

A

Photo 2. (A) Ground level photograph of liquefaction in parking lot of industrial complex (Photo by Charles R. Real) shown in Photo 1. (B) Close-up view of damaged area (Photo by Fumio Kaneko).

B

Ground failures - As mentioned, liquefaction :ffects accompanied by the ejection of water and sand (flow failure) were generally identifiable on IRIS-II imagery (Photos 1 and 2). Because of good contrast, dry sand was more easily seen on dark ground or pavement, while wet sand was nore easily seen on light colored ground. One case of suspected liquefaction at a high school football field in Santa Cruz proved not to be iquefaction, but runoff from water sprinklers. What appeared to be liquefaction along the boardwalk in Santa Cruz and at some locations near a shopping mall in Alameda, turned out, upon field nspection, to be ruptured water mains that had brought sand and water to the ground surface. We speculate that failure of the water mains probably esulted from liquefaction at depth.

Most of the damage related to slope failure ocurred in the Santa Cruz Mountains. Except for arge failures that removed vegetation or that occurred along open road cuts, most landslides vere difficult to identify because of dense vegeation. These conditions were severe enough that ven conventional low altitude aerial photography vas only marginally useful. In one instance, a 10-oot diameter block of rock broke off a cliff and ropped about 15 feet to rest alongside a small parking lot behind a store in Santa Cruz. The ailure could not be identified on the IRIS-II nagery because of lack of contrast between the allen block and similarly-colored talus slope.

CONCLUSIONS

A limited analysis of IRIS-II U-2 aerial photography has shown the value of high-altitude imagery for post-earthquake disaster assessments of damage and ground effects caused by a regional M7 event. It provided DMG scientists and management with the first region-wide view of the scope of the disaster, greatly clarifying misleading perceptions from sensationalized news media reports. Care and control during processing of film, contrast of objects under surveillance, time of day, and sun angle contribute to the level of damage detectability using the IRIS-II U-2 platform. While a 10 foot diameter rock could not be detected under conditions of poor contrast, 6 inch wide yard lines on a football field could be readily distinguished because of high contrast of white chalk lines against dark green grass.

Structural collapse can usually be recognized on IRIS-II imagery. Lesser damage to buildings must be severe, at least involving partial roof collapse, tilting, twisting of the structure, or other physical displacement in order to be recognized. Partial collapse of bridges, or misalignment with abutments and adjacent roadways are identifiable. In some cases minor separation of bridge abutments was identified by the strong contrast of dark, new asphalt patches against light-colored pavement.

Ground failures can also be recognized on IRIS-II imagery. The surface expulsion of sand associated with liquefaction is readily identifiable in some cases, as are hillside scars caused by slope failure.

Many of the damage or ground features detectable on high altitude imagery would probably also have occurred in a smaller earthquake occurring in a more localized urban area. However, we believe that the high-altitude IRIS-II imagery would be most useful under conditions of higher uniform damage than that caused by the Loma Prieta earthquake.

REFERENCES

Lee, C. J., and Praszker, M., 1969, Bay mud developments and related structural foundations, *in* Goldman, H. B., ed., Geologic and engineering aspects of San Francisco Bay fill, California Division of Mines and Geology Special Report 97, p. 43-85.

Miller, J., and Pocock, C., 1988, Lockheed U-2R/TR-1: Aerofax Minigraph Number 28.

Slama, C.C., ed., 1980, Manual of Photogrammetry, 4th ed.: American Society of Photogrammetry, Section 4.2.2, p. 196- 209.

ACKNOWLEDGMENTS

We thank Brigadier General Lawrence Mitchell, Commander, 14th Air Division, Beale Air Force Base, and the 9th Strategic Reconnaissance Wing for acquiring this imagery and making it available to government agencies responding to the Loma Prieta earthquake disaster. Chris Higgins of DMG assisted with initial air photo interpretation. We also thank Major John Dieken and First Lieutenant Steve Wilcox of the 9th Strategic Reconnaissance Wing, and Steve McNutt of DMG for reviewing the manuscript and making helpful suggestions.

LOMA PRIETA EARTHQUAKE RESPONSE ACTIVITIES OF THE DIVISION OF MINES AND GEOLOGY

by

Robert Streitz[1], Robert H. Sydnor[2], Allan G. Barrows[2], and Thomas E. Spittler[3]

ABSTRACT

The Division of Mines and Geology (DMG) responded to the Loma Prieta earthquake in five ways: (1) immediate data gathering, analysis of a developing situation, and briefings to state government officials and the news media working through the Governor's Office of Emergency Services (OES), (2) searching the epicentral area for surface rupture, (3) quick retrieval and timely publication of records from DMG strong motion stations, (4) field assistance to local government agencies in Santa Cruz and Santa Clara counties regarding landslides in the epicentral area, and (5) publication of earthquake information.

Initial field deployment of geologic staff was made using the DMG Event Response Plan which assigns appropriate projects to respond to a geologic event. One week after the event, the response plan was modified to allow geologists from other DMG projects to aid in landslide risk analysis.

Scientific publications resulting from the DMG response effort include California Strong Motion Instrumentation Program reports, four poster sessions presented at the December 1989 meeting of the American Geophysical Union in San Francisco, articles in California Geology magazine, open-file reports, and this special publication.

INTRODUCTION

The Loma Prieta earthquake was felt at 5:04 p.m. on Tuesday, October 17, 1989 in all three offices of the Division of Mines and Geology (DMG): felt sharply (MMI VI) in the Bay Area Regional Office in Pleasant Hill (with power outages); felt as a long rolling event (MMI IV) in Sacramento (from the long-period waves); and barely perceptible (MMI II) in Los Angeles.

Based on the DMG Event Response Plan and past experience, staff immediately began to gather information to determine the location and magnitude of the earthquake and the likely distribution of geologic effects that would require DMG response. The purpose of this article is to document DMG response activities and to provide a summary of specific lessons learned following the event. Since magnitude 7 earthquakes occur infrequently in California, this information may be of value to DMG staff and others who may need to respond to comparable events in the future. Much of the information presented here could not be anticipated in advance of the earthquake, but could only be obtained during actual response to the event.

INITIAL ACTIVITIES

A Public Contact Office was set up by 5:24 p.m. on October 17. The State Geologist and a Senior Seismologist immediately went to the State Headquarters of the Governor's Office of Emergency Services (OES) to provide technical information to that critical command post. The California Strong Motion Instrumentation Program (CSMIP) manager made plans to dispatch several teams of technicians to the Bay area to retrieve strong-motion records. Plans were made by the Fault Evaluation and Zoning project manager to put two teams into the epicentral area early Wednesday morning. Concurrently, the Landslide Hazard Identification project (LHIP) manager mobilized his team for field work, sending in several geologists from Los Angeles, Sacramento and Pleasant Hill.

From 5:19 to 8:45 p.m., 21 telephone calls were handled by the Public Information Office. Most of the calls came from local (Sacramento) and Bay area radio stations, television stations, and newspapers. On the first evening, there were no telephone communications in or out of the epicentral area; the telephone lines in the Bay area were overloaded with 20 million calls. Thus, field mobilization plans had to be made by program managers, based on the

[1]California Department of Conservation, Division of Mines and Geology, Publications and Information Program
[2]Division of Mines and Geology, Geologic Hazards Assessment Program
[3]Division of Mines and Geology, Environmental Protection Program

assumption that widespread damage had occurred throughout the epicentral region. Scientific communications between DMG and the U. S. Geological Survey (USGS) were hindered because telephone lines, computers, and electrical power were out of service at USGS offices in Menlo Park.

PUBLIC CONTACT OFFICE IN SACRAMENTO

The main purpose of the DMG Public Contact Office following a significant geologic event, such as the Loma Prieta earthquake, is to provide reliable geologic information to State and local emergency officials, to the news media, to earth science professionals, and to the public. The Public Contact Office staff provides background data on earthquakes and the geology of California and answers specific geologic questions. Calls to DMG came from across the country and from as far away as Japan and Australia.

DMG staff were hampered by regional post-earthquake telecommunications problems, so early information gathering relied on monitored television and radio broadcasts. As communications improved, technical information from DMG field geologists was provided to the Public Contact Office. Part of the service provided by the Public Contact Office was the clarification of unverified information on fault rupture.

In this regard, the two most important responsibilities of the Public Contact Office were: (1) to verify such reports before they were passed on to the news media and to the public, and (2) to correct erroneous reports as soon as accurate reports based on reliable (first-hand) field observations were received. During the first few days following the earthquake, findings were communicated to DMG management through the Public Contact Office.

For the first 16 days following the earthquake, the Public Contact Office responded to 152 calls from the news media, including radio, television and the press. The calls ranged from single quick questions, to reviews and updates about the event, to in-depth interviews regarding geology and seismicity of California as it relates to the Santa Cruz Mountains and this specific earthquake.

FIELD WORK DURING THE FIRST WEEK

The initial phase of field investigations was carried out between Wednesday morning, October 18 and Sunday evening, October 22, 1989. The Fault Evaluation and Zoning project sent two teams into the field early Wednesday morning following the main shock. Two geologists teamed up to inspect road crossings in the southern epicentral area (Hecker Pass Road to Hollister). A second team of two geologists inspected the northern epicentral part of the San Andreas fault. Here they found abundant ridgetop fissures and many large landslides, but found no through-going fault rupture on the San Andreas fault, as had been anticipated. LHIP geologists were mobilized early on the morning of October 18th. That night, DMG geologists met at the USGS offices in Menlo Park to coordinate State and federal field activities.

U-2 imagery of the San Francisco Bay area taken on October 18 was obtained from Beale Air Force Base. This imagery was available to DMG staff for specific studies (see Real and others, this volume). One other task completed during the first week following the earthquake involved assisting earth scientists from other areas in their earthquake research.

A DMG engineering geologist worked with the Santa Cruz County Geologist for five days following the mainshock, then returned to Sacramento with videotapes of epicentral landslide damage for review by DMG management. Landslides in the Santa Cruz Mountains and along the coastline affected hundreds of persons, leaving many homeless.

At the request of the Regional Director for OES Region II, a LHIP geologist from the DMG Pleasant Hill office provided information about earthquake-related geologic hazards to OES staff on Monday, October 23, 1989. The two offices are located adjacent to each other, facilitating close liaison between the two state agencies.

FIELD WORK DURING THE NEXT TWO MONTHS

Santa Cruz County Activities

One week after the earthquake, DMG responded to a request for assistance and technical advice from the Santa Cruz County Office of Emergency Services. The county requested DMG to evaluate the geologic hazards from reactivated large landslides.

Due to the urgent nature of the task and because of concern for public safety, five geologists from additional DMG programs were assigned to the initial systematic reconnaissance of the rugged terrain in the epicentral area.

A geologist with the LHIP set up a clearinghouse in the Santa Cruz County Emergency Operations Center. Data acquired by team members, the USGS, and other geologists were plotted on a master set of topographic maps. Specific notes regarding individual landslides were keyed to numbered site locations and entered into a computer database. This clearinghouse was maintained for four weeks. Following the initial evaluation of the most critically affected areas in Santa Cruz County, other DMG geologists and some private consulting geologists joined the team.

DMG geologists, in cooperation with USGS geologists, prepared a set of large-scale maps of the epicentral area in Santa Cruz County. These maps were prepared to: (1) provide county officials with regional landslide information that could be used for timely rehabilitation of damaged areas; (2) identify disturbed ground which is potentially vulnerable to debris flows during upcoming winter rains; (3) provide county planning officials with specific geologic hazard information that will be used for effective land-use decisions; and (4) document regional landslide features that might not otherwise be recognized during individual site investigations for reconstruction, remedial grading, or for future development. The landslide mapping products resulted in DMG Open File Report 90-6 and two technical papers prepared for the American Geophysical Union Fall Meeting.

Large-scale mapping of a 3,500 hectare (ha) zone in the epicentral region of the Santa Cruz Mountains identified several areas where earthquake-triggered landslides pose an on-going hazard to public safety (see Spittler and others, this volume). In response to this hazard, Santa Cruz County applied to the Federal Emergency Management Agency (FEMA) for assistance in evaluating the hazard. A Technical Advisory Group was formed, consisting of scientists and engineers from the U.S. Army Corps of Engineers (the managing agency), Santa Cruz County, the U. S. Geological Survey, U.C. Santa Cruz, the Santa Cruz County geologic review consultant, and DMG. The Technical Advisory Group began meeting in November 1989 and has overseen the collection of a large amount of data. The group is scheduled to continue to oversee the collection and analysis of slope-stability data through the winter of 1990-1991.

Santa Clara County Activities

Within a week of the earthquake, an urgent request for geologic assistance was received from the Santa Clara County Office of Emergency Services. Although not as common or widespread as in Santa Cruz County, landsliding was locally very damaging in the Santa Cruz Mountains portion of Santa Clara County, particularly in the villages of Redwood Estates, Chemeketa Park, Holy City, the Summit Road area, Aldercroft Heights, and the road to Lake Elsman. The LHIP manager set up a clearinghouse and provided a communications link between geologists in the field and the County Emergency Services personnel at the Emergency Operations Center in San Jose. Two LHIP geologists were called in to examine sites in the Summit Ridge area where cracking or other manifestations of ground failure that appeared to threaten homes were reported. Rapid evaluations were made of these localities, and the county was able to determine where significant problems existed and where many other features were not threatening to dwellings. This clearinghouse in San Jose was maintained for five days. The LHIP geologists then joined the team working in Santa Cruz County.

Other DMG Response Activities

The California Department of Forestry and Fire Protection (CDF) requested that the DMG Timber Harvest Project (THP) geologists, who are under long-term contract to CDF for review and analysis of geologic conditions affecting timber harvesting, perform an assessment of Soquel Demonstration State Forest, which is located in a remote mountainous area very near the epicenter. The results of that field work are reported by Bedrossian and Sowma (1990, this volume).

Timely briefings on the earthquake were given by DMG management to the Director of the Department of Conservation, to the State Mining and Geology Board, to the Governor's office, and to the Legislature. On January 11-12, 1990 a briefing and field tour of the epicentral region was given in Santa Cruz to the entire State Mining and Geology Board.

ADDITIONAL FIELD MAPPING

In mid-January 1990, two geologists from the Fault Evaluation and Zoning project returned to the Summit Road area, along the border of Santa Cruz and Santa Clara counties. Six work days of field mapping were performed to restudy the complex fissures, cracks, and scarps along the Summit Road area and Skyland Ridge. It was necessary to perform the field work before winter rains obscured fragile surficial features. The results of that field work are presented by Hart and others (1990, this volume).

On April 18, 1990, there were several aftershocks in the Watsonville area; the largest shock had a magnitude of 5.4. Two geologists from DMG's Pleasant Hill office responded, but found no surface rupture. Some small slope failures occurred along Highway 129 at River Oaks (near Chittenden). Dozens of sand boils formed in Soda Lake, where similar features formed during the Loma Prieta earthquake.

DMG's Landslide Hazard Identification project and the USGS have plotted the seismically-induced slope failures that resulted from the Loma Prieta earthquake on 7.5-minute quadrangle maps. These maps will be published as a joint DMG-USGS Open-File Report. DMG expects to publish a revised version of this report in the near future.

LESSONS LEARNED

This was the largest earthquake in 37 years in California. Some lessons that we learned in responding may prove useful to others in similar circumstances.

1. For a large magnitude earthquake, local government agencies need considerable help with ***landslides*** if the epicentral area is one with steep relief and has many scattered homes.

2. It is important for government geologists to be certain about the ***extent of large landslide complexes*** which may involve dozens of homes. County officials should be briefed on large landslide situations in a timely manner; in turn, officials should then notify constituent homeowners.

3. The complex and overlapping occurrence of geologic features such as landslide scarps, ground fissures, and other surficial effects tend to obscure the distinction between precise earth sciences investigations. An ***event response plan*** should thus call for broadly trained personnel to investigate landsliding, surface faulting, liquefaction and other earthquake-related geologic processes, products, and land forms.

4. ***Professional familiarities*** developed over years of liaison between state and county geologists are the foundation of close cooperation during an emergency event. Professional civil service staff at the local, state and federal level (geologists, planners, building officials, public works engineers, OES staff, and others) are essential to successful emergency response efforts.

5. ***Telephone communications*** cannot be relied upon for several days following a large earthquake. A pre-arranged general response plan must be followed. Routine communications with a centralized headquarters and clearinghouse are possible only after several days. Pay telephones may be used during daytime operations where available and functional in the epicentral area, but most calls should be made and received late at night or early in the morning. Cellular phones, where available, are very useful. Daytime telephone communications are readily made (without repetitive dialing) by the second week following the main shock.

6. The ***voice-mail system*** and personal home ***telephone recorders*** are useful communications devices for late-night and early morning messages during the first week of emergency response activities. In the future, it may be desirable to carry telephone recorders into the field for use in motel rooms and so gain the advantage of receiving out-going messages from a centralized headquarters.

7. ***Facsimile machines (fax)*** are used to great advantage during the earthquake response. There is lasting value to a typewritten field memorandum; it does not get garbled as a third-hand transcribed telephone message.

8. A ***computer bulletin board*** is useful for both internal communications and for disseminating public information. It may be more widely utilized in future years, as more persons become familiar with bulletin board systems and as more persons acquire computers equipped with modems.

9. ***Radio communications*** between geologists in Santa Cruz County were efficiently carried out using hand-held FM radios loaned by the County. It is an advantage to be on the same radio network as local county officials for coordination of communications.

10. Emergency response plans need to recognize that ***vehicle congestion*** is a very real delay in effective geologic field work. In order to perform their duties, it was necessary for DMG geologists to obtain passage through police roadblocks. Only OES-issued disaster worker ID cards were uniformly effective in gaining access through the blockades. Official logos on hats and vehicle doors, red safety vests, and Diamond-E state vehicle license plates were generally helpful.

11. ***Portable computers*** can be used effectively in the clearinghouse by field geologists. Field geologists can return each evening and enter new field site descriptions directly onto the computer; these are keyed to numbered site locations marked on a wall map composed of 7.5-minute topographic maps. Computerized data files may be sent via modem between the clearinghouse and other emergency offices.

12. A hand-held ***video camera*** is a useful method to record field notes and ephemeral data. Videotapes can be edited later for many diverse purposes, such as: (1) technical briefings for internal management; (2) news media and documentaries; (3) professional meetings and conferences; and (4) academic instructional uses.

13. ***Public schools*** within the epicentral area serve as important disaster recovery centers for local residents, families, and hundreds of school-aged children. The Red Cross and county government officials set up assistance centers at public schools. County supervisors may give evening townhall briefings to concerned local residents. These public schools would be useful places to display geologic maps and daily earthquake data to keep local residents informed in a timely manner.

14. Newly developed ***aftershock probabilities*** by Reasenberg and Jones of the USGS provided a useful quantitative method to answer questions from anxious homeowners in the epicentral area. For example, statements could be made that there was a certain percent chance of an aftershock of a given size or larger during the next week or other time period.

15. Rapid deployment of U-2 reconnaissance aircraft by the U.S. Air Force generated ***aerial photographs*** in a timely way which assisted in evaluation of some structural damage, landslides, liquefaction, and other types of ground failure. The high-resolution aerial photographs are systematic and reliable. However, many geologic features concealed by dense vegetation cannot be identified from the photographs and need to be field checked.

16. Geologists prefer to work on ***topographic maps*** and ***geologic maps*** in the epiecentral area. Enough complete sets of such maps at 7.5-minute quadrangle scale should be provided for a dozen geologists to work in the field simultaneously. Photocopied portions of such maps may be temporarily expedient, but these generally have poorer resolution and introduce some distortion.

17. Assistance requests from homeowners to county officials were relayed to DMG geologists in the field. Many of these requests included a street address in a rural area; however, most topographic maps do not show complete street names. ***Published street atlases*** are therefore needed for all counties in the epicentral area.

In summary, the most important problems for DMG were: 1) the abundance of ground failures in the epicentral area; 2) deployment of appropriate staff; 3) communications at many different levels; 4) logistics in the epicentral area; and 5) availability of maps and other general information publications. These elements are likely to present problems following future large earthquakes as well. The relative severities of the different types of problems, however, are likely to vary depending on such factors as the location, magnitude, and time of day of the earthquake.

SUMMARY OF DAMAGE AND LOSSES CAUSED BY THE LOMA PRIETA EARTHQUAKE

by

Stephen R. McNutt[1]

INTRODUCTION

The Loma Prieta earthquake of 17 October 1989 has been called the most expensive earthquake and one of the most expensive natural disasters in United States history. It is certainly the most significant earthquake to affect California since the 1971 San Fernando event, and is probably second only to the 1906 San Francisco earthquake in its overall impact. When reviewing the information presented in this paper, however, it is important to keep in mind that the earthquake occurred in a sparsely populated area. If a magnitude 7.1 earthquake had occurred near San Francisco or Oakland, the losses would have been considerably higher.

The purpose of this article is to systematically evaluate the damage and losses caused by the earthquake, and to compare the event to other destructive California earthquakes. The article does not fully consider the human impact, such as emotional or mental health issues. Most of the data were drawn from published sources, many of which included only preliminary data. The order of presentation of topics was chosen to match that of the Hayward Fault Scenario (Steinbrugge and others, 1987), with several additions. A map of the 10 affected counties is shown as Figure 1. For further information on specific topics, please see the References section at the end of the article.

SOCIAL DISRUPTION AND LOSSES

Deaths and Injuries

The official death toll from the Loma Prieta earthquake is 63, with 3,757 injuries reported as of April 12, 1990 (OES, written communication, 1990). Hospitalization was required for 368 persons (American Red Cross, written communication, 1990). Several estimates of the death toll were as high as 65 or 67. Some uncertainty was caused by deaths resulting from injuries that may not have been caused by the earthquake and by whether or not to include a person killed while attempting to direct automobile traffic just after the earthquake (E. Bortugno, personal communication, 1990).

The majority of deaths (42) occurred at the Cypress Structure (Interstate 880) in Oakland. Aside from this single structure, the deaths and injuries were fairly widely distributed (Table 1). Most of the deaths occurred at the time of the earthquake. However, two persons died much later: Mr. Buck Helm was rescued from the Cypress structure four days after the earthquake but died from complications to his injuries about three weeks later; the second person suffered injuries in San Francisco from the earthquake and died in April 1990.

Homeless

At least 12,000 people were rendered homeless by the earthquake (OES, written communication, 1990). An incomplete listing by county is shown in Table 1. It is also known that a disproportionately high percentage of low-income housing was lost in Santa Cruz, San Francisco, and Oakland (BAREPP, 1990).

On a temporary basis, many thousands of people were cared for by the American Red Cross and other organizations. The Red Cross alone enlisted the aid of 7,842 paid and volunteer workers and estimated that it served over 640,000 meals (American Red Cross, written communication, 1990).

Fires

A number of fires were caused by the earthquake. In San Francisco there were 27 structural fires, including the major fire in the Marina District, and there were also more than 500 responses to incidents (EQE, 1989; EERI, 1989). There was one structural fire in Berkeley but none in Oakland (EQE, 1989; EERI, 1989). About two dozen residential fires occurred in Santa Cruz County (Dames and Moore, 1989), and six occurred in Watsonville (G. Smith, personal communication, 1990). Overall, there were relatively few fires, thanks in part to the fact that there was very little wind at the time of the earthquake (EERI, 1989).

[1]California Department of Conservation, Division of Mines and Geology, Geologic Hazards Assessment Program

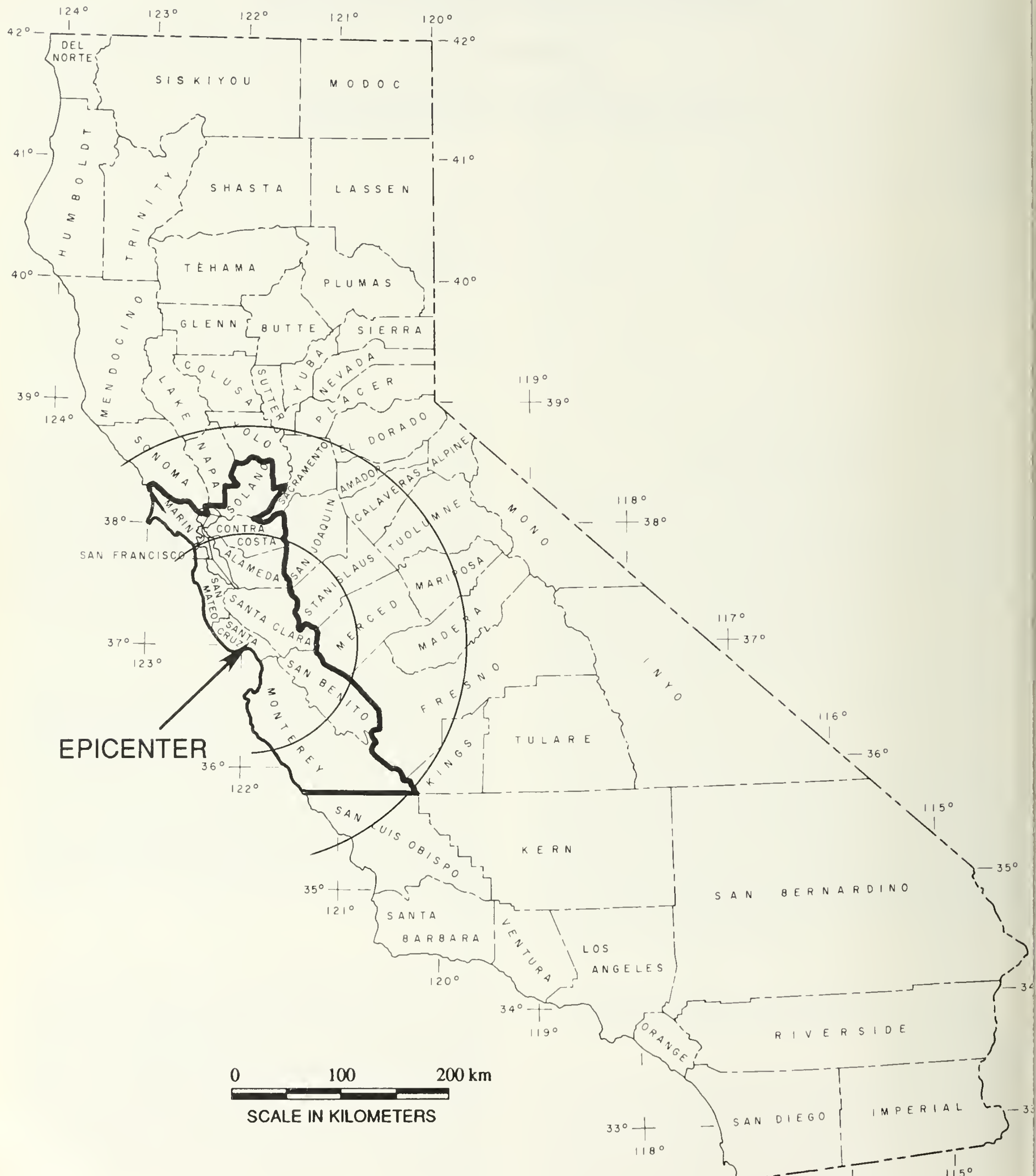


Figure 1. Index map showing California counties. The ten counties that suffered damage during the Loma Prieta earthquake are outlined by a bold line. Details of the damage are given in Table 1. Circles with radii of 100 and 200 km are drawn for reference.

BUILDINGS

Residential Damage

In total, 23,408 private homes were damaged and 1,018 private homes were destroyed (OES, written communication, 1990). The breakdown by county is shown in Table 1. Santa Cruz was the hardest hit county and had both the highest number of homes damaged or destroyed and the highest percentage of damage relative to the population. Assuming an occupancy of 3.5 persons per private home (J. Ryan, personal communication, 1990), at least 85,000 persons were adversely affected by earthquake damage to their homes.

Business Damage

In total, 3,530 businesses were damaged and 366 businesses were destroyed (OES, written communication, 1990). Table 1 shows the breakdown by county. The county that suffered both the highest number and the highest percentage of businesses damaged or destroyed was Santa Cruz County. Because the number of workers per business varies so greatly, no attempt was made to estimate the number of persons adversely affected by earthquake damage to their places of employment. Additionally, many people who had formerly been served by those businesses were adversely affected.

Hospitals

Engineered hospital buildings throughout the region performed well during the earthquake. Many suffered minor system damage, temporary losses of power and elevator stoppage, and cosmetic damage. However, there were no operational interruptions, and all facilities continued services throughout the emergency (EERI, 1989).

Public Schools

A preliminary survey of 1,544 public schools in the impacted area showed an estimated $81 million in damage (EERI, 1989). Severe damage occurred in eight schools (FEMA, 1989) in Watsonville, Los Gatos, and San Francisco. Eight others suffered damage substantial enough for them to be closed for more than two days. Other schools suffered only minor damage.

The California Community Colleges suffered an estimated $21 million in damage; the California State University system suffered $18 million in damage; and the University of California system suffered $33 million in damage (FEMA, 1989).

TRANSPORTATION LIFELINES

Highways and Bridges

Of the 1,500 highway bridges in the affected area, three had one or more spans collapse (EERI, 1989). These were Interstate 880 (Cypress Structure, Oakland), Interstate 80 (San Francisco-Oakland Bay Bridge), and Highway 1 (at Struve Slough, near Watsonville). Ten bridges were closed due to structural damage, including Highway 480 (the Embarcadero Freeway, San Francisco) and a portion of Interstate 280 in San Francisco. Ten other bridges required shoring in order to be used, and 73 other bridges had various types of less severe damage (EERI, 1989).

In addition to the structural damage, extensive liquefaction occurred at the toll area (east end) of the San Francisco-Oakland Bay Bridge. This damage alone would probably have caused closure of the bridge for several days had the fallen span not already caused the bridge to be closed (J. Hindmarsh, personal communication, 1990).

Two lanes of Highway 17 between San Jose and Santa Cruz were blocked by a landslide, resulting in closure of the road for 33 days in order to clear the debris. Portions of Highway 25, Highway 152, and Highway 129 were also closed. Many other roads suffered cracks that were for the most part filled in within a few days of the earthquake.

These bridge and highway closures caused substantial disruption to local transportation. Highway 17 normally handled 60,000 vehicles per day; there was no convenient alternative route. The Bay Bridge, which was closed for one month (it re-opened on 17 November 1989), normally handled an estimated 250,000 vehicles per day. Alternative routes took about an hour longer to traverse. The Cypress Structure normally handled about 170,000 vehicles per day, and the Embarcadero handled about 60,000 vehicles per day (Dames and Moore, 1989). Nearby surface streets handled much of the excess load created by these closures, as did Bay Area Rapid Transit (BART).

Airports

Damage to airports in the Bay area was moderate. There was both structural and non-structural damage at San Francisco International Airport, requiring it to be closed for 12 hours for repairs and inspections. At Oakland International Airport one building sufferered structural damage, and liquefaction caused extensive cracking, as well as settling of the northern 3,000 feet of the 10,000-foot main runway. The runway remained in service except for very large aircraft that required extended runway length (Dames and Moore, 1989). The nearby Alameda Naval Air Station also suffered runway damage caused by liquefaction (FEMA, 1989).

Bay Area Rapid Transit (BART)

BART's 75 miles of rail lines were virtually undamaged by the earthquake, and service was uninterrupted except for a short-duration inspection period immediately after the event. BART's ridership increased from 218,000 passengers per day before the earthquake to 308,000 passengers per day after the earthquake (Dames and Moore, 1989).

Railroads

Rail transportation was generally slowed for several days while rail lines were inspected. The railroad suffered substantial damage in the vicinity of Watsonville where the tracks subsided and a bridge was damaged (FEMA, 1989). Damage to the Caltrain trackbed, which runs along the San Francisco Peninsula, temporarily disrupted service between San Francisco and San Jose (EERI,1989). Such damage was mainly caused by local ground failure.

Marine Facilities (Ports)

Port facilities in Oakland and San Francisco were damaged. The Port of Oakland suffered considerable damage from settlement of uncompacted hydraulic fill (Dames and Moore, 1989). Of the 10 terminals and 26 cranes in operation, there was a loss of use of three large cranes (EERI, 1989) and about 30 percent of the terminal area (EQE, 1989). In San Francisco, Pier 45 had structural damage and was closed for repairs (EQE, 1989), and slight ground subsidence and cracking was observed at Pier 80 (Dames and Moore, 1989).

TABLE 1
ESTIMATED LOMA PRIETA EARTHQUAKE DAMAGES

County	Distance in km	Population[1]	Total $ Damages in millions[2]	Private Homes[2] Dmgd	Private Homes[2] Dstryd	Businesses[2] Dmgd	Businesses[2] Dstryd	People Dead[2]	People Injured[2]	People Displaced[2,3]
Alameda	48-100	1,252,400	$1,472	2,765	20	397	16	42	481	~1500[4]
Contra Costa	74-118	775,500	$25	485	0	124	0	0	22	--
Marin	100-168	231,900	$2	24	0	20	0	0	0	5
Monterey	19-203	349,300	$118	341	19	48	11	2	14	54
San Benito	27-139	35,250	$102	174	62	35	22	0	110	412
San Francisco	85-108	731,700	$2,759	382	11	134	0	13	700	~700[5]
San Mateo	30-90	632,800	$294	782	1	793	1	0	451	--
Santa Clara	7-60	1,440,900	$728	5,124	131	364	6	1	1,305	50
Santa Cruz	0-41	229,900	$433	13,329	774	1,615	310	5	671	6,377
Solano	107-165	321,100	$4	2	0	0	0	0	3	--
Totals		6,000,750	$5,936	23,408	1,018	3,530	366	63	3,757	~12,000

[1]Fay and Fay, 1990
[2]California Office of Emergency Services, written communication, April 12, 1990
[3]Incomplete
[4]Preliminary value, Office of Community Development, City of Oakland
[5]Preliminary value, Employee Relations Division, City of San Francisco

UTILITY LIFELINES

Communications

Damage to telephone facilities (primarily Pacific Bell) was minor and did not affect service (EERI, 1989). Some long distance calls from area codes other than 415 or 408 were blocked by long distance load control as a means of increasing the availability of local area service. As in many other earthquakes, the increase in telephone traffic in the days immediately following the earthquake overloaded the system, resulting in a delay in obtaining a dial tone. Cellular phones worked well in most, but not all, areas throughout the event.

Loss of electric power caused several types of communication problems. Some private branch exchanges (PBX) would not operate, and backup power was not fully adequate at some telephone company facilities (EERI, 1989). Several radio stations and newspapers lost power and could not carry out their normal communications functions. Finally, several radio transmission towers were damaged (e.g., station KGO).

Electric Power

Approximately 1.4 million customers suffered interruption of their electrical service as a result of the earthquake. Within 48 hours, service had been restored to all but 26,000 customers. Parts of Watsonville, however, were without electricity for 4 to 5 days (EERI, 1989).

Pacific Gas and Electric (PG&E) reported that two power plants were damaged, at Moss Landing and Hunter's Point, and three substations were also damaged, at San Mateo, Metcalf, and Moss Landing (Dames and Moore, 1989).

Water Supply

Water mains suffered breaks and leaks throughout the damaged area. Specific data were available from the San Francisco Water Department, the East Bay Municipal Utilities District, and the San Jose Water Company. In San Francisco there were 70 water main breaks and 50 service line breaks in the Marina District alone and 35 water main breaks throughout the rest of the city (Dames and Moore, 1989). There were over 200 water main breaks in the East Bay (FEMA, 1989), more than 100 in Hollister, more than 60 in Santa Cruz (EERI, 1989), and 155 in San Jose (Dames and Moore, 1989). In addition, the Santa Clara Water District experienced major disruptions (Dames and Moore, 1989). Ground failure, particularly liquefaction, played a large role in causing damage to water mains.

About a dozen dams were located within the epicentral area, and based on preliminary information, minor damage in the form of settlement, cracks, or small landslides occurred at six of them and moderate damage occurred at one (the Austrian Dam suffered $3 million in damage) (D.Babbitt, personal communication, 1990; Dames and Moore, 1989). Fortunately, the water level was low, between 10 and 50 percent of capacity, at the time of the earthquake.

Waste Water

Waste water systems were affected by direct damage to pipes and facilities and by indirect problems caused by the loss of electric power for several hours. Damage to pipes or facilities occurred in San Francisco and Oakland (Dames and Moore, 1989), the city of Santa Cruz and Santa Clara County (EERI, 1989), and in the epicentral area. Raw sewage overflows caused by power failures occurred in Monterey Bay (FEMA, 1989), the city of San Francisco, and at the East Bay Municipal Utilities District water treatment plant in Oakland (Dames and Moore, 1989).

Natural Gas Facilities

Of the total 3.2 million PG&E customers in northern and central California, about 150,000 suffered interruption of normal gas service, of which about 90 percent were customer initiated (Dames and Moore, 1989). In the Marina District of San Francisco, 5,100 customers lost service. The entire system there had to be replaced at a cost of $20 million and 2 months of time. There were approximately 400 other gas line breaks throughout San Francisco; and damage to gas lines was also reported in Los Gatos, Watsonville, Hollister, Richmond, Santa Cruz, San Jose, Oakland, and Alameda (Dames and Moore, 1989). Gas line damage mostly occurred in areas of strong shaking or where ground failure occurred.

Storage Tanks

Some damage to pipes and storage tanks occurred at two major oil terminals in Richmond. Most of the damaged tanks were unanchored with floating roofs and were either full or close to full at the time of the earthquake (Dames and Moore, 1989). Leaks were apparently minor and were locally contained.

Many other tanks used for storing water, beverages, and wine also suffered damage throughout the epicentral area (EQE, 1989).

ECONOMIC LOSSES

Direct Losses

Estimates of direct losses from the Loma Prieta earthquake are $4 billion in private property damage, $1.8 billion in public property damage, and $0.1 billion undetermined for a total of $5.9 billion (OES, written communication, 1990). These estimates include losses to both buildings and their contents.

For comparison, the Gross State Product (GSP) for California for 1989 was estimated to be $682 billion (computed by correcting the 1986 value of Fay and Fay (1990) by 8.5 percent per year, which is the average growth of the previous six years). The population affected by the Loma Prieta earthquake is 6,000,750 (Table 1), which is about 21 percent of California's total 1989 population of 28,662,000 (Fay and Fay, 1990). Assuming that the GSP is uniformly distributed throughout the state, the portion attributable to the Bay area is 21 percent of $682 billion or $143 billion. Thus, the earthquake direct losses of $5.9 billion represent about 0.9 percent of the entire 1989 GSP, but about 4.1 percent of the Bay area portion of the GSP. This provides some perspective on the economic scale of the disaster; the effect was similar to shutting down the Bay area economy for 11 days (assuming 260 workdays per year).

The above estimates do not include functional losses associated with the earthquake. These indirect losses include lost work time, transportation disruption, and emotional impacts such as loss of concentration. No exact figures are yet available, but because of the large number of people involved, the total indirect losses may be substantial.

Requests for Assistance

As of 21 February 1990, 36,096 applications had been received under the Temporary Housing Program, of which 12,463 were approved. In addition, there were 22,358 applications for the Small Business Administration Loans Program, 34,487 for the Individual and Family Grants Program, 1,632 for the Disaster Unemployment Program, and 241 applications for other programs. A total of 78,680 registrations were processed, and 97,918 hotline calls were received (OES, written communication, 1990).

Legislation and Taxes

As of 15 March 1990, 185 pieces of legislation pertaining to earthquake-related issues have been presented in the California State Legislature. One dozen pieces of Federal legislation have also been introduced. A special State emergency session was convened November 2-4, 1989, soon after the earthquake. To raise money for earthquake relief efforts, a special sales tax of 1/4 percent was added for the time period 1 December 1989 to 31 December 1990. This tax alone was expected to raise about $800 million (CSAC, 1990).

A report on unmet needs (CSAC, 1990) estimated that $2.9 billion in additional State and federal assistance was needed to help the ten affected counties (Table 1) recover from the earthquake. Approximately $2.3 billion were identified for hazard mitigation projects, with the remainder earmarked for replacement housing, temporary shelter, and loans for working capital (CSAC, 1990).

DISCUSSION

Other California Earthquakes

Other California earthquakes that have resulted in significant damage are shown in Table 2. Since 1812, there have been 25 earthquakes that resulted in loss of life. The Loma Prieta event is the fourth worst earthquake in California's history in terms of lives lost. It is easily the most costly event in terms of dollar loss, although the 1906 San Francisco earthquake would cost over $20 billion in today's dollars (Plafker and Galloway, 1989).

Worldwide Disasters

In a recent study, Housner (1989) noted that in the last 20 years natural disasters of all types accounted for the loss of 2.8 million lives, adverse effects to 820 million people, and economic losses of as much as $100 billion. Compared to these values, it is apparent that the Loma Prieta earthquake had a relatively small number of lives lost but a very high economic cost. A large part of the reason for this is that the United States is a wealthy country. It is likely that most natural disasters in the United States will yield high economic costs relative to deaths and injuries.

Unusual Features of Loma Prieta

Several features of the damage distribution of the Loma Prieta earthquake are noteworthy. First, the earthquake epicenter occurred in one of the most sparsely populated parts of a region adjacent to urban areas. Given the high damage levels in the epicentral region, the Santa Cruz Mountains region was about the best place for the event to occur in terms of minimizing losses. Second, less than 1 percent of the developed property in the affected region suffered damage, attributable in large part to the high quality of construction and to the adherence to strict building codes. Third, while a high percentage of damage occurred near the epicenter, much significant damage also occurred far from the epicenter. This fact reflected the importance of site conditions or local geology as well as the vulnerability of certain classes of structures. Fourth, the total number of deaths and injuries was relatively small for an event of this size near an urban area, and the ratio of deaths to injuries was very small. This reflects the fact that while many structures were severely damaged, only a small number completely collapsed. Finally, although direct damage losses were estimated at $5.9 billion, it is likely that the total losses will exceed this value when all the indirect costs are included.

TABLE 2

DESTRUCTIVE CALIFORNIA EARTHQUAKES, 1812-1990

Year	Location	Magnitude	Lives Lost	Dollar losses in thousands [1]	References
1812	San Juan Capistrano (?)	~7	40	--	Sherburne, 1981
1857	Fort Tejon	~8	1	--	"
1865	Santa Cruz Mountains	~6.6	--	$500	Sherburne, 1981; Coffman, 1969
1868	Hayward	~7	30	$350	" "
1872	Owens Valley	~8	27	$250	" "
1892	Vacaville-Winters	6.7	1	$225	" "
1898	Mare Island	6.5	--	$1,400	" "
1899	San Jacinto	6.9	6	--	" "
1906	San Francisco	8.3	>3,000	>$500,000	Hansen & Condon, 1989
1915	Imperial Valley	6.3	6	$900	Sherburne, 1981; Coffman, 1969
1918	San Jacinto and Hemet	6.8	1	$200	" "
1925	Santa Barbara	6.3	13	$8,000	" "
1926	Santa Barbara	5.5	1	--	" "
1932	Humboldt Co.(offshore)	6.4	1	--	" "
1933	Long Beach	6.3	115	$40,000	" "
1940	Imperial Valley	7.1	9	$6,000	" "
1941	Santa Barbara	5.9	--	$100	" "
1941	Torrance-Gardena	5.4	--	$1,000	" "
1949	Terminal Island[2]	3.7	--	$9,000	" "
1951	Terminal Island[2]	3.1	--	$3,000	" "
1952	Kern County	7.7	14	$60,000	" "
1954	Eureka-Arcata	6.5	1	$2,100	" "
1955	Terminal Island[2]	3.3	--	$3,000	" "
1955	Oakland-Walnut Creek	5.4	1	$1,000	" "
1957	San Francisco	5.3	1	$1,000	" "
1961	Terminal Island[2]	?	--	$4,500	" "
1969	Santa Rosa	5.6	1	$8,350	" "
1971	San Fernando	6.4	65	$504,950	" "
1975	Oroville	5.7	--	$2,500	" "
1978	Santa Barbara	5.1	--	$12,000	" "
1979	Imperial Valley	6.6	--	$30,000	" "
1980	Livermore Valley	5.5	1	$11,500	Sherburne, 1981; OES, 1990
1980	Mammoth Lakes	6.2	--	$2,000	" "
1980	Northern California	6.9	--	$1,750	" "
1983	Coalinga	6.5	--	$31,000	Bennett and Sherburne, 1983
1984	Morgan Hill	6.2	--	$10,000	Bennett and Sherburne, 1984; OES,1990
1986	Palm Springs	5.6	--	$5,300	OES, 1990
1986	Oceanside	5.3	1	$720	"
1986	Chalfant Valley	6.4	--	$437	"
1987	Whittier Narrows	5.9	8	$358,000	"
1987	Superstition Hills	6.6	--	$2,700	"
1989	Lake Elsman	5.2	1	--	Sacramento Bee, 1989
1989	Loma Prieta	7.1	63	$5,936,000	OES, written comm.,1990
1990	Upland	5.5	--	$10,400	OES, 1990

[1]At the time of the earthquake
[2]Oil wells only

REFERENCES

BAREPP (Bay Area Regional Earthquake Preparedness Project), 1990, The once and future quake, all about Loma Prieta: Networks, Earthquake Preparedness News, v. 5, no. 1, 28 p.

Bennett, J.H., and Sherburne, R.W., eds., 1983, The 1983 Coalinga, California Earthquakes: California Division of Mines and Geology Special Publication 66, 335 p.

Bennett, J.H., and Sherburne, R.W., eds., 1984, The 1984 Morgan Hill, California Earthquake: California Division of Mines and Geology Special Publication 68, 271 p.

Coffman, J. L., 1969, Earthquake investigation in the United States: Coast and Geodetic Survey Special Publication 282, Revised Edition, U. S. Govt. Printing Office, Washington, D. C., 58p.

CSAC (County Supervisors Association of California), 1990, Loma Prieta earthquake unmet needs action plan: CSAC Earthquake Relief Legislative Task Force, Supervisor Fred Keeley, Chair, Sacramento, California, 181 p.

Dames and Moore, 1989, A special report on the October 17, 1989 Loma Prieta earthquake: Dames and Moore, Los Angeles, California, 30 p.

EERI (Earthquake Engineering Research Institute), 1989, Loma Prieta earthquake October 17, 1989: Preliminary reconnaissance report: El Cerrito, California, Report 89-03, 51 p.

EQE, 1989, The October 17, 1989 Loma Prieta earthquake, A quick look report: EOE Engineering, San Francisco, California, 40 p.

Fay, J.S., and Fay, S.W., eds., 1990, California Almanac, 4th edition: Pacific Data Resources, Santa Barbara, California, 610 p.

FEMA (Federal Emergency Management Agency), 1989, State and Federal hazard mitigation team report for the October 17, 1989 Loma Prieta earthquake, California: Report FEMA-845-DR-CA, 112 p.

Hansen, G., and Condon, E., 1989, Denial of disaster: the untold story and photographs of the San Francisco earthquake and fire of 1906: Cameron and Company, San Francisco, California, 160 p.

Housner, G.W., 1989, An international decade of natural disaster reduction: 1990-2000: Natural Hazards, v. 2, no. 1, p. 45-75.

OES (California Office of Emergency Services), 1990, Significant California Earthquakes: OES Information and Public Affairs Office, Sacramento, California, 2 p.

Plafker, G., and Galloway, J.P., 1989, Lessons learned from the Loma Prieta, California, earthquake of October 17, 1989: U.S. Geological Survey Circular 1045, 48 p.

Sacramento Bee, 1989, 5.2 quake gives Bay Area shudder: The Sacramento Bee, Sacramento, California, August 9, 1989, p. A-1, A-21.

Sherburne, R.W., 1981, Seismology Program: California Geology, v. 34, no. 1, p. 3-6.

Steinbrugge, K.V., Bennett, J.H., Lagorio, H.J., Davis, J.F., Borchardt, G., and Toppozada, T.R., 1987, Earthquake planning scenario for a magnitude 7.5 earthquake on the Hayward Fault in the San Francisco Bay area, California Department of Conservation, Division of Mines and Geology Special Publication 78, 245 p.

ACNOWLEDGMENTS

I thank Jane Hindmarsh of OES and Tousson Toppozada of DMG for reviewing this manuscript. Jeff Ryan of Farmers Insurance Company, Carol Biancalana of the California Department of Conservation, Don Babbitt of the California Department of Water Resources, Virginia Bowser of the American Red Cross, and Jim Williams of Northern California Cardiologists Associates provided helpful information.

LOMA PRIETA AND EARTHQUAKE PREPAREDNESS

Modified from Testimony to the

House of Representatives

Committee on Science, Space and Technology

by

Richard A. Andrews[1]

INTRODUCTION

The Loma Prieta earthquake of 17 October 1989 provided a dramatic test of the level of California's preparedness for a large-magnitude earthquake in a metropolitan area. Because of California's long-standing involvement with the National Earthquake Hazards Reduction Program (NEHRP), Loma Prieta was an occasion to measure aspects of NEHRP. On balance, the emergency response to this 7.1 magnitude earthquake was remarkably effective at every level, particularly within the counties and cities of the affected areas.

Residents overwhelmingly did the right things. Cooperative efforts spontaneously broke out where immediate life-threatening emergencies existed. At the Cypress Structure, the Marina, downtown Santa Cruz, Candlestick Park, Watsonville, Hollister, and on the Bay Bridge, first responders were often individuals who happened to be at places where damage occurred. Fire and police worked alongside citizen volunteers in the first hours.

There is much to be proud of in what has been accomplished in California since the issuance of the 1981 report, "An Assessment of the Consequences and Preparations for a Catastrophic California Earthquake" (FEMA, 1981). Since 1981, there has been steady progress in earthquake preparedness in California's cities and counties. The private sector has initiated many emergency preparedness programs and established organizations to share emergency strategies. The State has expanded its support for earthquake preparedness, completed detailed response plans for northern and southern California, and conducted frequent drills. Federal agencies have a detailed plan to support state and local resources at the time of a "catastrophic" earthquake. The federal plan has been tested in a large-scale table-top exercise with California on August 8, 1989 and again on October 17, 1989 after the earthquake.

Nevertheless, there are many lessons to be learned from this earthquake, and areas where action is needed to enhance operational capabilities, accelerate hazard reduction programs, and broaden public preparedness.

The first section of this report focusses on developments in California. The second deals with federal programs and their interaction with those of the State; the third part addresses priority needs.

EARTHQUAKE VULNERABILITIES: AN EMERGENCY RESPONSE PERSPECTIVE

Loma Prieta was arguably the most significant California earthquake since the Long Beach temblor of 1933 because it provided a real-life test of earthquake risk and programs that have been undertaken to reduce California's vulnerabilities (all carried live before a nationwide television audience).

With the notable exception of the damage to the Bay Bridge, the Loma Prieta earthquake reaffirmed what had been learned in earlier earthquakes. Older structures, particularly those built before 1950, are vulnerable to severe damage or collapse. The collapse of sections of the Interstate 880 Freeway underscored the special danger posed by nonductile, reinforced concrete structures built prior to the mid-1970's. It is likely that this class of structures will pose the greatest risk to life in future California earthquakes. In general, engineered structures built according to codes in place since the mid-1970's performed well.

While recognizing that it is likely that the State's metropolitan areas will be shaken by even larger earthquakes within the next 30 years, the Loma Prieta event suggests that structures built since the mid 1970's, including high-rises, freeway overpasses, many types of office buildings—including developments on marginal soils—may not fail catastrophically even in a large earthquake. Substantial damage or even many serious injuries can occur from things inside the building; but the type of life-threatening collapses seen in Mexico City, Armenia, and at the Cypress Structure are not likely to occur in great numbers in modern California structures.

Emergency planners look at earthquake risk somewhat differently than engineers, building owners, or the insurance industry. Planners are primarily interested in collapse potential, the likelihood that a structure will fail in a catastrophic way. Evidence from Loma Prieta, Mexico City, and earlier San Francisco suggests that fatalities tend to be concentrated in structures that fail catastrophically rather than in evenly distributed patterns of destruction.

In planning for emergency response in the areas of search, rescue, medical, firefighting, and engineering operations, better data are

[1]Deputy Director, Governor's Office of Emergency Services, State of California

needed on: (1) which types of structures have the greatest potential to collapse, (2) how many people use them at what times of the day, and (3) where are they concentrated. To date, little of this information exists. Moreover there is no generally accepted definition of what constitutes collapse potential.

Research that seeks to develop an acceptable method for estimating collapse potential and application of that technique to California cities would be of great significance to our efforts to fine-tune our response plans. This is particularly true in regional planning and in determining how many trained heavy search and rescue teams are needed.

Therefore, the highest priority research should be addressed to rapidly developing the ability to reduce the risk to life in those structures where there is consensus that there is significant potential for life-threatening failure. Closely related to this is the need for better data on earthquake injury epidemiology. How are people injured in earthquakes; and how should they be treated, particularly those who may be trapped in collapsed structures?

One fortuitous surprise on October 17 was the low number of life-threatening toxic releases. Though no general estimates existed prior to October 17, many emergency planners feared that toxic releases in the Silicon Valley could be very serious. Additional work is needed to understand in detail the concentrations of toxic materials and to collect better data on techniques for safely storing hazardous materials.

We should not feel overconfident in our ability to respond to an even larger earthquake or suggest that with current systems all major earthquakes in California can be managed effectively. Such notions are tempered by the recognition that there is no certain knowledge on how structures will perform when the epicenter is closer to more heavily populated areas, the strong ground motion is of longer duration, or the time of day is different.

EARTHQUAKE PREPAREDNESS IN CALIFORNIA DURING THE 1980'S

California accelerated its seismic safety programs in the early 1980's, largely as a result of the first credible scientific estimates of the potentials for great earthquakes. The first actions in California's recent preparedness efforts came in early 1981 with: (1) the creation of the Southern California Earthquake Preparedness Project (SCEPP) as a joint federal-state prototype effort, and (2) the establishment of a Governor's task force on preparedness, bringing together a broad spectrum of the state's private groups from industry, finance, and the media to talk about the risk and to develop broad strategies.

These efforts have continued, in various forms, to the present time. Governor Deukmejian signed bills in 1983 and 1987 to continue SCEPP and to establish a similar effort in northern California, the Bay Area Regional Earthquake Preparedness Project (BAREPP). In September of 1989, Governor Deukmejian signed legislation authorizing a five-year extension of both projects through June 1995. SCEPP and BAREPP work with local governments, industry, schools, volunteer groups, and the public. The projects approach groups to enlist their participation in earthquake preparedness; they do not regulate planning. Instead, they provide technical assistance to local governments like those in San Jose, San Francisco, Oakland, Los Angeles City and County, San Bernardino, and Orange County in developing comprehensive, multi-year programs to reduce risk and enhance local preparedness.

The effectiveness of SCEPP and BAREPP is also based on the fact that their work program results from decisions made within each region through recommendations of a policy advisory board for each project. These boards include local elected and appointed officials, representatives of industry, schools, and volunteer groups, scientists, and engineers. This local involvement is unique among preparedness programs. It helps account for the broad support that BAREPP and SCEPP have enjoyed in each region.

Earthquake Planning Scenarios published by the California Department of Conservation's Division of Mines and Geology (DMG) beginning in 1982 were used effectively by emergency planners in developing the basic strategies for response at the local and state levels. The scenarios provided a realistic portrait of the general level and distribution of damage on October 17, 1989, although the scenarios were developed for other nearby fault segments.

Since January 1983 California has steadily increased its commitment to earthquake preparedness. Governor Deukmejian has signed over 25 earthquake-related measures, which include: (1) making the Seismic Safety Commission a permanent state agency; (2) requiring earthquake planning and drills in grades K-12 throughout the state; (3) requiring all new essential services facilities to meet rigorous seismic standards; (4) expanding the Strong Motion Instrumentation Program; and, (5) participating in the Parkfield Earthquake Prediction Experiment.

Two additional laws enacted since 1983 are particularly significant: (1) all local governments in UBC seismic zone 4 are required to inventory their unreinforced masonry buildings and, before January 1990, develop a strategy to reduce the identified hazard; and, (2) the California Earthquake Hazards Reduction Program was created to establish a goal for the State to "significantly reduce California's earthquake risk" by the year 2000 through a series of five-year plans developed by the Seismic Safety Commission in cooperation with other state and local agencies (SSC, 1986).

The Earthquake Task Force, established in 1981, continued through 1985. It developed many recommendations that influenced State emergency response planning. More importantly, through the involvement of private industry, an ongoing program of disaster preparedness within business and industry in California was developed. In both northern and southern California, business and industry preparedness groups have been formed to provide a forum for discussing planning strategies, exchanging technical information, and conducting exercises.

The effectiveness of California's earthquake preparedness programs results from a comprehensive approach that addresses mitigation, response, and recovery strategies. The involvement of both government and private industry has been crucial, and so has the emphasis on the need for preparedness actions by each resident, reinforced through countless community preparedness efforts, the State's Annual Earthquake Preparedness Month, and publications such as the DMG Earthquake Planning Scenarios.

In addition, it has been assumed that preparedness is not a static process. Given the scale of the potential problems that we face in the aftermath of a major earthquake, an incremental approach is necessary in which basic themes are reiterated and encouragements to preparedness are conveyed through many methods of communication.

While we believe the basic approach to preparedness is sound, unquestionably the actual occurrence of earthquakes since 1981 has provided fundamental credibility to the effort. Since 1983, California has experienced eight damaging earthquakes. These events have acted as a catalyst to preparedness efforts. Together with forecasts for even larger temblors, these events stimulated the on-going involvement by the print and electronic news media in the state in support of governmental preparedness programs.

As we look to the future in California's earthquake programs, the Seismic Safety Commission's *California at Risk* (SSC, 1986) should serve as the basic guide to approach the programs that should be undertaken.

The approach needs to be comprehensive. It should emphasize the reduction of existing risk through aggressive mitigation programs that target those areas of greatest life threat. It should pay careful attention to insuring that soil conditions are taken into account in future development. It should insure that building codes continue to incorporate lessons learned from events like Loma Prieta.

We need to enhance our operational capabilities to carry out the plans that have been developed by local and state government, particularly immediately following even larger earthquakes. Special attention should be paid to: (1) more detailed regional planning; (2) modernizing communications systems; (3) construction of emergency operations facilities; (4) information management systems; (5) search and rescue capabilities and strategies; and (6) on-going training for state and local governments, including large-scale drills like those held in southern California in 1987 and northern California in 1989.

Public education and preparedness efforts should be broadened. The annual Earthquake Preparedness month provides a focus for these efforts, but strategies like those in Los Angeles County of emphasizing a preparedness action each month—strapping down water heaters one month, stockpiling emergency medical supplies another month—should be encouraged statewide.

Particularly in the areas of mitigation and enhancement of our emergency response capabilities, we have addressed many of the most inexpensive initiatives. Further progress will require a substantial commitment of funds. Some programs, like the construction of new emergency operations centers in southern and northern California or installation of an emergency communications system less vulnerable to disruption during earthquakes, are essentially one-time expenditures.

Other projects that address risks posed by existing structures constructed to earlier standards will require commitment of significant resources. Important policy decisions will have to be made regarding whether, in some instances, to invest in new construction or to strengthen existing structures.

As the 56-year history of the 1933 Field Act or the 16-year history of the 1973 Hospital Seismic Safety Act demonstrate, progress in mitigation occurs over years and decades. Hazards will not be immediately eliminated. The essential step is the first one: commitment to reduce the risk with a rational program based upon reasonable data that sets forth a timetable for gradual risk reduction.

SEISMIC SAFETY IN CALIFORNIA AND ITS RELATIONSHIP WITH THE NATIONAL EARTHQUAKE HAZARDS REDUCTION PROGRAM (NEHRP)

California has been an active participant in the National Earthquake Hazards Reduction Program since its inception in 1977. Indeed much of the impetus to the establishment of NEHRP came as a result of the perception of earthquake risk in California.

The national program has been of value to the State's earthquake safety efforts in a number of ways. Support for scientific research on earthquake probabilities has added greatly to the understanding of California's seismic history and potential. Research that has identified recurrence intervals has, as noted, added the credibility essential to convince individual citizens, corporate leaders, and elected officials to support preparedness efforts.

Since 1985 California has worked with the USGS and with DMG in developing more effective ways to use scientific information in forecasting short-term earthquake potential. The State is a full partner in the Parkfield Earthquake Prediction Experiment in central California. In cooperation with the USGS and DMG, the Office of Emergency Services (OES) has developed detailed plans for how we would respond to a short-term prediction of a moderate-sized earthquake along the Parkfield segment of the San Andreas fault in southern Monterey County.

OES has also pioneered the use of scientific assessments of increased probabilities along significant seismic gaps in the state. Importantly, OES issued advisories to counties in the Bay Area following the Lake Elsman and Lexington Reservoir earthquakes of June 1988 and August 1989. These events, which occurred near the epicentral area of the Loma Prieta earthquake, appear to be preshocks to the October 17 event. OES' advisories, developed through the cooperative efforts of USGS and DMG scientists and the California Earthquake Prediction Evaluation Council, represent the most significant use of earthquake forecasting for public policy purposes since the 1975 Haicheng prediction in the People's Republic of China (Raleigh and others, 1977). (Evidence supports the view that the issuance of these advisories helped stimulate preparedness actions among the local governments and citizens who performed so effectively on October 17.)

The Federal Emergency Management Agency (FEMA) has been an active participant in California's earthquake preparedness efforts since 1981. NEHRP funds have provided almost 50 percent of the total support for Southern California Earthquake Preparedness Project (SCEPP) and Bay Area Regional Earthquake Preparedness Project (BAREPP). FEMA has also funded portions of the State's Earthquake Preparedness Month activities, as well as special projects like the development of the methodology and field guide used to conduct post-earthquake safety inspections of buildings.

Although each federal agency involved in NEHRP has attempted to focus research on application needs, greater attention is needed in this area. All too often research is funded at levels disproportionate to allocations for actual program implementation. For example, a $100,000 federally funded research grant was used to assess the effectiveness of a $40,000 public information effort in the counties that would be impacted by a short-term Parkfield earthquake prediction. Greater attention should be given to funding research that addresses specific needs of local and state governments involved in seismic safety programs rather than projects defined by the logic of the various disciplines involved in hazards-related work.

Greater coordination is needed between the activities in FEMA that fall under NEHRP and those that address federal response planning and disaster recovery programs. These program elements are important parts of a comprehensive preparedness effort. It can be confusing for state and local governments to work with elements of the same agency that have little knowledge of what other program offices are doing.

The Loma Prieta earthquake, like the Whittier-Narrows earthquake of 1987, has highlighted issues related to disaster assistance programs that need consideration. Contemporary demographics, with multiple families living in residences in many communities, may conflict with regulations governing assistance programs.

Damaging earthquakes near metropolitan areas disproportionally affect the housing inventory for low and marginal income levels. Some estimates are that between 40 and 70 percent of the low-income housing was damaged or destroyed in Oakland, San Francisco, Santa Cruz, and Watsonville.

Immediate attention is needed to develop strategies at the local, State, and federal levels for both short- and long-term housing needs that will exist on a broader scale after larger earthquakes forecast for California. These strategies should involve FEMA, HUD, State, and local agencies who share responsibility for housing.

The Federal Catastrophic Earthquake Response Plan provides a sound basis for making federal resources available to assist State and local governments. Attention is needed to detail the operational procedures for specific functions. This is particularly true regarding issues of incident management at the local level and how federal resources will be integrated with those of State and local governments.

It is important to keep in mind that quantity of resources is almost never a problem during the emergency response. Rather, the problem is the allocation of the right resource to the right incident in a timely basis. Federal resources provide an essential component of the nation's response capability, but care must be taken not to overwhelm local and state management systems in an effort to establish a federal presence.

Accelerated training programs are needed to further define the procedures for application of federal resources. Ad hoc response efforts, which are understandable given the scale of the emergencies created by large-magnitude earthquakes, must be minimized. It is our view that response strategies that assume a lead operational role for federal resources, including search and rescue, may clash with the principle of local incident management that is one of the essential strengths of California's emergency systems.

During the Loma Prieta earthquake there were examples of ad hoc responses at the local, State, and federal levels. In almost every instance these activities confused rather than enhanced operational effectiveness. Only through on-going programs of training and exercises like the August 1989 federal-state exercise, can a broader understanding be created of how the various response systems are intended to work.

FUTURE PROGRAM NEEDS

The Loma Prieta earthquake demonstrated the usefulness of forecasts of future seismic activity in California.

It is important to remember that the probability of one or more magnitude 7.0 or greater earthquakes is believed to be highest in southern California. In addition, we must take note of the fact that an 1865 earthquake centered near the Loma Prieta event was followed three years later by a comparable earthquake on the Hayward fault.

This is emphasized because we cannot continue to view earthquake preparedness in California as business as usual. Efforts must be made to accelerate preparedness and critical mitigation programs to enhance our readiness for even more damaging events.

It is time to develop strategies to encourage mitigation actions by local, State, and federal agencies. As a general principle, it is probably more cost-effective to invest in mitigation and preparedness before an earthquake than to allocate billions of dollars after a region has been devastated.

CONCLUSIONS

The response to the October 17 earthquake demonstrated that progress can be made in preparing for large-magnitude earthquakes. There remain, however, significant needs at the local, State, and federal levels if we are to continue the advances of the last decade. Larger earthquakes closer to heavily populated areas will pose even more serious problems.

The needs are clear. Mitigation efforts must be accelerated. Response capabilities must be enhanced. Public education programs must be broadened, and assistance programs must be updated.

The challenge is to translate the interest in seismic safety shown since 5:04 p.m. on October 17 into programs that can enhance public safety before we experience the even larger earthquakes that are likely to occur in California.

REFERENCES

Raleigh, B. and others, 1977, Prediction of the Haicheng earthquake: EOS, Transactions of The American Geophysical Union, v. 58, p. 236-272.

SSC (Seismic Safety Commission), 1986, California at Risk: Office of State Printing, State of California, Sacramento, California, 92 p.

FEMA (Federal Emergency Management Agency) and the National Security Council, 1981, Assessment of the Consequences and Preparations for a Catastrophic California Earthquake: Government Printing Office, United States, Washington, D.C.

89 79772