EARTHQUAKES AND OTHER PERILS
SAN DIEGO REGION

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Prepared for
Geological Society of America
field trip
by
San Diego Association of Geologists

November, 1979

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Library of Congress Catalog Card Number:

Printed by Fidelity Printing, San Diego, CA

PREFACE

As the Earth and its processes are dynamic, so also is our knowledge of the Earth. Since the GSA Cordilleran Section meeting in San Diego in 1961, new information and new interpretations of Southern California/Northern Baja California/Offshore geology have been added to the library. Some of these new, revised, and often heatedly disputed data are presented herein.

There is never a last word in geology, but to the extent possible, we have tried to bring together some of the latest words - including opposing viewpoints. It is hoped that the field trip, plus the written text, will stimulate worthwhile discussion and help direct the next round of data collection and interpretation.

William J. Elliott   Patrick L. Abbott

July, 1979

ACKNOWLEDGEMENTS

We would first like to express our appreciation to the authors for their time and efforts expended in preparing these papers.

Much of the quality of this volume must be attributed to the invaluable assistance of Lynn Henry, who participated in every phase of production.

Everyone will appreciate the inimitable touch added by John Holden's original cartoons. Patricia Bell drew the landslide sketch.

A significant amount of camera-ready copy was typed by Kathy Jessup with assistance from Marge Neun.

Publication of this book was made possible by the generous contributions from the geotechnical firms listed on the following pages.

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FAULTS AND LINEAMENTS IN THE BASEMENT TERRANE OF SOUTH-CENTRAL SAN DIEGO COUNTY, CALIFORNIA

by

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INTRODUCTION

The Peninsular Ranges of San Diego County, between the coastal plain and interior deserts, are underlain primarily by Late Mesozoic batholithic rocks and associated roof pendants of metamorphosed Paleozoic and Mesozoic rocks (Jahns, 1954). The northwest-trending San Jacinto and Elsinore fault zones (Figures 1 and 2) are the dominant structural features of the region.

Images from spacecraft and high altitude aircraft photography have provided a new perspective of the area. From a study of Gemini and Apollo photographs, Lowman (1969) noted northeast-trending lineaments, expressed by prominent valleys, that were not explained on existing geologic maps. These features, as well as the San Jacinto, Elsinore and other northwest-trending faults, are apparent on the Skylab image reproduced in Figure 3. A number of west-northwest-trending lineaments and one north-south-trending lineament are also visible. As indicated in Figure 2, some of these lineaments have been previously mapped as faults, but other lineaments are not explained on existing maps. The geology of the area is shown on the Geologic Map of California (Rogers, 1965; Strand, 1962) and the Geologic Map of San Diego County (Weber, 1963), which are compilations of mapping by Larson (1948), Merriam (1955, 1958) and Everhart (1951). This earlier mapping was at reconnaissance scales of 1:62,500 or smaller and, for the most part, without the benefit of aerial photographs. Large areas between these early maps were covered by a cursory reconnaissance for purposes of the small-scale compilation by Weber (personal communication, 1974). More detailed investigations of selected areas are in progress (Todd, 1977a,b; Hoggatt and Todd, 1977).

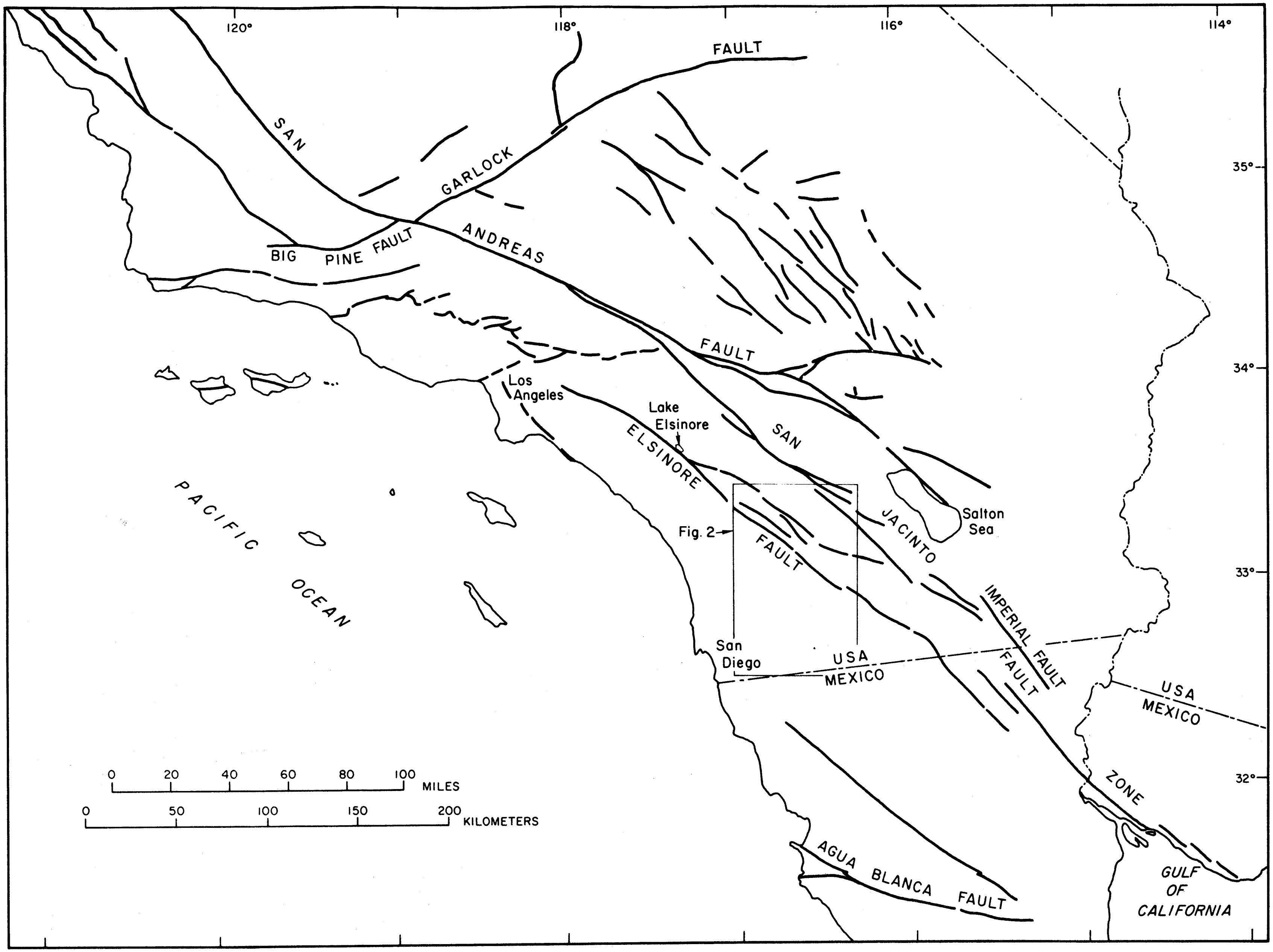

Figure 1 - Index map showing major faults and the area covered by the generalized fault and lineament map of Figure 2.

Using small-scale imagery from Skylab and Landsat spacecraft, and color infrared imagery from high-altitude RB-57 and U-2 aircraft, our attention was focused on prominent lineaments not explained on existing maps and not readily apparent on the ground or in large-scale aerial photographs. Field investigations, aided by large-scale aerial photographs, were undertaken to determine the nature of the most prominent of the unexplained lineaments. Several lineaments were identified as faults by displaced contacts and/or by well-developed breccia zones and slickensided shear surfaces aligned with the lineament. Others were determined to be the result of erosion along foliation or joints. The origin of still others could not be established with certainty (Lamar and Merifield, 1975; Merifield and Lamar, 1976). The work described in this paper was supported by NASA-Johnson Spacecraft Center Contract NAS 2-7698 and U.S. Geological Survey Contract No. 14-08-0001-13911.

SAN YSIDRO CREEK FAULT

The northeast-trending San Ysidro Creek fault was first recognized as a prominent 7-km (4-mile) long lineament on satellite images by Lowman (1969). Discovery of exposures of gouge up to 7 m (20 feet) wide with striated shear surfaces parallel to the lineament demonstrates the existence of the fault. Data are insufficient to determine the slip direction on the San Ysidro Creek fault, but striations on shear surfaces suggest predominantly horizontal (strike-slip) movement. The ends of the San Ysidro Creek fault appear to terminate against northwest-trending faults (Figure 2).

SAN DIEGO RIVER FAULT

The northeast-trending San Diego River valley southwest of the Elsinore fault forms a 30-km (20-mile) long lineament separated 10 km (6 miles) from the southwest end of the San Ysidro Creek fault. Although the San Diego River lineament and San Ysidro Creek fault are approximately aligned, Skylab imagery, as well as larger scale air photographs, clearly show that these features do not connect. The northeast end of the San Diego River lineament appears to abut the Elsinore fault.

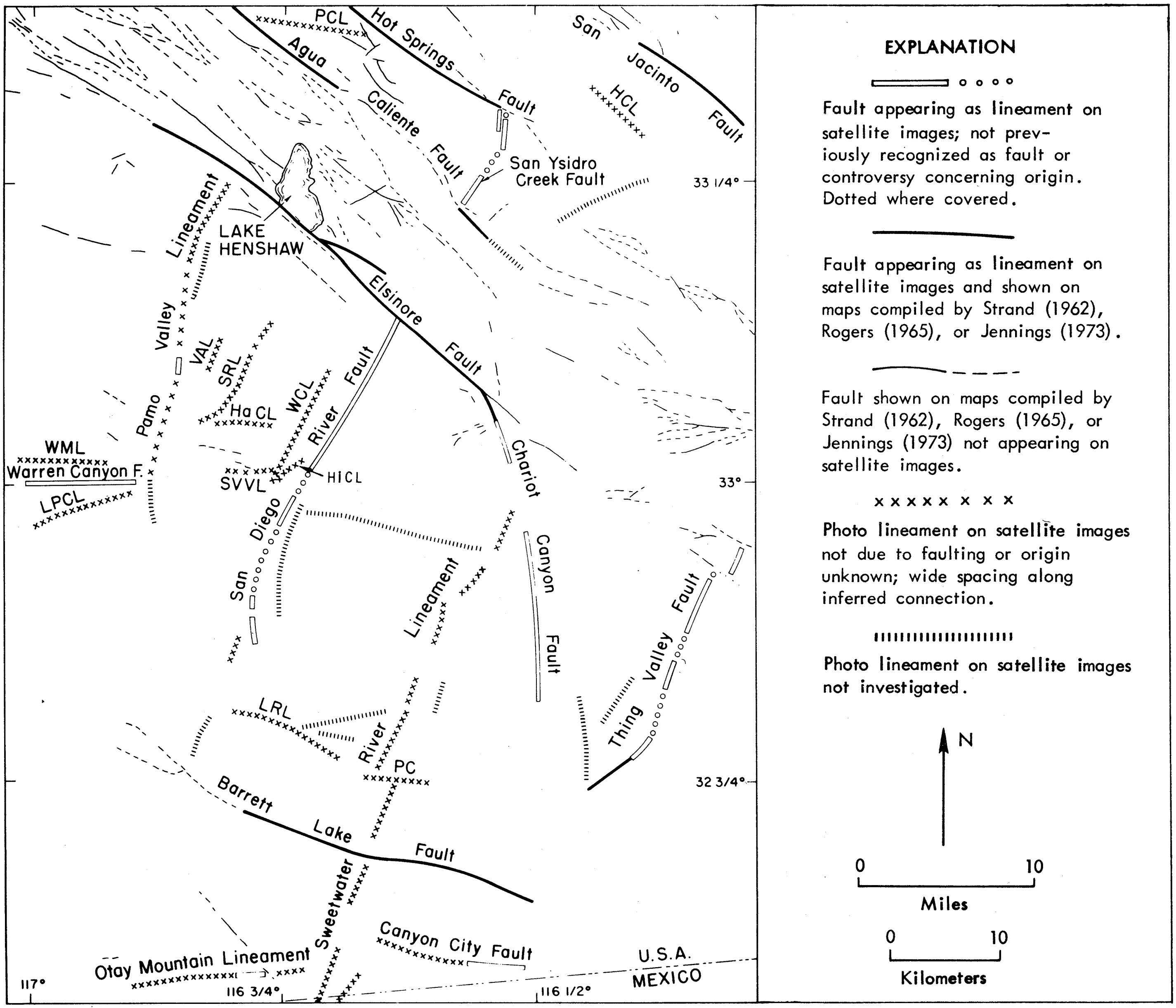

Figure 2 - Faults and lineaments recognized on Skylab and ERTS images and previously mapped faults, southwestern California. Abbreviations: HaCL: Hatfield Creek lineament; HCL: Henderson Canyon lineament; LPCL: Los Penasquitos Canyon lineament; LRL: Loveland Reservoir lineament; PC: Pine Creek lineament; PCL: Previtt Canyon lineament; SRL: Sutherland Reservoir lineament; SVVL: San Vicente Valley lineament; WML: Woodson Mountain lineament.

Some previous maps (Sauer, 1929; Miller, 1935; California Department of Water Resources, 1967; Jennings, 1973) show a fault or inferred fault along the San Diego River, while others do not (Everhart, 1951; Merriam, 1958; Strand, 1962; Rogers, 1965; Fitzurka, 1968). None of the previous maps or reports which indicate a fault describe any field observations of fault zone exposures or offset rock contacts.

In a detailed study along a segment of the San Diego River valley, Fitzurka (1968) found a right-separation of contacts between Julian Schist and plutonic rocks of from 300 to 600 m (1000 to 2000 feet). A fault along the river, in the area mapped by Fitzurka, was obscured by alluvium, and he reported no direct evidence of faulting. Our field work substantiated the apparent separation observed by Fitzurka and also revealed a probable 420-m (1400-foot) right-separation of a schist body within quartz diorite along the same trend to the northeast. An _en echelon_ pattern of zones of sheared and altered breccias and alignments of straight canyon segments, saddles and benches was also discovered along the river valley. The orientation of the _en echelon_ pattern is consistent with right-slip along a shear zone.

THING VALLEY FAULT

One of the most prominent lineaments seen on satellite images stretches for 15 km (9 miles) in a north-northeast direction through Thing Valley in southeastern San Diego County. In several places along the lineament, breccia, fault gouge and slickensided shear surfaces are exposed. A minimum of 100 m (300 feet) of right-separation is demonstrable on the fault at the southwest end of Thing Valley. The true sense of slip is indeterminant. A recent, more detailed study by Sawicki (1978) concluded that the lineament was an expression of erosion along intrusive contacts, foliation and jointing, as well as faulting. Just as in the case of the San Diego River lineament, the Thing Valley lineament is marked by a series of short fault segments rather than a continuous single trace.

Although the relationship is obscured by alluvium, the north end of Thing Valley fault appears to be displaced 700-1300 m (2300-4300 feet) in a right-lateral sense by the south branch of the Elsinore fault as

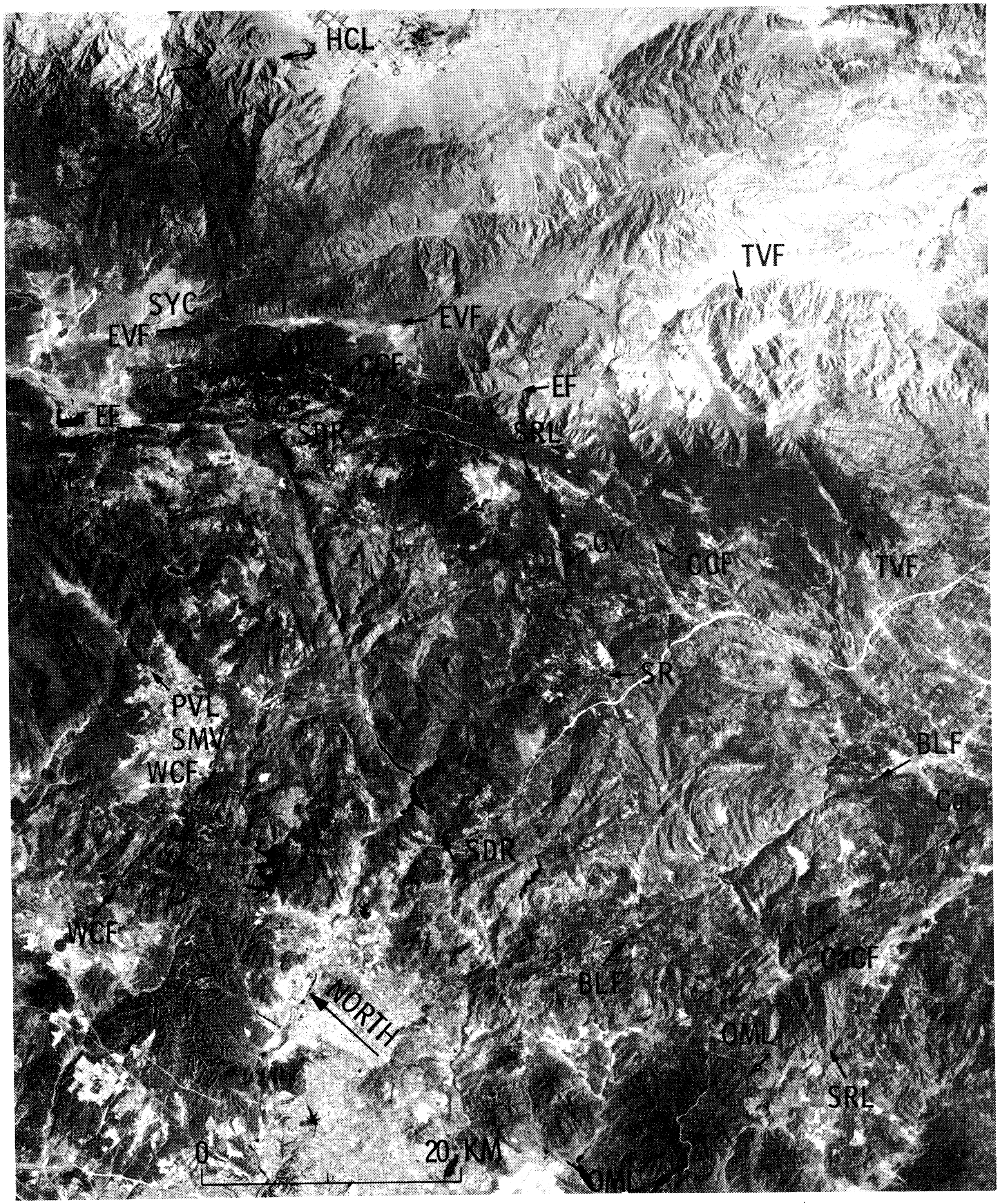

Figure 3 - Major faults and lineaments, Peninsular Ranges, southwestern California. Portion of Skylab 3, 190B camera, Roll 87, Frame 111 (original in color infrared). Abbreviations: BLF: Barrett Lake fault; CCF: Chariot Canyon fault; CaCF: Canyon City fault; EF: Elsinore fault; EVF: Earthquake Valley fault; HCL: Henderson Canyon lineament; GV: Green Valley; OML: Otay Mountain lineament; PVL: Pamo Valley lineament; SDR: San Diego River fault zone; SMV: Santa Maria Valley; SR: Sweetwater River; SRL: Sweetwater River lineament; SYC: San Ysidro Creek fault; TVF: Thing Valley fault; WCF: Warren Canyon fault.

mapped by Merriam (1955) and Buttram (1962). However, Todd (1977a) concluded that rock relations probably do not permit large-scale lateral displacement on the Elsinore fault, and this northern segment may be related to a thrust fault north of the Elsinore fault. The north end of the fault abuts the north branch of the Elsinore fault at Agua Caliente Hot Springs; a concentration of breccia at the fault intersection may provide a conduit for the hot water.

WEST-NORTHWEST AND EAST-WEST-TRENDING FAULTS AND LINEAMENTS

In addition of the northeast-trending faults described above, several west-northwest to east-west faults have been identified. The most prominent of these, the Barrett Lake fault (Figures 2 and 3), was mapped by Weber (1963) over a 40-km (24-mile) length in a west-northwest direction from El Cajon to Campo. Our attention was drawn to additional lineaments of this trend by studies of Skylab, ERTS and RB-57 photos. Fault breccia and slickensided shear surfaces have been found along two of these lineaments which are referred to as the Canyon City and Warren Canyon faults. Due to the lack of distinctive contacts between rock units, the amount and sense of displacement on these faults is indeterminant.

An apparent 200-m (600-foot) left-separation of flows dipping 40° northeast in the Santiago Peak Volcanics was observed at the eastern end of the east-west-trending Otay Mountain lineament. The exposures are not adequate to prove that the separation is due to faulting and no other evidence of faulting was observed along this feature.

CHARIOT CANYON FAULT

A north-south-trending lineament was studied and named the Chariot Canyon fault by Allison (1974a,b), who reported 8 km (5 miles) of right-separation based on the distribution of Julian Schist and plutonic rocks. Our examination of a number of exposures in Chariot Canyon did not reveal a single fault separating Julian Schist on the west from granitic rocks on the east but a broad shear zone that appears to occupy the width of the canyon. Steeply dipping, slickensided shear surfaces were observed to strike between north-south and $N30^{\circ}W$. The foliation in schist and gneiss is locally undulatory but has a general strike conformable with the shear surfaces and the trend of the canyon.

LINEAMENTS NOT DUE TO FAULTING

Several other lineaments which show no evidence of faulting were investigated; they are indicated in Figure 2. In some cases, the exposures were sufficient to make us reasonably certain that the feature is due to erosion along foliation (Henderson Canyon lineament) or joints (Sutherland Reservoir lineament). Intrusive contacts along the Sweetwater River in Cuyamaca Rancho Park curve to the right as they cross the river valley, and no distinct break is evident. Thus, the Sweetwater River lineament (Figure 2) corresponds to the axis of a small flexure or perhaps shear (slip) fold. The Witch Creek lineament is shown as a fault by Jennings (1973); our study indicates that a contact in basement rock is not displaced along this feature, and no evidence of faulting was found. The origin of some of the other lineaments could not be established with certainty because of the lack of exposures and mappable contacts.

TECTONIC IMPLICATIONS

Of particular interest is the relationship of the northeast- and west-northwest-trending faults to the northwest-trending faults of the San Andreas set. If the northeast-trending faults form a conjugate shear system with the presently active northwest-trending right-slip faults, the northeast-trending faults should be left-slip. However, a right-slip component is probable on the Thing Valley and San Diego River faults. Also, the northeast and west-northwest-trending faults are restricted to pre-Tertiary rocks and nowhere cut the northwest set.

It is possible that the northeast and west-northwest sets were formed by an older stress system unrelated to the presently active system. East-northeast, west-southwest crustal shortening is consistent with the fault pattern and probable right-separation of the Thing Valley and San Diego River faults. No conclusive evidence of the slip direction on the west-northwest-trending faults has been found, although left-separation on the east-trending Otay Mountain lineament is possible. Data concerning slip directions on the faults studied are not, therefore, adequate to prove this hypothesis. However, on the basis of north-south-trending thrust faults and mylonitic zones, Sharp (1968) has also suggested an earlier period (middle Cretaceous to Eocene?) of east-west crustal shortening in the eastern Peninsular Ranges. The plate tectonic model of a subduction zone parallel to the continental margin during the Mesozoic (Hamilton, 1969; Hill, 1971) is also consistent with earlier east-west crustal shortening.

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SEISMICITY OF THE SAN DIEGO REGION

by

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INTRODUCTION

San Diego occupies a unique location with respect to the distribution of southern California seismicity. Although the San Diego area has experienced only a limited number of small, locally generated earthquakes, it is surrounded, at least on the landward side, by areas with much more active seismicity and moderate to large (M=6 to 7.1), damaging earthquakes. The historical record of seismicity in southern California is too short to fully express all of the seismotectonic processes that might be present. This paper reviews the seismicity that has been observed in the region around San Diego out to distances of about 200 km, somewhat more distance to the northwest and southeast. Another paper by R. S. Simons (this volume) provides more detail on San Diego's local shocks.

Instrumental observations of earthquakes began in the southern California area in 1926, and one of the early seismograph stations was established at La Jolla in 1927. The La Jolla station operated until 1952 and was then supplanted by a station at Barrett, about 50 km east of San Diego. Over the years, particularly recently, more stations have been added to the southern California seismographic network until there are presently about 160 stations. Although operated for many years primarily by the Seismological Laboratory of the California Institute of Technology, the network is now a joint effort of the Seismological Laboratory and the U. S. Geological Survey, with other agencies supporting some stations. As the network was augmented, the ability to determine earthquake locations improved greatly. Every earthquake hypocenter determination has an accompanying uncertainty. When particular shocks are potentially significant because of their proximity to a site of investigation or their possible relationship to faults, the location uncertainties must be considered carefully. Generally these uncertainties are expressed as a location quality in seismicity catalogs.

Several data sources are available for seismicity in the San Diego region. Early earthquakes, known mainly by reports of the effects of shaking, are catalogued by Townley and Allen (1939) for the period 1769 to 1928. The Caltech Seismological Laboratory is the original source for most of the instrumentally determined locations since 1932: Hileman et al (1973) for 1932 to 1972, Friedman, et al (1976) for 1973 and 1974, and preliminary listings for subsequent shocks are available from the Seismological Laboratory. The California Division of Mines and Geology has combined the Caltech data with data from other sources to prepare a file of all California shocks reported from 1900 to 1977 (Real, et al, 1978); an extension to include pre-1900 shocks is forthcoming soon. The National Geophysical and Solar-Terrestrial Data Center (NGSDC) maintains a catalog with worldwide coverage of earthquakes; but the recent, smaller shocks (M less than 3) in southern California are not included because of their great number. In addition, special studies of the seismicity data have been placed into the public record for environmental reports and safety analysis reports for various critical facilities such as the San Onofre Nuclear Generating Station about 80 km northwest of San Diego. With current regulatory requirements, some level of assessment of seismic hazards is being required for practically all engineered projects.

Faults shown in the figures have been compiled from two sources. Those faults in California represent the traces identified as Quaternary by Jennings (1975) on his Fault Map of Southern California. The faults shown in Mexico are from Gastil, et al. (1971) and are probably largely Quaternary in age.

SIGNIFICANT EARTHQUAKES OF THE REGION

For this discussion, the San Diego region is taken to include the entire area shown in Figure 1. Consideration of the large distances within this area is warranted because many of the earthquakes shown have been felt in San Diego, and the occurrence of maximum earthquakes postulated for some of the faults would be felt strongly in San Diego (C. B. Crouse, this volume).

Considerable variation exists in the certainty with which epicenters can be assigned. The locations with the greatest speculation are indicated

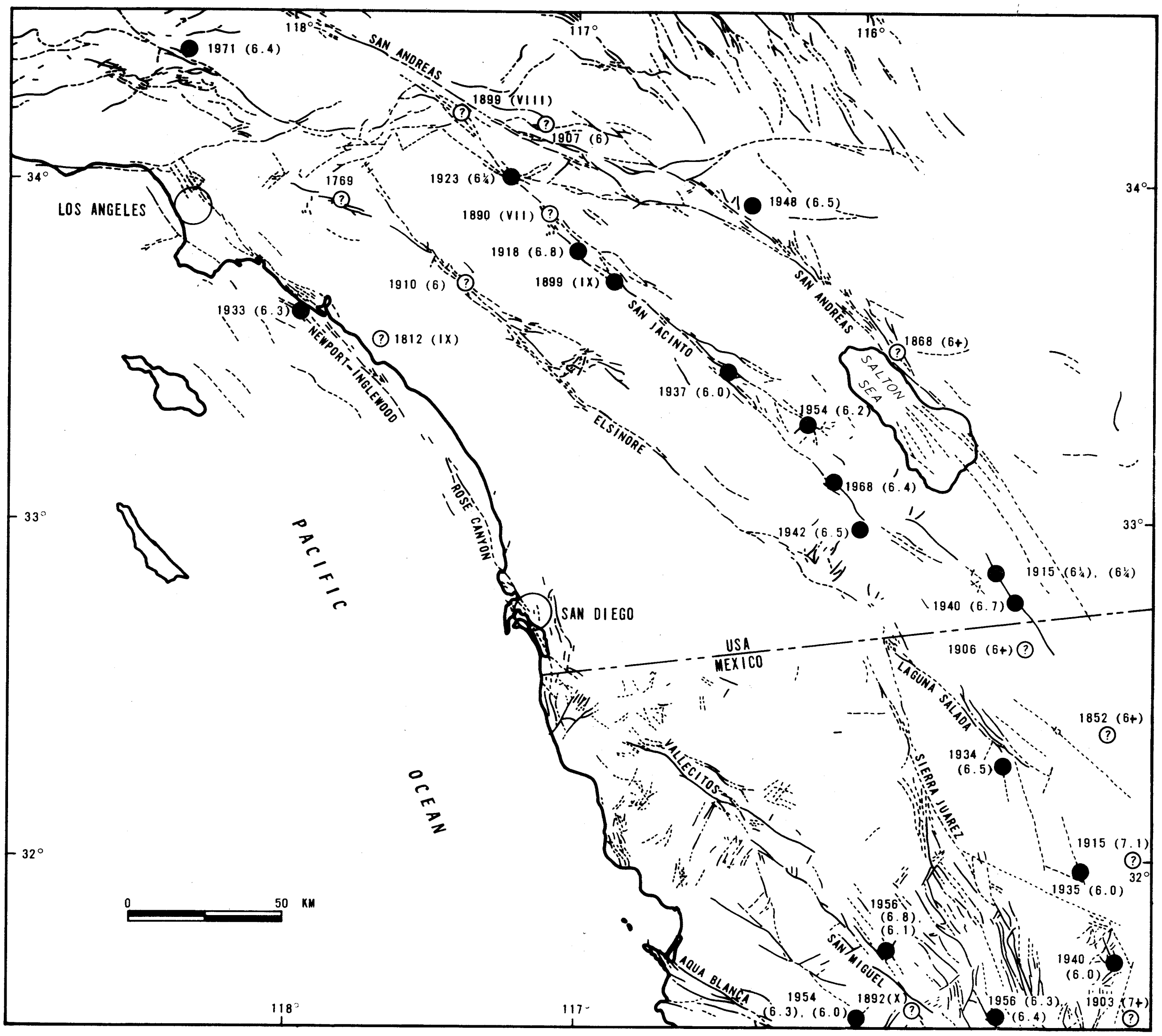

Figure 1. Earthquakes of magnitude 6 and greater in the San Diego region. Solid circles show epicenters with year of earthquake and magnitude or maximum intensity. Open circles with question marks indicate poorly known epicenters. Epicenters are compiled from Richter (1958), Hileman, *et al.* (1973), and Thatcher, *et al.*,(1975); faults are compiled from Jennings (1975) and Gastil, *et al.* (1971).

in Figure 1 by a circled question mark. For example, the 1812 shock south of the Los Angeles area is shown near the mission San Juan Capistrano where damage was most severe, but the epicenter might well have been on either the Elsinore or the Newport-Inglewood faults. Shocks occurring in northwestern Mexico even today are located with less accuracy than those in southern California because nearly all the seismograph stations are in California.

For the region, 34 shocks with magnitudes of about 6 or greater are shown. Rupture from an 1857 earthquake along the San Andreas fault extended into the northern portion of the region, but the shock isn't shown on the figure because maximum rupture occurred farther north. Presumably, the population density has been high enough that no shock of magnitude 6 or greater has passed unrecorded in the region since 1900 (probably earlier for most of southern California and possibly later in Baja California). In the last 80 years, 26 large shocks have affected the region, about once every three years on the average. However, the actual occurrence is not regular in time, and the "average" could easily be adjusted by a judicious choice of regional limits.

The larger earthquakes are clearly not regular in their spatial distribution (Figure 1). For example, the San Jacinto fault system (including the Imperial fault) has been the most active fault system during our limited period of observation. Using seismicity recorded since 1912, Brune (1968) estimated that the San Jacinto fault has slipped at the rate of 1.5 cm/yr. Geologic data (Sharp, 1967; Clark, et al., 1972) indicate about 0.3 cm/yr over the past 2 m.y. These different rates can be reconciled because the seismic strain release could be episodic. Although about 14 shocks of magnitude 6 or greater (Figure 1) can be associated with the San Jacinto fault system (there are others along the same trend farther southeast), the largest shocks observed seem to be limited to about magnitude 7. The 1940 Imperial Valley earthquake has been assigned magnitude 7.1 in some sources (Coffman and Von Hake, 1973), and earthquakes with magnitudes of 7.0 and 7.1 occurred on the Colorado Delta (just southeast of Figure 1) in 1934. Thatcher, et al. (1975) have estimated the seismic slip along the San Jacinto fault and have identified two significant, 40-km gaps; one between Cajon Pass and Riverside along the northernmost portion of the fault (where an 1899, VIII shock is shown) and the other between Anza and Coyote Mountain (where the 1937 earthquake is shown). These gaps were suggested as likely sites for future moderate-sized earthquakes, magnitude 6 to 7, along the San Jacinto fault.

Another feature of the seismicity distribution that is readily apparent is the concentration of large shocks in northwestern Mexico, mostly south of about 32°N latitude. These earthquakes seem to represent an active region rather than any particular, dominant fault. Many of these epicenters in Mexico are uncertain by 15 km or more (Hileman, et al, 1973).

The remaining larger shocks in the region are more widely scattered and reflect lower levels of activity. Only one or two large shocks have been observed for any particular fault.

The lack of larger earthquakes within about 100 km of San Diego is an equally significant feature of the seismicity distribution. Is this local area different from the surrounding ones, or is the seismicity record misleading because of its limited duration? The distribution of smaller shocks, Figures 2 through 4, can provide some insight, but geologic data are also needed to provide a longer time sample and better understanding.

REGIONAL SEISMICITY

Instrumentally determined epicenters for earthquakes with magnitudes of 4 or greater in the San Diego region are shown in Figure 2 using Caltech data files. Similar data are found in the worldwide catalog file, NGSDC, which contains some shocks as early as 1915 for this region and occasionally reports different magnitudes.

The distribution of magnitude 4 and above seismicity since 1932 (Figure 2) is similar to that of the larger earthquakes. A lower limit of magnitude 4 was chosen to assure uniform representation of the seismicity throughout the region. For smaller shocks, the distribution of seismograph stations influences whether sufficient data are available for epicenters to be determined. The San Jacinto fault shows high activity along its southern half, but considerably less along the northern half where several large shocks occurred prior to 1932. Aftershocks have not been removed from this data set; but if

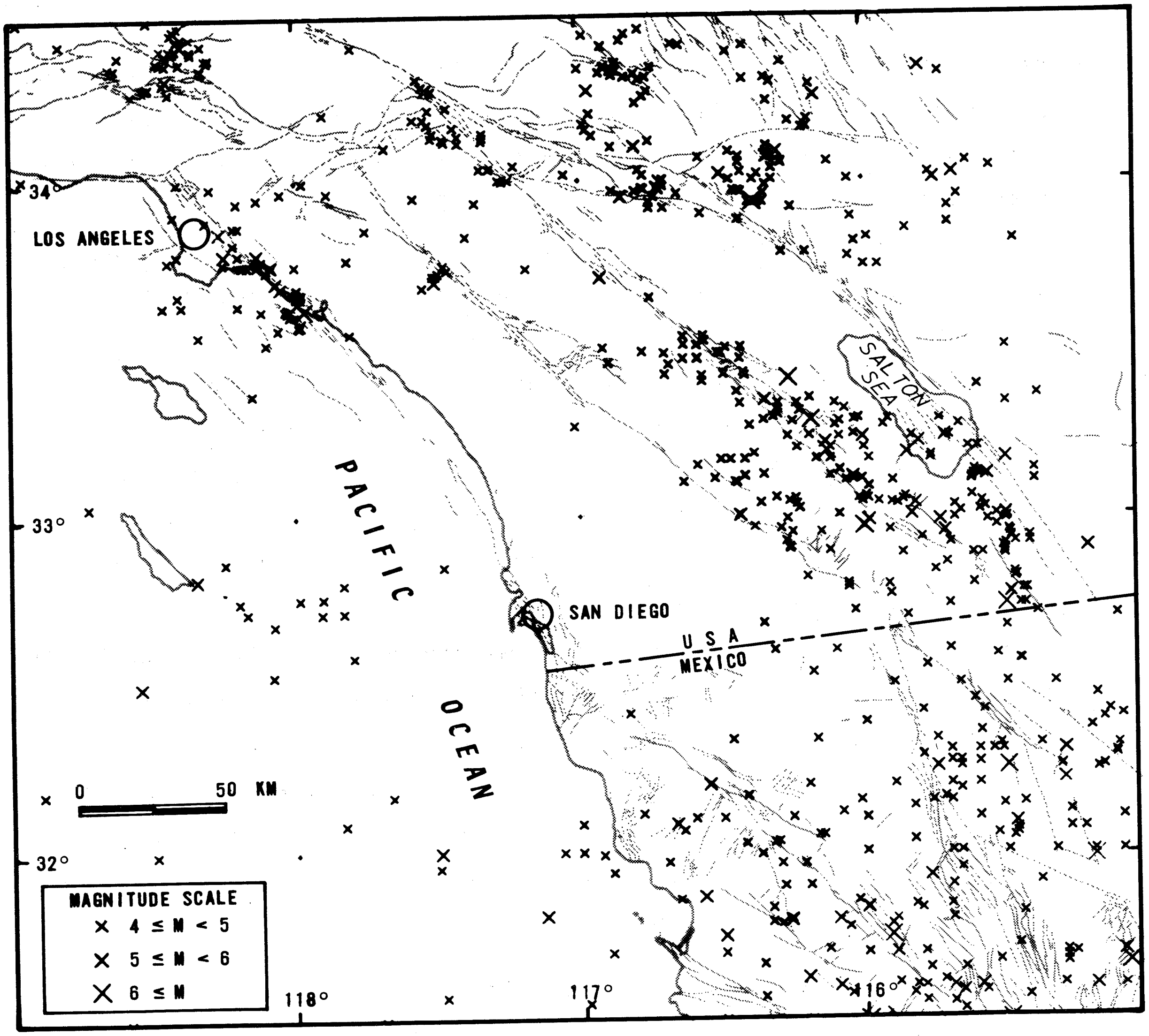

Figure 2. Seismicity of the San Diego region, 1932 through 1977, for earthquakes of magnitude 4 and greater. Data are from the Seismological Laboratory of the California Institute of Technology.

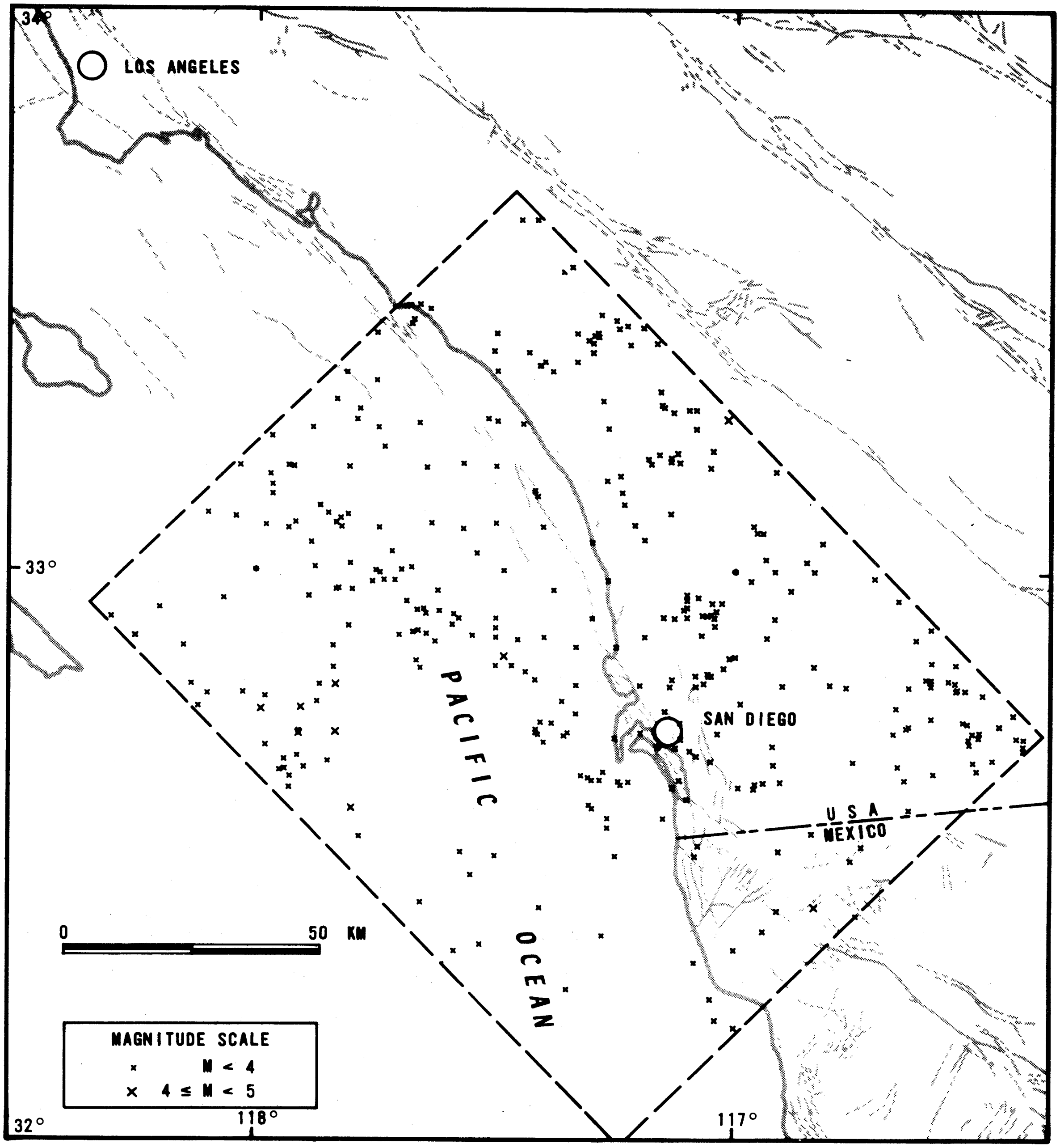

Figure 3. Seismicity in the vicinity of San Diego, 1932 through 1975, for all shocks whose locations have been determined. Much higher levels of seismicity are present, but not shown, in the landward areas outside the dashed box. Data are from the Seismological Laboratory of the California Institute of Technology.

they are, the same distribution results along the San Jacinto fault (Thatcher, et al, 1975). The zone of high activity in Mexico is also apparent as is the low level of seismicity around San Diego. The magnitude 4 and above seismicity shows a concentration along the southern one-third of the Elsinore fault where large shocks have not been observed. There are scattered epicenters in the offshore area.

The San Diego area is one of historically low seismicity for shocks of magnitude 4 and greater, as demonstrated in Figures 1 and 2. When smaller shocks are considered, the area is shown to have a scattered distribution of microseismic activity. Figure 3 shows the earthquakes of all magnitudes in the Caltech catalog in the vicinity of San Diego for 1932 through 1975. Figure 4 is a similar plot for 1976 through 1978. Some of the shocks in these figures have magnitudes down to 1.0 or less. When considering such small earthquakes, the distribution here is incomplete because not all small shocks are recorded well enough at a sufficient number of stations to allow epicenter determination. Figure 3 shows 44 years of data. During much of that time, the seismographic network was considerably less dense and less capable of locating small events than it is now. Figure 4 shows the data for the past three years, when there has been a more systematic effort to locate the smaller shocks. The surrounding areas (Los Angeles Basin, along the Elsinore and San Jacinto faults, and in northern Mexico) are much more active than the San Diego area, and they are not shown because the epicenter plot would be saturated with symbols. There are only a few shocks greater than magnitude 4 in the area, and most of these are located offshore. The epicenter distribution seems somewhat random except for an indistinct N45^{o}W trend offshore. Many of these smaller shocks have location uncertainties on the order of 5 to 15 km, and they are few enough that clusters and trends are not strongly defined. Many of these shocks are being relocated to reduce their uncertainties.

SUMMARY

Only small shocks have been observed in the vicinity of San Diego (within 100 km), and this area seems characterized by a lower level of seismicity than much of the rest of southern California. However, many

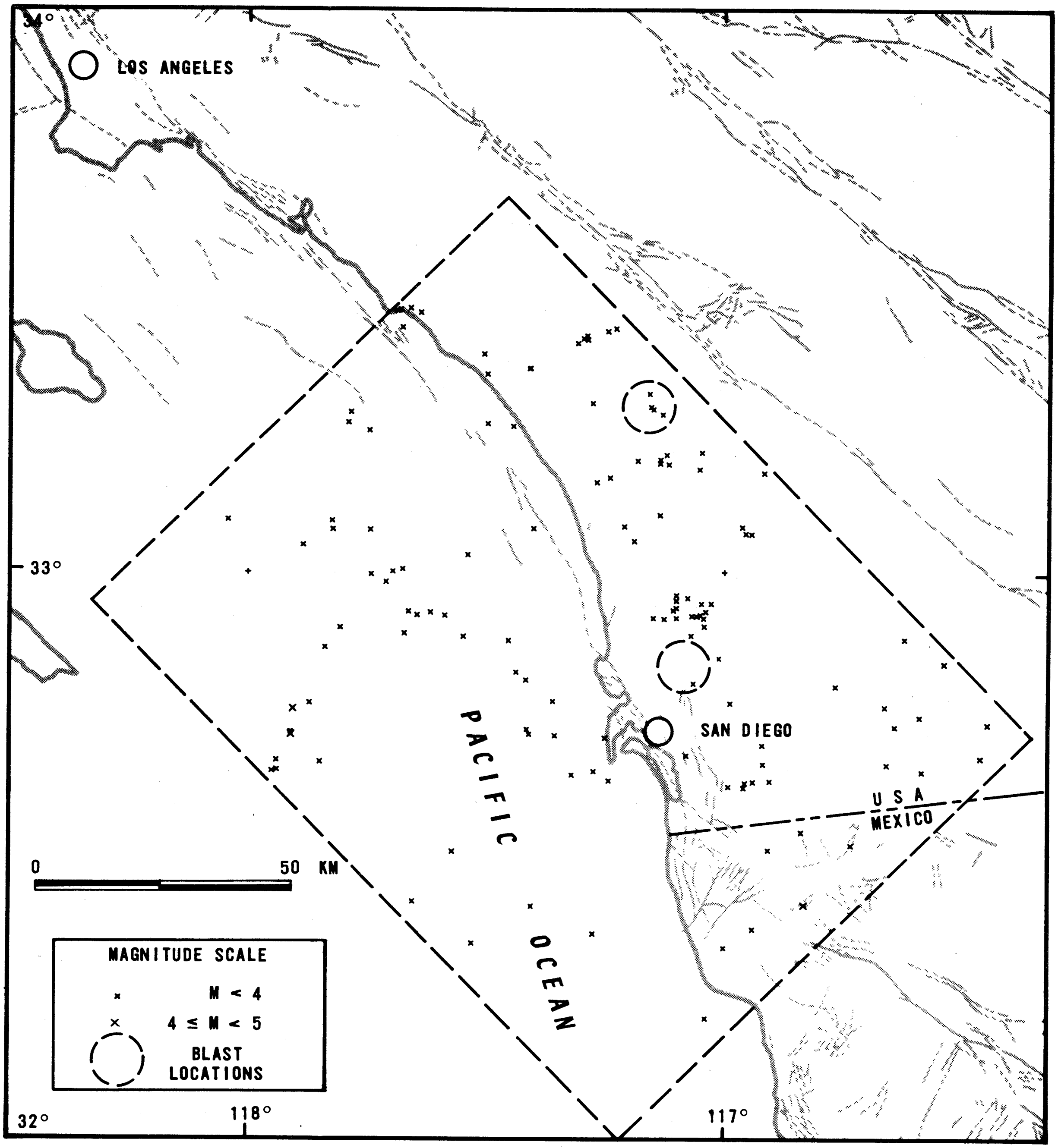

Figure 4. Seismicity in the vicinity of San Diego, 1976 through 1978, for all shocks whose locations have been determined, dashed box as in Figure 3, Caltech data.

large earthquakes, with magnitudes up to about 7, have occurred in the region and have been felt moderately in San Diego. Because the seismicity record is short compared to some seismotectonic processes, geologic data are also needed to supplement the data base.

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IMPLICATIONS OF FAULT PATTERNS OF THE INNER CALIFORNIA CONTINENTAL BORDERLAND BETWEEN SAN PEDRO AND SAN DIEGO

by

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INTRODUCTION

Marine geophysical surveys by the U.S. Geological Survey in the Gulf of Catalina and San Diego Trough show a complex structural pattern. Preliminary interpretations of offshore continuous seismic reflection profiles suggest that the dominant structural pattern of the inner part of this area, between Palos Verdes Hills and the Mexican border, reflects late Cenozoic right-lateral wrenching along two major fault zones. The character of this tectonic activity is similar to that described by Moody and Hill (1956), Harding (1973), Eaton (1923-24, 1933), and Reed and Hollister (1936) for the Newport-Inglewood fault zone onshore.

A closely-spaced marine geophysical data-collection grid (4 to 8 km track-line spacing) between San Pedro and San Diego (Figure 1) has enabled us to study in detail the complex structure of this region. Our data consist of moderate-resolution, deep penetration 120 kj sparker profiles, high-resolution, moderate penetration boomer profiles, and high-resolution, shallow penetration 3.5 kHz seismic reflection records. Navigation was by a precision, transponder-based positioning system; maximum error in positioning is approximately 50 m.

DISCUSSION

The predominant structural grain within the Gulf of Santa Catalina and San Diego Trough has a northwest-southeast trend (Figure 1). Two major fault zones within these areas bound a relatively undeformed structural block, here referred to as the Catalina block (Figure 1). The Newport-Inglewood-Rose Canyon fault zone forms the northeast boundary of this block, and the Palos Verdes Hills-Coronado Bank fault zone forms the southwest boundary. Both of these fault zones are composed of discontinuous, generally right-stepping, *en-echelon*

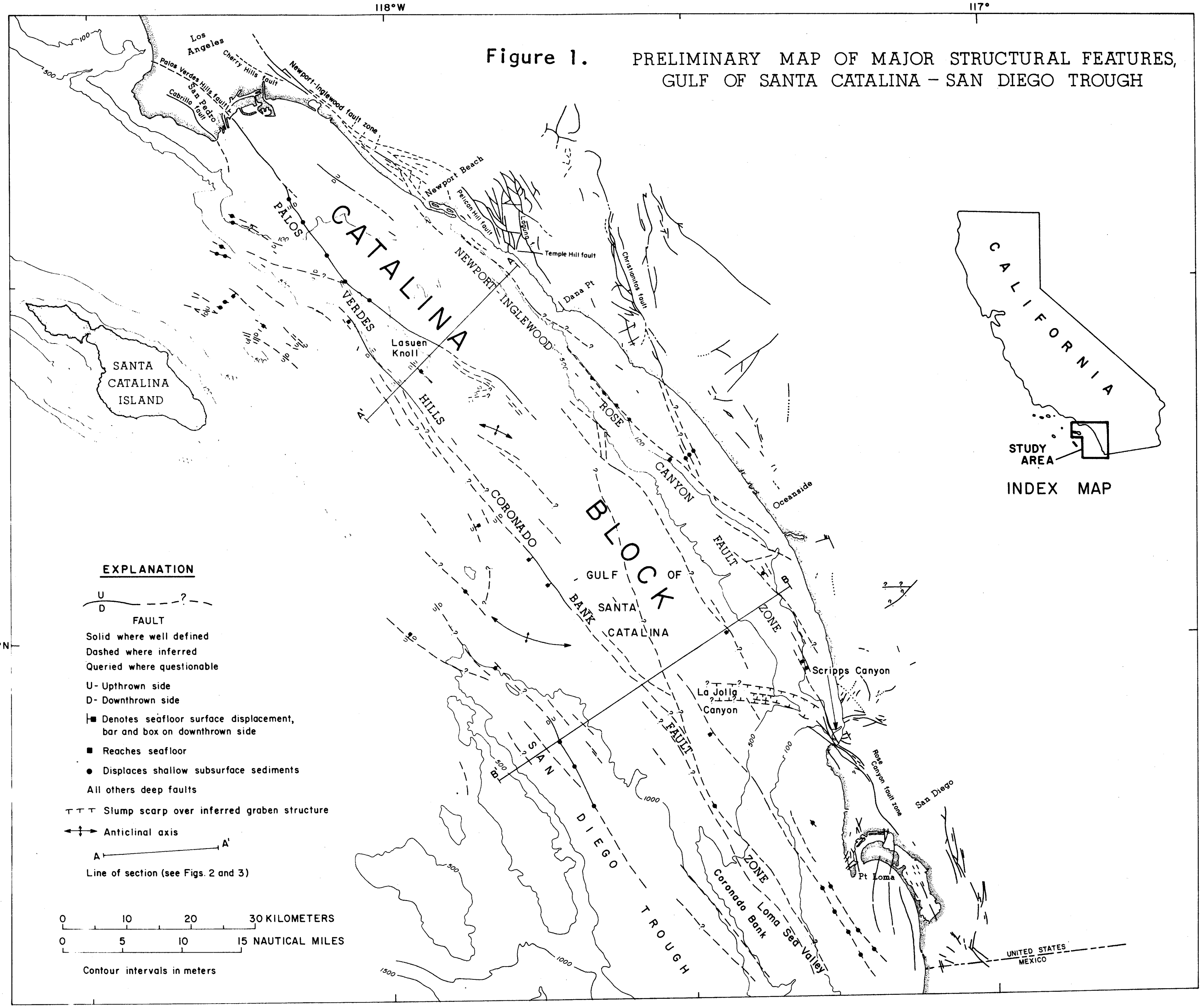


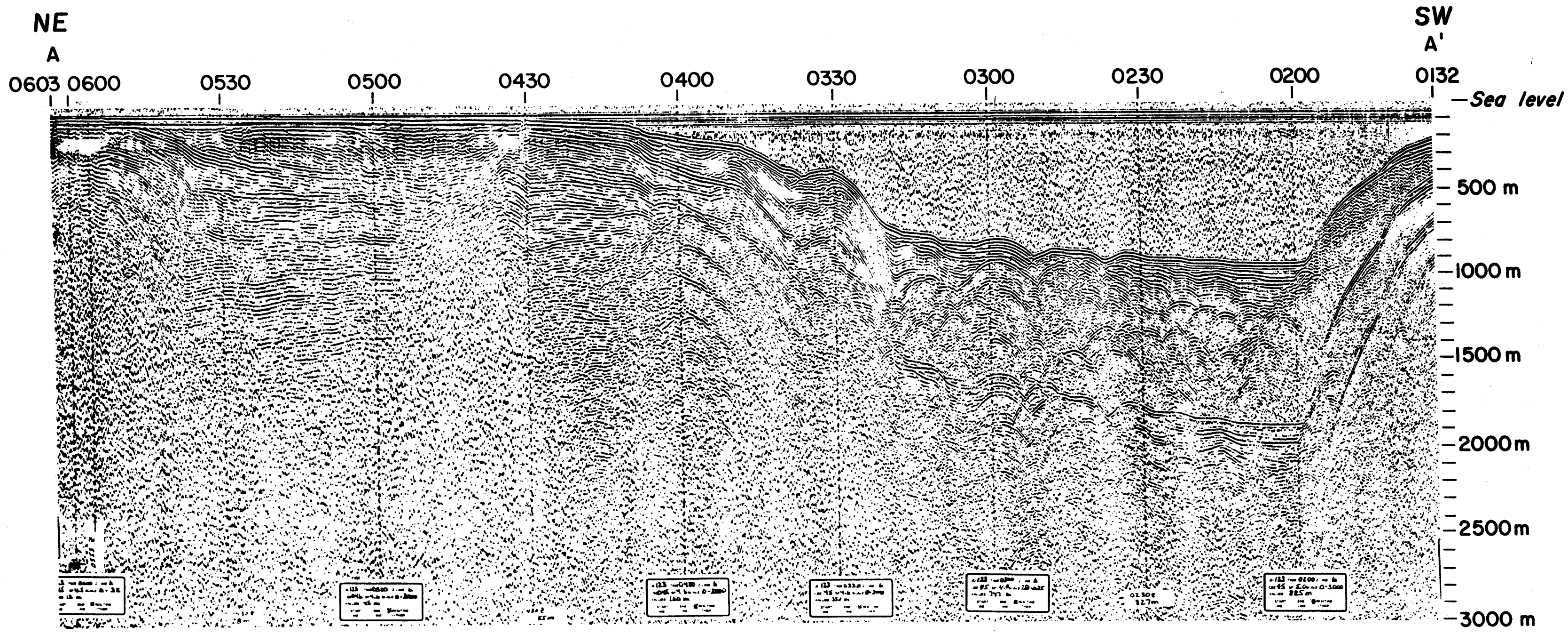
Figure 1. PRELIMINARY MAP OF MAJOR STRUCTURAL FEATURES, GULF OF SANTA CATALINA – SAN DIEGO TROUGH

faults and associated folds. No single fault within either zone appears to continue uninterrupted for more than 40 km. This pattern resembles other fault zones of California, onshore and offshore, which are composed of short, en-echelon faults in relatively narrow (1 to 10 km wide) zones.

The Newport-Inglewood-Rose Canyon fault zone, which extends offshore at Newport Beach, appears to have influenced development of the eastern slope of the Gulf of Santa Catalina physiographic basin. The zone is defined at the surface by discontinuous, generally northwest-trending faults and folds within Tertiary and Quaternary strata; these structural features form a discrete belt that extends for at least 240 km from near the Santa Monica Mountains into Baja California. To the south, near Oceanside, the faults of this zone step to the west and continue southward to La Jolla. Onshore and northwest of Newport Beach, the fault zone extends northward across the western Los Angeles Basin and appears to terminate abruptly at the Santa Monica fault (Barrows, 1974; Ziony, et al., 1974; Jennings, 1977). Moody and Hill (1956) and Harding (1973) postulate a right-slip wrench tectonic model for the Newport-Inglewood fault zone in the Los Angeles Basin. Features suggesting this same sense of motion have been noted offshore along the southern extension of the zone: e.g., Scripps submarine canyon appears to be a right-laterally offset head of the La Jolla submarine canyon. The inner, north-trending segment of La Jolla Canyon also is fault-controlled; it probably was formed by erosion along a shear zone created by motion along the Rose Canyon fault.

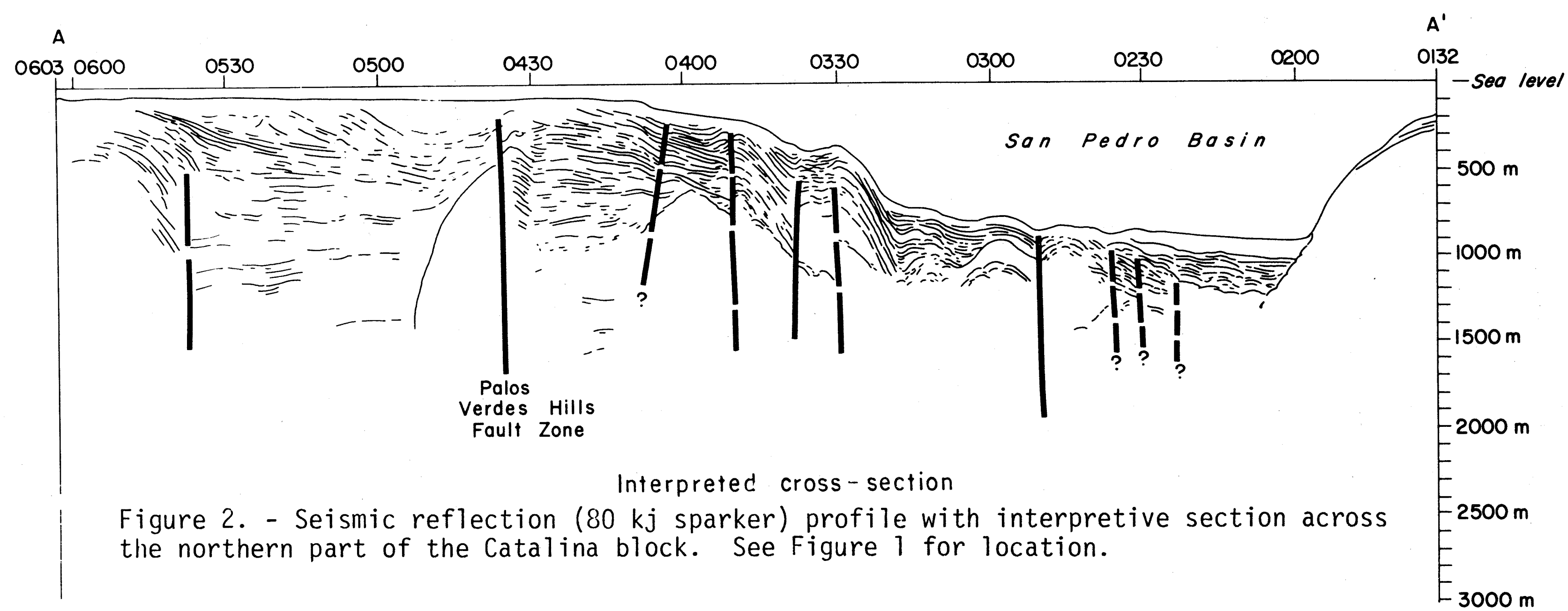
The Palos Verdes Hills-Coronado Bank fault zone extends from Santa Monica to Loma Sea Valley and beyond. The segment of the fault zone near San Pedro forms the western margin of the Catalina block and is well-defined and continuous. However, farther south it is discontinuous along the eastern edge of Lasuen Knoll. Here strands of the fault zone step westward, directly along the western edge of Lasuen Knoll. This fault zone may be traced southward for 30 km or more, to its intersection with a more north-trending fault. From this intersection, the Palos Verdes Hills-Coronado Bank fault zone continues southward as two separate segments skirting the eastern edge of Coronado Bank. We suggest that the fault zone has exerted structural control on the development of Loma Sea Valley and the eastern slope of the Coronado Bank during the Quaternary.

The length, trend, and character of these two major offshore fault zones are comparable to the Whittier-Elsinore and San Jacinto fault zones onshore. Short, en-echelon, second-order faults are associated with each major fault zone and commonly splay from the primary faults at angles from 20 to 40 degrees.



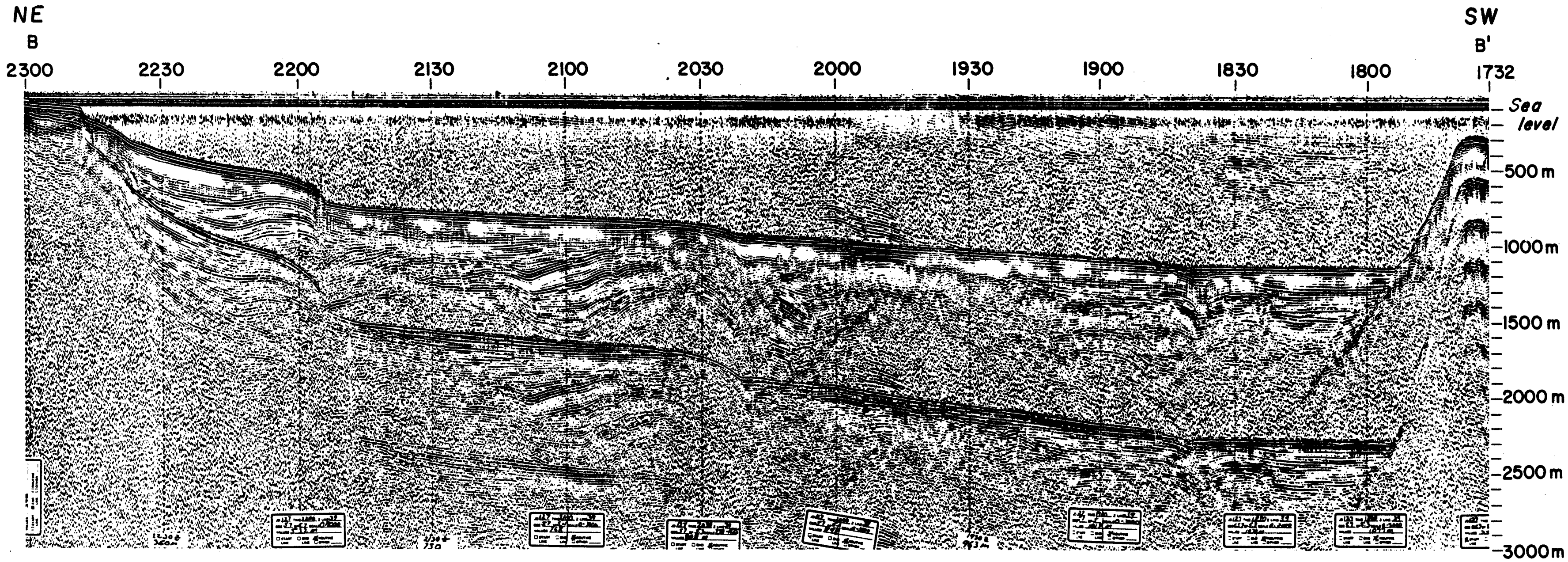
Acoustical profile

VERTICAL EXAGGERATION: x 5



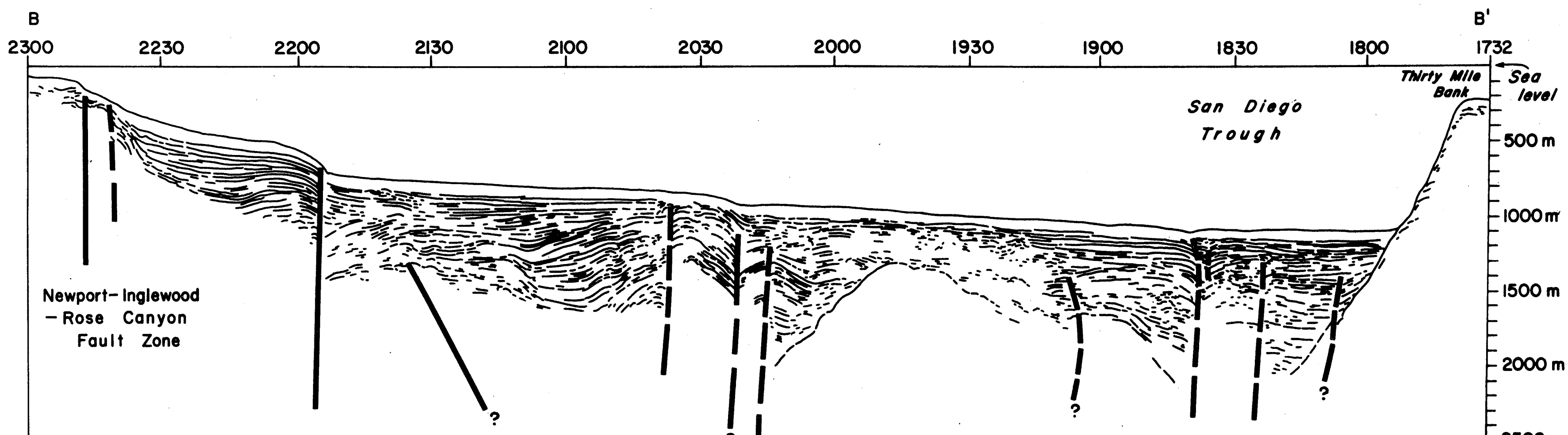
Interpreted cross-section

Figure 2. - Seismic reflection (80 kj sparker) profile with interpretive section across the northern part of the Catalina block. See Figure 1 for location.



Acoustical profile

VERTICAL EXAGGERATION: x 6



Interpreted cross-section

Figure 3. Seismic reflection (80 kj sparker) profile across southern part of Catalina block. See Figure 1 for location.

Second-order fold axes are similarly related to these fault zones. These structural relationships follow the stress pattern for wrench faulting described by Moody and Hill (1956) and Wilcox, et al. (1973) and suggest that the offshore zones represent through-going, right-slip faults within the underlying basement rocks.

Major structural and physiographic features within and bounding the Catalina block are compatible with the model of wrench tectonics. We suggest that La Jolla submarine canyon, for example, is a graben that has formed as the result of tension associated with dilation within the Catalina block. Coronado Bank, Point Loma, and other banks and ridges within and adjacent to the Catalina block appear to be horsts produced by compression. Horst and graben topography and buried sedimentary basins and ridges in the San Diego region (Michael Kennedy, oral comm., 1978) also could be an expression of wrench tectonics.

CONCLUSIONS

The Gulf of Santa Catalina-San Diego Trough region of the southern California continental borderland contains a major structural block, here called the Catalina block, which probably was formed and is presently being influenced by wrench tectonics. The Catalina block is bounded by two major fault zones, the Newport-Inglewood-Rose Canyon fault zone and the Palos Verdes Hills-Coronado Bank fault zone, and appears to have undergone slight deformation caused principally by right-slip along the bounding fault zones. Differences in the rates of right-slip along these fault zones could result in elongation and rotation of the block.

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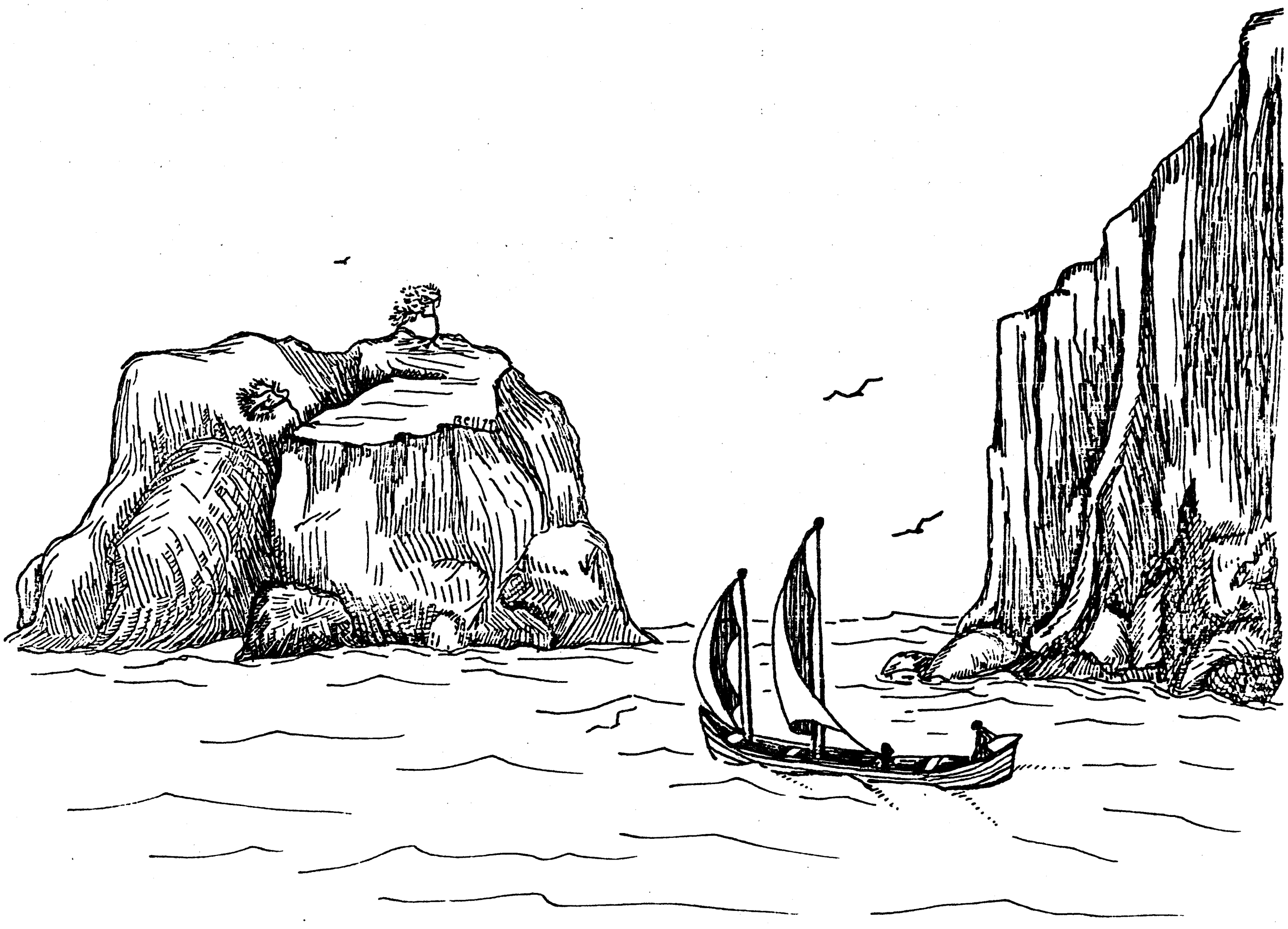

FAULTING OFFSHORE SAN DIEGO AND NORTHERN BAJA CALIFORNIA

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INTRODUCTION

The offshore area considered in this discussion (Figure 1) comprises the inner continental borderland of southern California and northern Baja California, Mexico. It is bounded on the west by the San Clemente fault zone and on the east by the shoreline. It extends north to Santa Catalina Island and south to Punta Santo Tomás, Baja California. Although the northern and southern boundaries are well removed from metropolitan San Diego, it is important to discuss several major faults that extend from these boundaries to the San Diego area, since they directly affect the seismic hazard in San Diego. It is becoming more apparent, as more data are collected, that a significant portion of the earthquake hazard in the San Diego area is from offshore sources (Anderson, 1979; Legg and Ortega, 1978). It has been estimated that as much as 20% of North American--Pacific relative plate tectonic motion in southern California occurs offshore (Anderson, 1979). This paper describes the significant faults in the offshore region which directly affect the San Diego area. Legg (1979) suggested that faults in the inner southern California borderland are capable of accommodating most, if not all of the Quaternary offshore relative plate motion.

The offshore faults are divided into four major fault zones as suggested by Junger (1976) and Legg (1979). These zones are represented by one or more relatively long and continuous faults with many sub-parallel, *en echelon*, or conjugate faults forming a wrench fault zone as shown by Wilcox, *et al* (1973). The fault zones are, from west to east: (1) Santa Cruz-San Clemente-San Isidro; (2) San Pedro-San Diego Trough-Maximinos; (3) Palos Verdes Hills-Coronado Banks-Agua Blanca; (4) Newport-Inglewood-Rose Canyon-Vallecitos-San Miguel. Three of these zones pass onshore within the area shown in Fig. 1.

Many faults studied have existed since the middle Miocene, when the spreading center to the west of North America collided with the continent, and a triple junction migrated southward along the Pacific coast of Baja California (Atwater, 1970). These faults have had recurrent movement to the present. Total amounts of displacement in the offshore area are unknown in general, because of the obvious difficulty in finding genuine "piercing points". Most estimates of displacements on offshore faults have been based upon bathymetry (Shepard & Emery, 1941; Krause, 1965; Legg, 1979).

SANTA CRUZ-SAN CLEMENTE-SAN ISIDRO FAULT ZONE

The first, and probably longest and most continuous fault zone in the inner continental borderland consists of the San Clemente-San Isidro fault (Moore, 1969; Legg, 1979). There are many sub-parallel and oblique conjugate faults that also show sea-floor breaks associated with the San Clemente-San Isidro fault zone, especially in the vicinity of Fortymile, Boundary, and Navy Banks (Loc. 3,4,5, respectively, Fig. 1).

The San Clemente-San Isidro fault appears to be more than 350 km in length and quite continuous in nature. It has dramatic sea-floor scarps along much of its length. The most familiar escarpment along this fault forms the eastern side of San Clemente Island (Loc. 1, Fig. 1) which shows a total vertical relief of up to 2300 m (Junger, 1976). Lonsdale (1979) observed a 50-75 m high scarp, with an upper slope inclined 60 degrees, and with mounds of barite believed to have been deposited by hydrothermal activity, along the San Clemente fault in the vicinity of the Navy submarine fan (Loc. 6, Fig. 1). The San Clemente fault continues southward, through the San Clemente Rift Valley (Loc. 2, Fig. 1), (Shepard & Emery, 1941), and along the northeastern margin of the San Clemente basin. The fault forms the western face of Fortymile Bank (Loc. 3, Fig. 1), which might suggest 25 miles (40 km) of right-lateral, strike-slip displacement between Fortymile Bank and San Clemente Island (Shepard & Emery, 1941). Also in the vicinity of Fortymile Bank are several sub-parallel faults associated with the San Clemente-San Isidro fault zone, some of which appear to be splays of the main fault. In particular, one at the southern end of Fortymile Bank turns more easterly and appears to trend toward Navy Bank (Loc. 4, Fig. 1) and beyond, possibly connecting with the

Maximinos fault zone to the south. This branch is suggested by Legg (1979) to be the previously inferred connection between the San Clemente and Agua Blanca faults (Moore, 1969), although Legg (1979) finds a "gap" (Loc. 5, Fig. 1) in the continuity of this fault southeast of Navy Bank.

The main trace of the San Clemente fault continues south along the northeast side of San Clemente basin where it has a small bend ($\sim$25 km long) south of Navy Bank. This bend (Loc. 6, Fig. 1) trends more westerly (N65°W) than the typical strike (N45°W) of the San Clemente fault and has a 250 m high ridge associated with it. This ridge is commonly cut by the most prominent trace of the fault zone. Where this fault does not displace rocks of the ridge itself, it lies along its base. There are many small, sub-parallel reverse faults cutting the sea-floor along the flanks of the ridge. The more westerly strike of this possibly compressional feature is suggestive of right-lateral, strike-slip along the northwest trending San Clemente fault. In addition, apparent vertical offsets of as much as 500 m (Junger, 1976) and additional compressive features along this fault indicate that there is also a significant dip-slip component.

Moore (1969) and Legg (1979) trace the San Clemente fault southward, connecting it with the San Isidro fault offshore Mexico, at a point more than 30 km southwest of Punta Banda and the Agua Blanca fault. Major sea-floor scarps alternating from west-side up to east-side up are common along this part of the fault zone, and may further indicate combined strike-slip and dip-slip faulting (Loc. 7, Fig. 1). The offshore Santo Tomás fault of Krause (1965) (Loc. 8, Fig. 1) has 15 km of reported left-lateral offset and is truncated by the San Clemente-San Isidro fault as shown by the long, eastward-facing escarpment (Krause, 1961; Moore, 1969). The onshore Santo Tomás fault passes offshore at Bahia Soledad (Loc. 9, Fig. 1) and appears to have had right-lateral movement (Allen, *et al*, 1960; Suarez, personal communication), which is inconsistent with the movement reported offshore by Krause (1961, 1965). Legg (1979) concludes that the Santo Tomás fault offshore is not continuous with the Bahia Soledad (or onshore Santo Tomás) fault, but is probably closely related to the San Clemente-San Isidro fault zone.

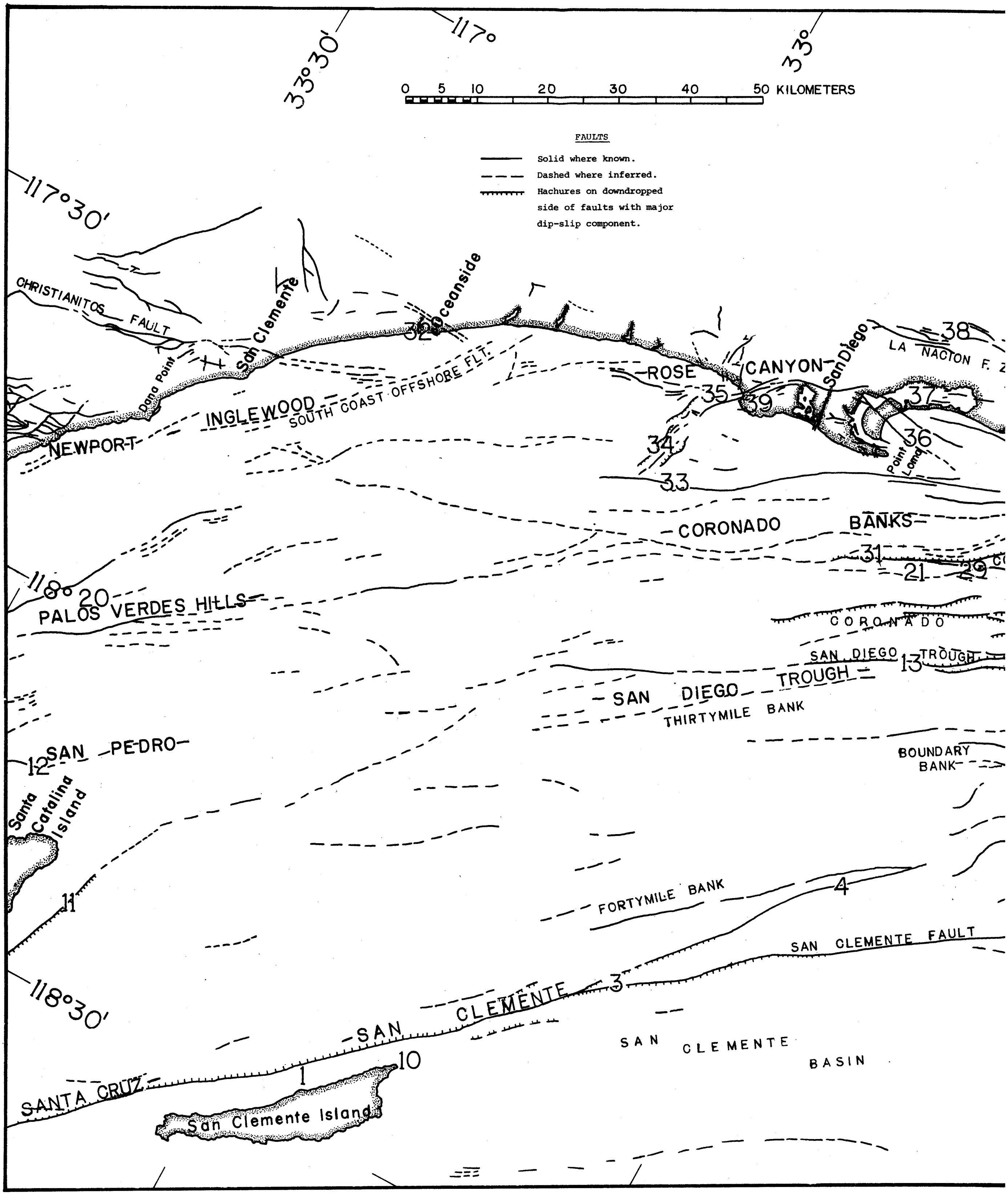
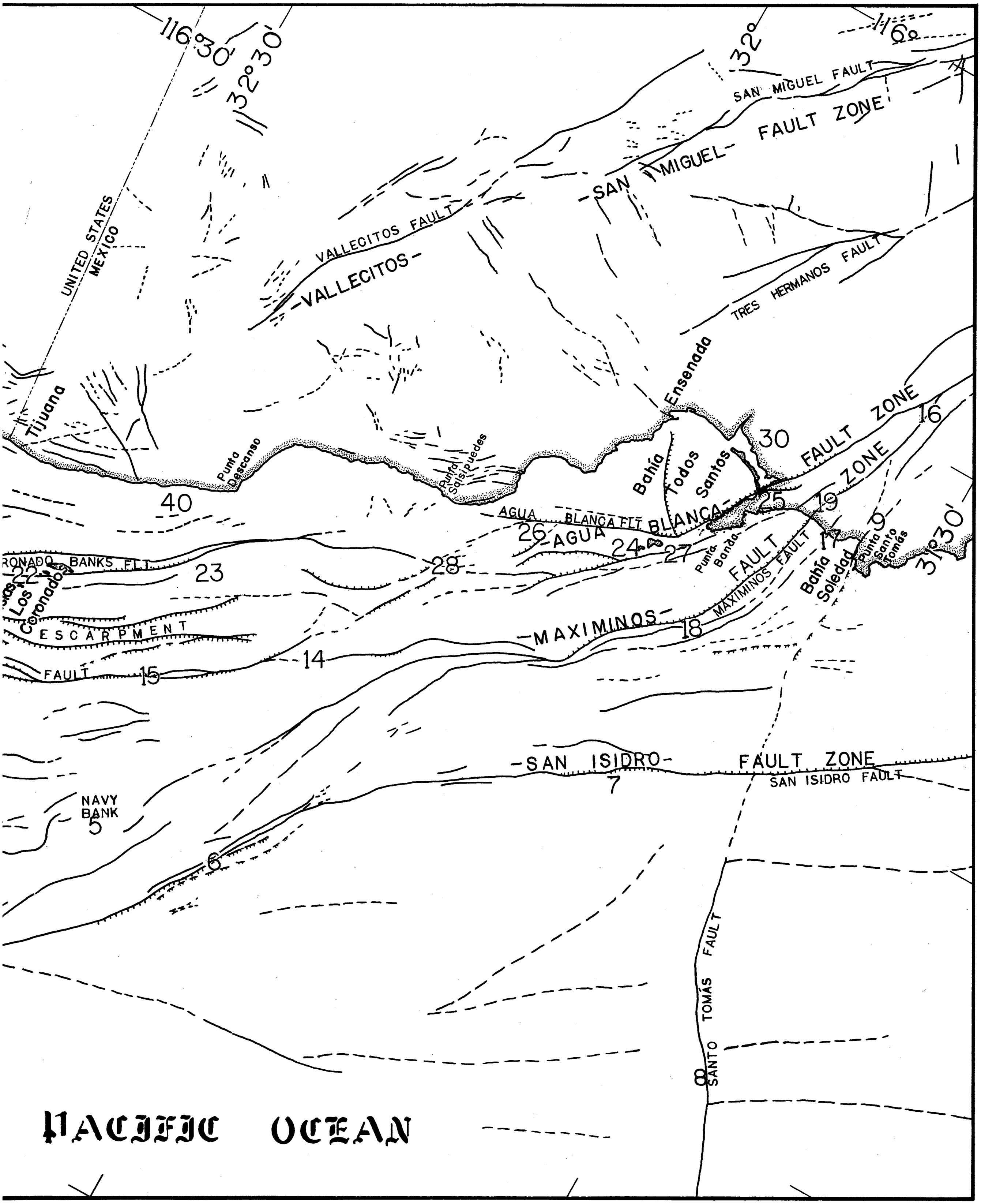


Figure 1. FAULTING OFFSHORE SAN DIEGO AND



ORTHERN BAJA CALIFORNIA, MEXICO

In summary, the known length of the San Clemente-San Isidro fault is more than 350 km . If this fault were to rupture along half of its mapped length, it could conceivably produce an $M_L \geq 7\frac{1}{2}$ earthquake as inferred from the fault length *versus* magnitude relationships of Housner (1969) The frequency of occurrence of such large events, if they occur at all, is probably much lower than that of the San Andreas fault. The largest earthquake recorded along the San Clemente-San Isidro fault zone since 1932 was $M_L = 5.9$, occuring on December 25, 1951 at the southern tip of San Clemente Island (Loc. 10, Fig. 1). Due to the close proximity of the San Clemente-San Isidro fault zone to San Diego (and because of the tsunami potential) an event of this size or greater, with associated sea-floor displacement, could be very destructive to the coastal cities of San Diego, Tijuana, and Ensenada. Moderate earthquakes ($M_L \sim 4$-5) occur along this fault zone every few years, demonstrating the seismically active nature of this major, offshore fault zone.

SAN PEDRO-SAN DIEGO TROUGH-MAXIMINOS FAULT ZONE

The San Pedro-San Diego Trough-Maximinos fault zone lies somewhat closer to San Diego. Principal faults of this zone are the San Pedro (Loc. 11, Fig. 1) and Santa Catalina faults (Loc. 12, Fig. 1), the San Diego Trough and Thirtymile Bank faults, and the Maximinos fault. There may not be one continuous, through-going fault in this zone, but based upon current studies of seismic profiles of these faults, they appear to be sub-parallel or *en echelon* segments of a deeper, continuous wrench fault system. The Santa Catalina and San Pedro faults are discussed in more detail elsewhere (Vedder, *et al.*, 1974; Junger & Wagner, 1977). To the south, the San Diego Trough fault forms the major component of this zone (Loc. 13, Fig. 1), extending from the central San Diego trough to a point about 20 km southwest of Punta Salsipuedes (Loc. 14, Fig. 1). At its southern end the structure is very complex, and the fault may be continuous with, or *en echelon* to, the Maximinos fault or branches of the Agua Blanca fault (Legg, 1979). The San Diego Trough fault breaks the sea-floor with alternating east- and west-side up scarps (as high as 10-20 m) suggesting strike-slip. The fault splays along its strike many times, but re-connects with sub-parallel branches, suggestive of wrench faulting as described by Wilcox, *et al.* (1973). Eastward-facing scarps (Loc. 15, Fig. 1) of the San Diego Trough fault act to block the down-stream end of the Coronado submarine canyon and force the channel to the south (Shepard & Emery, 1941; Shepard & Dill, 1966; Emery, *et al.*, 1952).

The Maximinos fault extends from a splay in the Agua Blanca fault, near Valle Santo Tomás, Mexico (Loc. 16, Fig. 1), and passes through Cañada Maximinos, and offshore near Punta Los Maximinos, turning more northerly to a point where it connects with the San Diego Trough and/or Fortymile Bank fault zones. The details of faulting at both the northern end of the Maximinos fault and southern end of the San Diego Trough fault are extremely complex and not completely understood. There are two or more major, sub-parallel faults associated with the Maximinos fault that trend offshore north of Bahia Soledad (Loc. 17, Fig. 1) and along the channel of a submarine canyon that heads near Bahia Soledad (Loc. 18, Fig. 1). To the north, these sub-parallel branches splay and trend towards Navy Bank (Loc. 4, Fig. 1). Based upon 3.5 kHz echo-sounder records, all of these faults either break the sea-floor, or displace the upper sedimentary layers interpreted as Quaternary in age (Legg, 1979). The Maximinos fault passes through a small canyon north of the Canada Maximinos immediately before it passes offshore (Loc. 19, Fig. 1). Here it is seen to have scarps with very youthful appearances, right laterally offset stream channels, and aligned ground-water barriers as manifested by contrasting vegetation. Scarps are uplifted to the south and west along the main branch of the Maximinos fault.

In summary, the San Diego Trough-Maximinos fault zone is considered herein to be a principally right-lateral, strike-slip, northwest-trending, Quaternary fault zone. The main, through-going traces of the San Diego Trough fault lie within 40 km of metropolitan San Diego, where the eastward-facing scarps force the Coronado Canyon to turn southward along the base of the Coronado escarpment. The presence of sea-floor scarps suggests a small dip-slip component, but certainly not as great as that observed along the San Clemente-San Isidro fault zone. The San Diego Trough-Maximinos fault zone appears to have very few earthquake epicenters located near it in the southern portion, although the inaccuracies in the epicentral locations in the southernmost part of the area do not allow definite conclusions regarding activity. Some of the smaller faults associated with this system might suggest possible connections with the San Clemente fault near Navy Bank and Fortymile Bank, but Legg (1979) finds "gaps" within the sedimentary cover through this area.

PALOS VERDES HILLS-CORONADO BANKS-AGUA BLANCA FAULT ZONE

Greene, *et al.* (this volume) discuss the Palos Verdes Hills fault zone in more detail. The Palos Verdes Hills-Coronado Banks-Agua Blanca fault zone is typified by high vertical relief at Palos Verdes Hills (not shown in Fig. 1), Coronado Banks (Loc. 21, Fig. 1), Islas Los Coronados (Loc. 22, Fig. 1), Descanso Shelf-Ridge (Loc. 23, Fig. 1), Islas de Todos Santos (Loc. 24, Fig. 1) and Punta Banda (Loc. 25, Fig. 1). Vertical displacements of several hundred meters occur locally along these segments, even though the major component of slip is lateral. At the southern end of the offshore portion of this fault zone, the Agua Blanca fault shows clear evidence of vertical movements as shown by dramatic Quaternary seafloor scarps (Loc. 26, Fig. 1). Right-lateral, strike-slip is suggested by stream offsets on Punta Banda (Allen, *et al.*, 1960; Gastil, *et al.*, 1975), offsets in the Punta Banda (Loc. 27, Fig. 1), Salsipuedes (Loc. 28, Fig. 1), and Coronado (Loc. 29, Fig. 1) submarine canyons (Legg, 1979), and by the configurations of Punta Banda and the Coronado Banks (Legg, 1979). Legg (1979) suggests 11 km of post-Pliocene displacement along the Coronado Banks fault by realigning the north bank with the south bank. Allen, *et al.* (1960), Gastil, *et al.* (1975), and Suarez (personal communication) suggest that not more than 20 km of right-lateral displacement exists along the onshore segment of the Agua Blanca fault. Since the San Diego Trough-Maximinos fault zone joins the Agua Blanca fault onshore, the total displacement on this, plus that on the Coronado Banks fault zone is probably limited by the amount suggested for the onshore Agua Blanca fault zone.

The region just offshore from Punta Salsipuedes is very complex, and direct connections between the Agua Blanca and Coronado Banks fault have not been established. Krause (1961, 1965) inferred northward continuation of the Agua Blanca fault through the Islas Los Coronados using magnetic data. The Agua Blanca fault is also very complex along and to the north of Punta Banda. There are at least two sub-parallel traces of this fault that lie along opposite sides of Punta Banda, forming the Punta Banda horst (which includes the Islas de Todos Santos). The main trace of the fault on the north side of Punta Banda marks a major structural boundary between the Punta Banda basement ridge high and the sediment-filled Valle Maneadero (Loc. 30, Fig. 1) which extends into Bahia Todos Santos. The faults on the south side of Punta Banda offset the Punta Banda submarine canyon (Loc. 27, Fig. 1) as much as 4 km in a right-lateral sense, and control the shape of a northwest trending canyon to the west of the Islas de Todos Santos (Legg, 1979). The main trace on the northeast side of the Punta Banda ridge passes along the east side of the Islas de Todos Santos, forming a steep escarpment. This trace curves through a 25° - 35° angle between Punta Banda and the Islas de Todos Santos. East of the Islas de Todos Santos, acoustic basement highs are juxtaposed where the Valle Maneadero ends in an east-west trending normal fault that trends toward the Ensenada breakwater. This relationship was observed on gravimetric and magnetic data by Serrano (1977). Farther north along the fault, and southwest of Punta Salsipuedes, the acoustic basement is again deeper (∿500+ m) to the east, and sea-floor scarps are present along the main trace of the Agua Blanca fault. The fault passes very near the coast at Punta Salsipuedes, and there are no data close enough to the shore to accurately delineate its northward extent.

The Coronados Banks fault zone is found west of Punta Salsipuedes, along the Descanso ridge (Loc. 23, Fig. 1), within the sediment-filled channel between the ridge and the coast. To the north, the fault splays around Middle and South Coronados Islands, with one trace passing very near to the west side of Middle Island. Coronado Canyon (Loc. 29, Fig. 1) cuts transversely across the Coronados Banks fault zone and a right-lateral offset is suggested. Loma Sea Valley (Loc. 31, Fig. 1) is eroded along the Coronado Banks fault and its main trace lies along the steep, western flank of the valley where a major basement discontinuity exists (Legg, 1979). In addition to the main trace of the fault, numerous sub-parallel fault traces lie along the more gently sloping eastern side of the Loma Sea Valley.

Legg, *et al.* (1977) suggested that the Coronado Banks fault zone extends northward from the Coronado Banks along a N45°W trend of earthquake epicenters (Fig. 2). The trend of epicenters becomes more diffuse in the vicinity of Lasuen Knoll (Loc. 20, Fig. 1), perhaps because of complexities in the fault zone (Greene, *et al.*, this volume). South of Coronado Banks (Loc. 21, Fig. 1), the activity appears to cease at about the latitude of south San Diego Bay until the Salsipuedes area where earthquake swarms have been recorded (Hileman, *et al.*, 1973).

In summary, the Palos Verdes Hills-Coronado Banks-Agua Blanca fault zone is a complex, multi-part, Quaternary zone of deformation suggestive of wrench faulting (Wilcox, *et al.*, 1973; Legg, 1979). Earthquake epicenters located near these faults, as well as questionably faulted Holocene sediment, indicate that this fault zone is active. However, it is significantly less active seismically than the San Clemente or Elsinore faults, based upon data reported by Hileman, *et al.* (1973). Its close proximity to the San Diego greater metropolitan area (∿25 km) makes it of great interest with respect to producing moderate-sized (M_L = 5-6) earthquakes. Although large vertical relief is present along this fault zone in the vicinity of San Diego, fault movement appears to be dominated by strike-slip, and so tsunami generation is probably less likely in this fault zone than from the San Clemente fault, (notwithstanding the possibility of seismically induced submarine slumping and associated sea wave generation along the steep slopes of the Coronado escarpment or the Loma Sea Valley).

NEWPORT-INGLEWOOD-ROSE CANYON-VALLECITOS-SAN MIGUEL FAULT ZONE

The Newport-Inglewood-Rose Canyon-Vallecitos-San Miguel fault zone passes closest to metropolitan San Diego as a series of sub-parallel, *en echelon*, and conjugate faults characteristic of a wrench zone (Wilcox, *et al.*, 1973; Harding, 1973). The Newport-Inglewood zone is described elsewhere (Harding, 1973; Barrows, 1974; Ziony, *et al.*, 1974), and is especially well known for the 1933 Long Beach earthquake (M_L = 6.3). Barrows (1974) discussed the similarities between the Newport-Inglewood and South Coast Offshore fault zones, and Euge, *et al.* (1973) suggested a branch of the Rose Canyon fault passes northeastward, onshore in the Oceanside area (Loc. 32, Fig. 1). Moore (1972), Moore and Kennedy (1975), and Kennedy, *et al.* (1978) have mapped in detail, the offshore portions of the Rose Canyon fault zone in the immediate San Diego area.

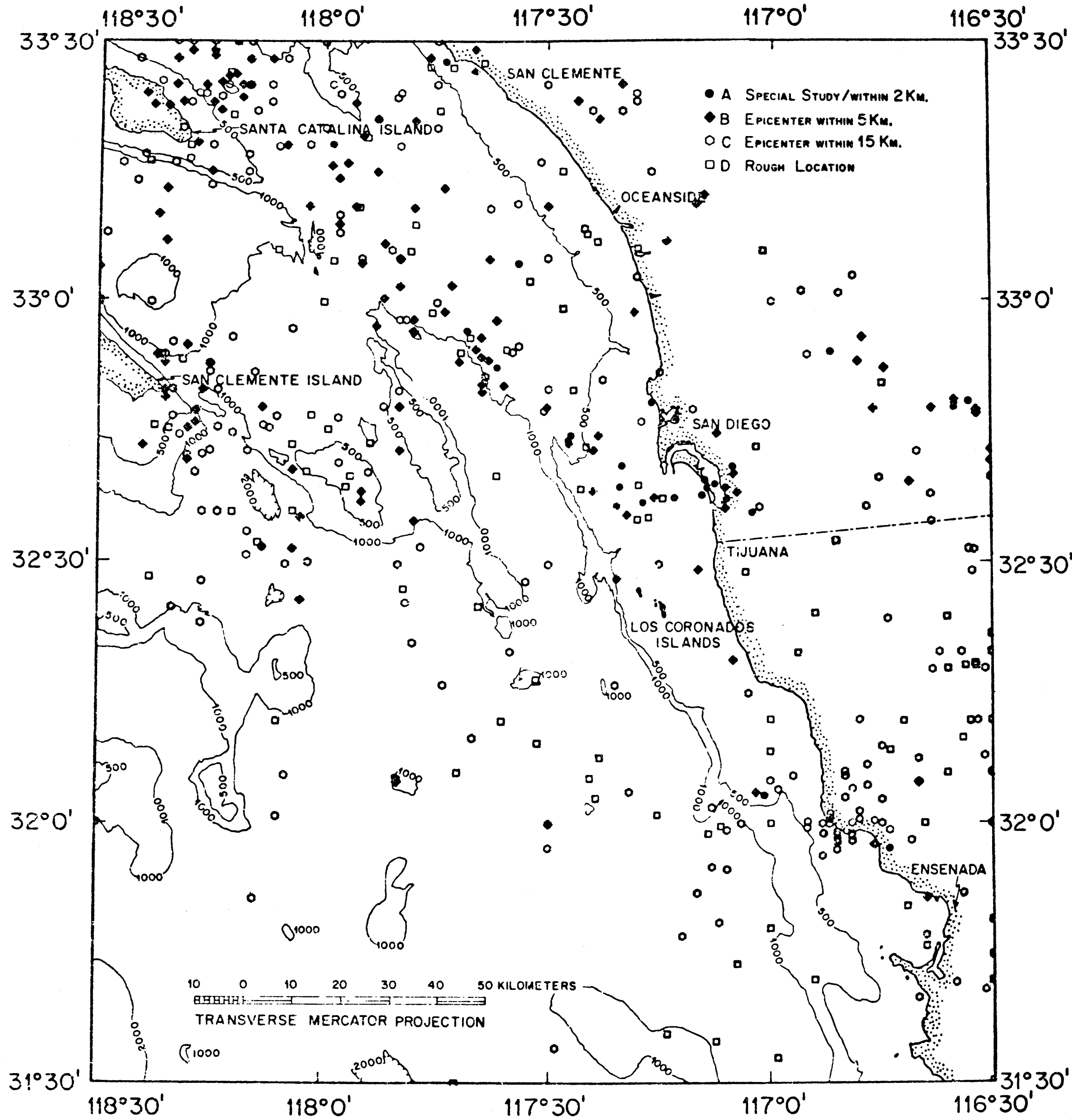


Figure 2: Map showing epicentral locations of earthquakes in the offshore region of southern California and northern Baja California, Mexico. The data covers the period from 1 January, 1932 to 30 September, 1976, and are from the Caltech seismograph array in southern California. Sources for the locations are Hileman, *et al.* (1973), Friedman, *et al.* (1976), Fuis, *et al.* (1977), and Simons (1977). Magnitudes for the earthquakes in the figure range from M_L=1.5 to M_L=5.9, and the epicenters have been coded for accuracy of the location. Note the linear trend of more accurately located epicenters that delineate the Coronado Banks fault zone, and also the trend of epicenters further offshore that marks the San Clemente-San Isidro fault zone.

North of Point La Jolla, Kennedy, *et al.* (1978) described four distinct fault patterns constituting the Rose Canyon fault zone in that area. The westernmost faults (Loc. 33) trend northwesterly, and are, in general, either overlain by 5 m of unfaulted Quaternary sediments, or lie totally within older (Late Cretaceous to Tertiary) acoustic basement. Most of these fault segments are relatively short (∿10 km), discontinuous, sub-parallel or *en echelon*. The central zone of faulting forms the almost symmetrical, La Jolla graben, through which the La Jolla submarine canyon is cut (Loc. 34, Fig. 1). Faults in this sub-zone consist of short segments (∿1 km) with thin, discrete zones of slip, and stratigraphic separations of more than 9 m. The general trend of the La Jolla graben is N70°-80°W, although individual fault segments may strike from WNW to NNE. Fault or fault-line scarps are observed, and disruption of the acoustically transparent, uppermost sedimentary layer in this zone suggests Holocene activity.

A nearshore sub-zone of northwest trending faults, to the east of the La Jolla Canyon, is described by Kennedy, *et al.* (1978), (Loc. 35, Fig. 1). The faults are discontinuous, sub-parallel and *en echelon* breaks similar to those observed onshore in the Rose Canyon fault zone (Kennedy, 1975; Kennedy & Peterson, 1975; Kennedy, *et al.*, 1978), and display some surface manifestations such as sea-floor scarps and small submarine canyons. Reflection profiles indicate these faults to be nearly vertical with the faulting extending into the near surface, Quaternary sediments. Kennedy, *et al.* (1978) suggest a right lateral offset of 2.5 km since early Pleistocene, by realignment of the Scripps Canyon with an abrupt change in course in the lower La Jolla Canyon (Loc. 35, Fig. 1).

Along the onshore coastal plain, Kennedy (1975) delineated many northeasterly-trending faults that pass offshore. Vertical separations on these faults is small (∿10 m), and Kennedy *et al.* (1978) do not observe these faults, in general, in their seismic profiles. Onshore, however, displacement of the Pleistocene Bay Point Formation (∿120,000 years) is observed locally on some of these small faults (Kennedy, 1975).

As the Rose Canyon fault zone is traced south, the main faults form a gentle S-shaped curve around Mt. Soledad (Loc. 39, Fig. 1) and Mission and San Diego bays. Structural relief of these highs and lows is suggested to be a consequence of alternating local compression and tension respectively, created by the predominantly strike-slip movement across the bends in the Rose Canyon fault zone (Moore & Kennedy, 1975; Kennedy, *et al.*, 1978).

Complex, multi-part, *en echelon*, right-stepping faults characterize the zone throughout the San Diego area with Mission Bay, San Diego Bay and La Jolla Canyon forming structural lows in the tensional zones, and Mt. Soledad (Loc. 39, Fig. 1) and Point Loma forming the structural highs in the compressional zones. Moore and Kennedy (1975) described faulting in the San Diego Bay and offshore bight (Loc. 36, Fig. 1), and suggested that these faults form the western side of a graben. They observed Quaternary (and in some places, Holocene?) displacements along the faults in San Diego Bay (Loc. 37, Fig. 1), which display strike-slip character as expressed by fault bounded anticlines, chevron-shaped dilational synclines, and other complex folds not characteristic of dip-slip drag. The eastern boundary of the San Diego Bay structural low (graben) is marked by the La Nación fault, (Loc. 38, Fig. 1), described by Artim and Pinckney (1973) and Marshall (this volume).

South of Point Loma, the Point Loma anticline, and associated faults, are observed in the seismic profiles of Legg (1979) and Kennedy and Welday (1979). This feature is traced as far south as Rosarito Beach, Baja California, Mexico (Loc. 40, Fig. 1), by Legg (1979), but it trends too close to the shoreline to be seen in their profiles farther south. Connection or relation to the Tres Hermanos or Agua Blanca faults is possible, but not known at this time. Krause (1961, 1965) also observed this fault in his magnetic data, just south of Point Loma, and, perhaps, offshore of Punta Descanso.

In summary, the Newport-Inglewood-Rose Canyon-Vallecitos-San Miguel fault zone is characterized by right-stepping, *en echelon* faults with Quaternary to Holocene offsets in many places. Gastil, *et al.*, (1975) and Brune and Simons (this volume) discussed the details of the Vallecitos and San Miguel fault zones, and Greene, *et al.* (this volume) discussed the details of the Newport-Inglewood zone. Curvature in the Rose Canyon fault zone bounds prominent structural lows in Mission Bay, San Diego Bay, and La Jolla Canyon, and structural highs at Mt. Soledad and Point Loma. This vertical relief is suggested to be a result of the right-stepping, oblique-slip along the Rose Canyon fault zone, forming local regions of tension and compression. To the north, the fault zone merges with the Newport-Inglewood fault zone; to the south, it apparently merges with the Vallecitos-San Miguel fault zone, although a connection with the Tres Hermanos or

Agua Blanca fault zones is also possible.

Since the Rose Canyon fault zone passes directly through the San Diego metropolitan area, it may pose the greatest seismic hazard to the city. The seismicity of this zone has been very low since the establishment of the Caltech seismograph network in southern California (Simons, 1977), although several small (M_L=3.5-3.7) earthquakes have been located within this zone. The occurrence of moderate sized (M_L=5-6) earthquakes along this fault zone, within heavily populated regions of the San Diego coastal area could cause extensive damage.

CONCLUSIONS

The faulting in the inner continental borderland offshore from San Diego County, and northern Baja California, Mexico is a region extensively deformed and tectonically active. The faults in the region are predominantly strike-slip in character, and form a part of the broad shear zone associated with the San Andreas fault and the North American-Pacific tectonic plate boundary in southern California. The four fault zones discussed are the Santa Cruz-San Clemente-San Isidro, San Pedro-San Diego Trough-Maximinos, Palos Verdes Hills-Coronado Banks-Agua Blanca, and Newport-Inglewood-Rose Canyon-Vallecitos-San Miguel. All four zones are typical of major wrench fault zones as described by Wilcox, *et al.*, (1973). These zones are typified by one or more relatively continuous main faults and numberous smaller, sub-parallel, *en echelon*, and oblique faults. Transversely-oriented folds near steps or curves in the main faults were also observed. All of these fault zones show signs of Quaternary activity, and in many areas, sea-floor displacements, faulted Holocene sediment and/or associated seismicity.

Previous seismic-risk studies in the area (McEuen & Pinckney, 1972) briefly mentioned the hazard from offshore faults, but only the San Clemente and Rose Canyon faults were known in any detail at that time. Now it is known that the San Clemente-San Isidro fault zone is currently active with moderate seismicity, and it appears capable of large, though infrequent, earthquakes. Its distance from the San Diego metropolitan area lessens the hazard from the more frequent, moderate-sized (M_L=4-6) events, although some of these have caused slight damage in San Diego (Agnew, *et al.*, this volume). Closer to the populated coastal area of San Diego, the San Diego Trough and Coronado Banks fault zones may pose a significant earthquake hazard from even moderate-sized events. Perhaps the greatest hazard from earthquakes may be presented by the Rose Canyon fault zone which passes directly through metropolitan San Diego. Small earthquakes in this zone (M_L=3.5-3.7) have caused slight damage (Legg, *et al*, 1977), and moderate-sized events located within the metropolitan area could cause more extensive damage. Quantitative studies of the risk in San Diego including the newly collected offshore fault data have only recently begun, thus it cannot be said which, if any, of these offshore faults pose the greatest earthquake hazard to the city. It can be stated that the four fault zones described appear to be capable of generating earthquakes large enough to be damaging to metropolitan San Diego.

ACKNOWLEDGEMENTS

This paper represents preliminary results of research supported by the NOAA office of Sea Grant, project #04-8-M01-189, California State Resources Agency project #R/CZ-43, NSF grant #EAR76-84324, and U.S.G.S. contract #14-08-0001-17699.

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ACTIVE AND POTENTIALLY ACTIVE FAULTS: SAN DIEGO COUNTY AND NORTHERNMOST BAJA CALIFORNIA

by

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INTRODUCTION

This discussion includes 1) faults which create the eastern escarpment of the Peninsular Ranges, 2) faults of the eastern edge of the Pacific coastal basin, and 3) the transverse strike-slip fault systems from San Diego south. The plate boundary faults system to the northeast and east of San Diego (Elsinore, San Jacinto, Cucupa, Cerro Prieto faults) are not included.

EASTERN ESCARPMENT FAULTS

This system of down-to-the-east, dip-slip faults are responsible for the uplift of the eastern edge of peninsular California. They presumably extend from Mount San Jacinto in the north to the southern tip of Baja California. Segments of this fault system, north of the Elsinore fault, have been disrupted and obscured by the more northwesterly trending strike-slip faults.

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From Coyote Valley (along the Elsinore fault, San Diego County), a zone of faults extends south-southeast along the eastern escarpment of the Sierra Juarez. At the south end of Laguna Salada, this zone appears to widen eastward to include the Sierra de la Tinaja. What happens to this zone as it approaches the northern end of Valle San Felipe is not known, but it is currently being studied by students of Richard Merriam at the University of Southern California. The old erosion surface of the Sierra Juarez stands as high as 1,830 m (6,000 feet) and locally is covered by Miocene basalt and andesite, and older conglomerates; the surface is down-dropped by a series of step faults to elevations near sea level west of Laguna Salada. A gravity survey of Laguna Salada (Kelm, 1972) suggests that the crystalline floor of that depression is about 6,000 m below sea level. Thus the fault has on the order of eight km of vertical separation.

Exposures of the fault planes are best observed along the eastbound portion of U.S. Interstate Highway 8 and along Mexican Highway 2. Almost all of these does not support hypotheses that (a) the East Pacific Rise passed under the peninsula between ten and five million years ago, or that (b) the peninsula has been tipped up on one flank of an asymmetric rise. Antithetic faults of the desert ranges facing the escarpment are, however, consistent with the hypothesis that they are part of a collapse structure related to the spreading of the gulf (Figure 1). The lack of comparable structures on the continental side of the spreading centers may indicate that the spreading is asymmetric (Figure 2).

FAULTS OF THE PACIFIC BASIN MARGIN

The Sweetwater-La Nacion fault system of southwestern San Diego County (Figure 3), faults southwest of Tijuana, faults of the La Mision area, trend north to northwest and are predominantly down-to-the-west, normal faults. Gravity surveys indicate that these faults lie in the zone where the sedimentary section thickens rapidly to the west (Elliott, 1970). Detailed geologic mapping across the La Nacion-Sweetwater fault zone, and gravity studies (Marshall, this volume), show that the stratigraphic section thickens to the west across many of the fault breaks, indicating down-dropping that dates back to at least Miocene time.

SWEETWATER-LA NACION FAULT ZONE

A compilation by Lee Van der Hurst (1976) (Figure 3) shows that en echelon, discontinuous faults extend from Montezuma Road (just south of Mission Valley), south to San Ysidro where they apparently intersect the Rose Canyon(?) fault system (Figure 3). Most of the traces show offsets of the Lindavista Formation (early Pleistocene) and thick sections of strata mapped as Bay Point Formation (e.g. just east of Lincoln Acres). Some older river terraces intermediate in age between the Lindavista and Bay Point Formations (Richard T. Higley, unsubmitted MS thesis at SDSU) show no measurable offset. There are no scarps associated with these fault traces and Elliott and Hart (1977) reported radiocarbon dates as old as 13,000 years in unfaulted alluvium.

Movement on these faults may be differential subsidence across the hingeline of the Pacific margin basin. A minimal thickness of post-Pliocene deposition has been accompanied by minimal amounts of movement on the fault zone. It is not believed to be a continuous fault rupture capable of a major earthquake and it probably has no genetic relation to the Rose Canyon-San Miguel fault system.

TRANSVERSE STRIKE-SLIP FAULTS

Two very different northwest-trending, strike-slip fault systems cross the western and central portions of the area under consideration. These are the

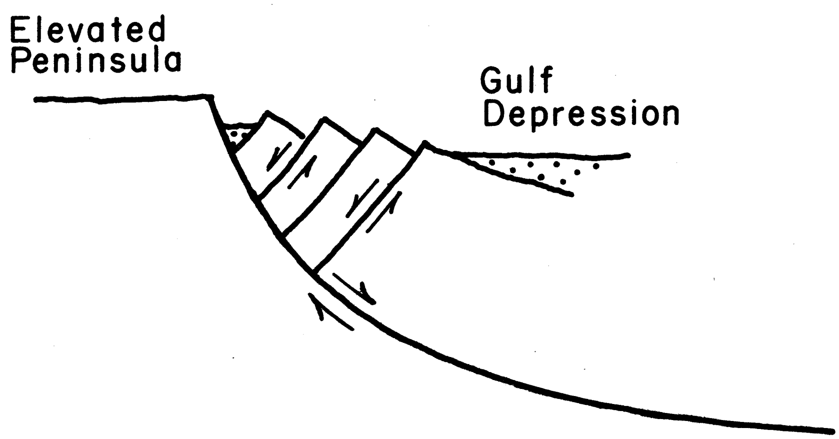


Figure 1. Antithetic fault blocks along eastern escarpment of the Sierra Juarez.

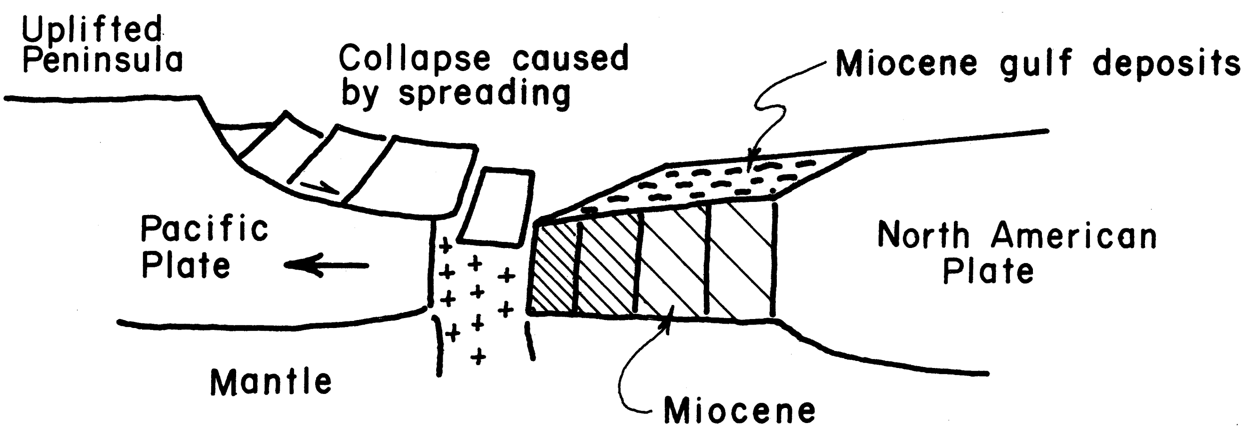


Figure 2. Relation between spreading of the Gulf and origin of faults along eastern edge of Pacific Plate.

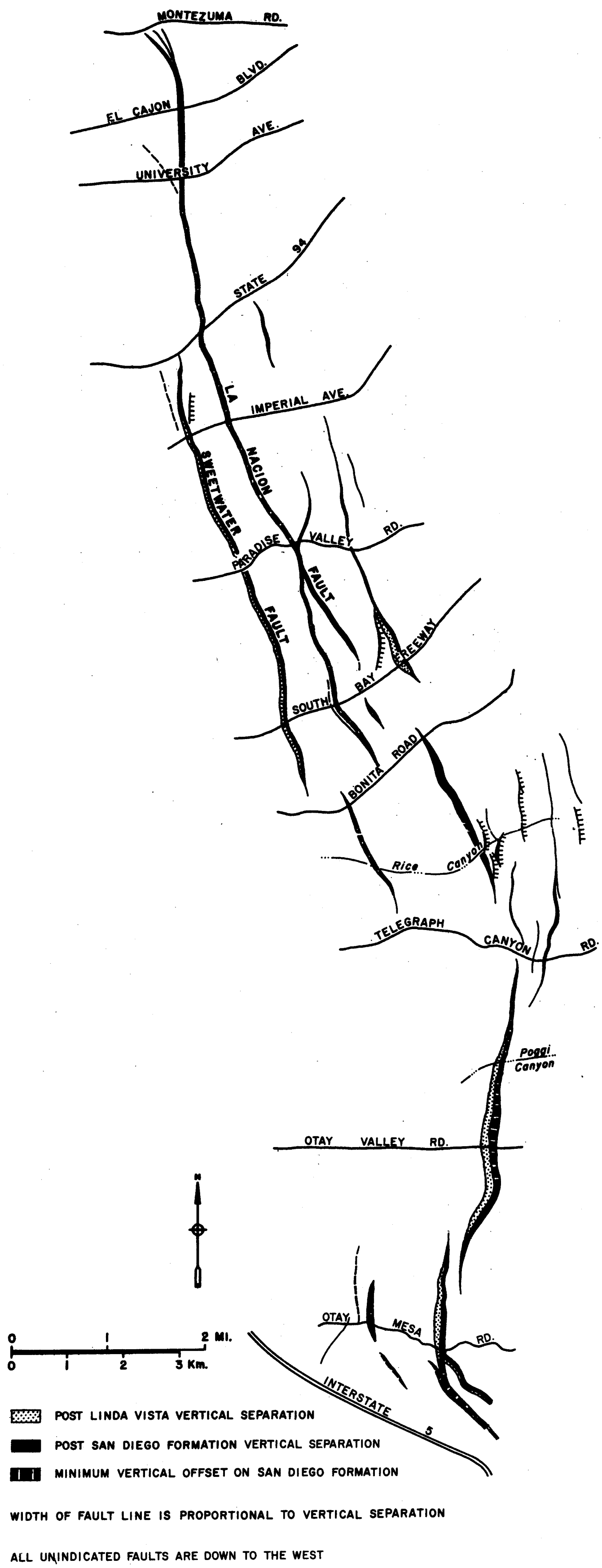


Figure 3 Sweetwater – La Nacion Fault System

faults, some with fault gouge several meters thick, dip to the southwest, with the sense of slip down-to-the-southwest (antithetic). However, large topographic drops down-to-the-east probably mark the positions of unexposed faults dipping to the northeast. The fault system is visualized as in Figure 1, with one or several master faults down to the east, and many secondary faults on the down-dropped block inclining to the southwest to intersect the master fault at depth. The valley which lies between the Sierra Juarez and the Sierra de la Tinaja (Gastil, et al., 1975) is a graben between the master fault system to the southwest and a secondary fault to the northeast.

At most places along the Sierra Juarez escarpment there is little, if any, evidence of recent fault motion. However, at the northern end of the Sierra de la Tinaja there are several places where fault scarps appear to cut the alluvial surface.

SIERRA SAN PEDRO MARTIR FAULT

From San Matias Pass (Mexican Highway 15), it is possible to trace a discrete fault at, or close to, the boundary between crystalline rocks and alluvial fill for approximately 100 km to the southeast. South of that point the separation on the master fault diminishes rapidly, the fault zone widens, and the importance of antithetic faults increases. From the top of the escarpment (3,080 m Mount Diablo), to the base of the sedimentary fill (Slyker, 1964), is an elevation difference of 5 km. It is possible that the desert ranges to the east (Sierra San Felipe and Sierra Santa Clara), are antithetic fault blocks related to the master fault, as is the Sierra de la Tinaja to the north.

Brown (1978) studied the recent fault scarps near Arroyo Agua Caliente near the southern end of the Sierra escarpment. Five or more uplifts of several meters each were found to have occurred here during the past few thousand years. An earthquake of Richter magnitude 5.4 was centered there in 1975. Microseisms have not been detected along the Sierra San Pedro Martir fault.

REGIONAL TECTONICS OF THE SIERRA JUAREZ AND SIERRA SAN PEDRO MARTIR FAULTS

Uplift of the eastern edge of peninsular California bears an analogy to the uplift of the eastern edge of the Sierra Nevada of Alta California. The sedimentary record of the California gulf depression (Gastil, et al., 1979) indicates that rapid uplift of the range began about ten million years ago and was active at times during the Pliocene and Pleistocene. The eastern margin of the California gulf depression has not shared this history of uplift. The record topographically distinct, but weakly active, Agua Blanca system, and the topographically obscure, but very active, San Miguel system.

AGUA BLANCA FAULT

The Agua Blanca and associated Santo Tomás faults are distinctive for their west-northwest trend, which is more westerly than other strike-slip faults associated with the Pacific-North American plate margin. Abundant topographic evidence for right-lateral slip along the northwestern part of the Agua Blanca fault (Allen, et al., 1960) indicates Holocene motion, but seismic records (James Brune, personal communication, 1978) indicate no major earthquakes along the fault since records for the area began, and microseismic activity is less than on the San Miguel system. Although Allen, et al. (1960) report offsets of basement rock up to 20 km and of Quaternary(?) gravels up to 4 km, the strike-slip component of the fault does not extend east of Valle Trinidad. Careful mapping of San Matias pass (Gastil, et al., 1975) shows that the fault dies out completely before reaching the eastern escarpment of the peninsular uplift.

SAN MIGUEL FAULT ZONE

This zone of faults, collectively named the San Miguel by Reyes, et al. (1975), is actually at least four separate en echelon faults: from north to south, the Calabasas, Vallecitos, San Miguel, and Tres Hermanos. These faults (identified in Gastil, et al., 1975) are currently being mapped in greater detail by students at San Diego State University and investigators at CICESI, Ensenada.

Falle de Calabasas. On the 1975 map, the fault extends from La Hiedra about 30 km to Valle de Las Palmas. Mapping by Frazer (1972) improved the understanding in the Valle de Las Palmas area and extended the fault zone to the northwest. The northeast strand of the Calabasas fault appears to displace Quaternary alluvium immediately northwest of Mexican Highway 3. Along the southern edge of Valle de Las Palmas are essentially uneroded scarplets in bedrock that could be of recent origin.

Falle de Vallecitos. A nearly continuous fault extends 65 km from the Eocene conglomerates southeast of Tijuana to Rosa de Castillo, midway across the batholith. There is no evidence of this fault offsetting anything younger than the crystalline basement rocks. An unpublished map by Raymond Elliott in the area west of Rosa de Castillo shows lateral separation of a pluton boundary by approximately three km. At its northwestern end the fault appears to die out in, or be covered by, Eocene conglomerates.

Falle de San Miguel. As shown by the 1975 map (Gastil, et al.) of the State of Baja California this fault consists of two segments, one extending along the eastern side of Valle San Rafael to southeast of San Salvador, and a second extending from Mezquite southeast to the road east from El Rodeo. The northern of these two segments is easily followed on air photographs; the latest (most clearly expressed) fault traces appear to separate vertical dikes of Mesozoic age by only 100 m or so. The southeasterly of the two segments broke over a distance of 17 km in 1956 (Shor and Roberts, 1958). The northwestern portion of the 1956 breaks appear en echelon to the Valle San Rafael segment. These segments appear to form a set of right-stepping, en echelon segments, analogous to the steps of the Elsinore and San Jacinto fault zones, and to the transform faults of the Gulf of California.

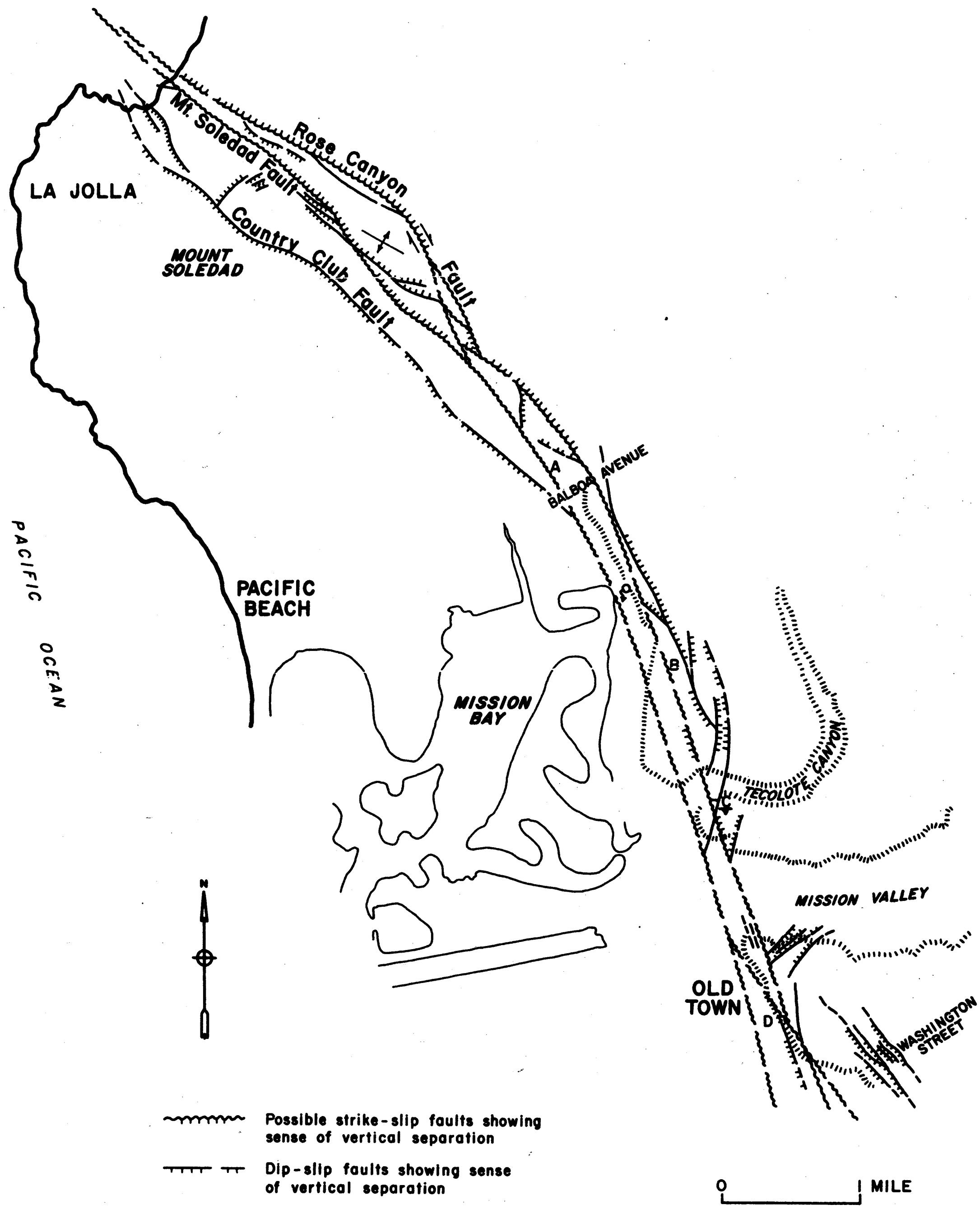
Falle de Tres Hermanos. Midway between the Agua Blanca and San Miguel faults is a fault approximately 45 km in length with pronounced topographic expression. Recency and sense of motion are unknown.

Activity along the San Miguel Fault. Microseismic studies of northwestern Baja California, a cooperative investigation by Mexican and American seismologists (Reyes, et al., 1975) indicate that this is an active area with broadly distributed epicenters. The strands of the San Miguel fault which broke in 1956 only displace Miocene or older conglomerate by a few meters. The zone has not been successfully traced northwest toward the Rose Canyon fault system or southeast to intersect either the Agua Blanca or the Sierra San Pedro Martir faults.

ROSE CANYON FAULT

Recent detailed mapping by students at San Diego State University (Kies, 1979, and Melius, 1979) shows that although there may be pre-Pleistocene deformation of pre-Pliocene strata of Mount Soledad, the Rose Canyon and associated faults represent predominantly post-Linda Vista, right-lateral strike-slip motion (Figure 4). Although Kennedy, et al., (1975) and Kern (1973) interpreted horizontal separation during Quaternary time on the order of one kilometer, based on coastal offset and the offset of the Pliocene pinchout beneath the Lindavista Formation, it could not be proven that these features did not result from unrelated erosion.

Kies (1979) pointed out that key piercing points are provided by the westernmost of the beach ridges illustrated by Peterson (1970). The north-trending beach ridge, which is truncated by the Rose Canyon fault at Ardath Road, is



Mapping adapted from Ron Kies, Doug Melius and Geology 508 Advanced Field Mapping class

Figure 4 Rose Canyon Fault System

believed to have paralleled more easterly ridges. It probably curved southeastward across the area now occupied by Mount Soledad to connect with a remnant ridge on Clairemont Mesa (Figure 5). Along the Mount Soledad fault, south of the Easter cross, are fault slivers of beach ridge protected from erosion by small grabens in the fault zone. If this beach ridge deposit is part of the Ardath Road beach ridge, then they demonstrate right-lateral separation of at least half a kilometer, and possibly a kilometer. Figure 5 also locates two small patches of beach ridge farther west on Mount Soledad, but connecting these would require a right-swinging flexure or left-lateral motion on the fault. Until a technique for discriminating between the different beach ridges is developed, the separation evidence cannot be considered conclusive. However, it tends to independently substantiate estimates made earlier by others, and is probably the best evidence yet presented.

Near the mouth of Rose Canyon (point A, Figure 4), a strand of the Rose Canyon fault zone offsets the lower portion of the Bay Point Formation (post-Lindavista Pleistocene) and is overlain by the upper portion. At point B, there is a 0.6 m vertical separation in Pleistocene strata which includes a kitchen midden in its upper portion. If the midden deposit was in place at the time of motion, it indicates movement subsequent to human occupation (generally considered less than 40,000 years; J. Philip Kern, personal communication). At point C, Liem (1977) reported a fault separation younger than 27,000 years on the basis of radiocarbon dating.

South of the San Diego River, Eocene, Pliocene, and early Pleistocene strata are steeply inclined (up to vertical) due to deformation by northwest-, north-, and northeast-trending faults. As in the Mount Soledad area, variations in the stratigraphic section and angular unconformities indicate deformation perhaps as early as Eocene time, and certainly pre-San Diego Formation (Pliocene). Near the south end of Congress Street, point D, steeply-tilted San Diego and Lindavista formations have been reverse faulted over the lower part of the Bay Point Formation. The upper part of the Bay Point unconformably overlies this fault, but is itself uptilted to the east and separated one foot by a different reverse fault. Based upon the inclination of faulted beds and the character of the fault zones, it would appear that a major fault zone (probably involving strike-slip movement) is located west of Heritage Park, just east of Congress Street, and west of the exposures on Washington Street.

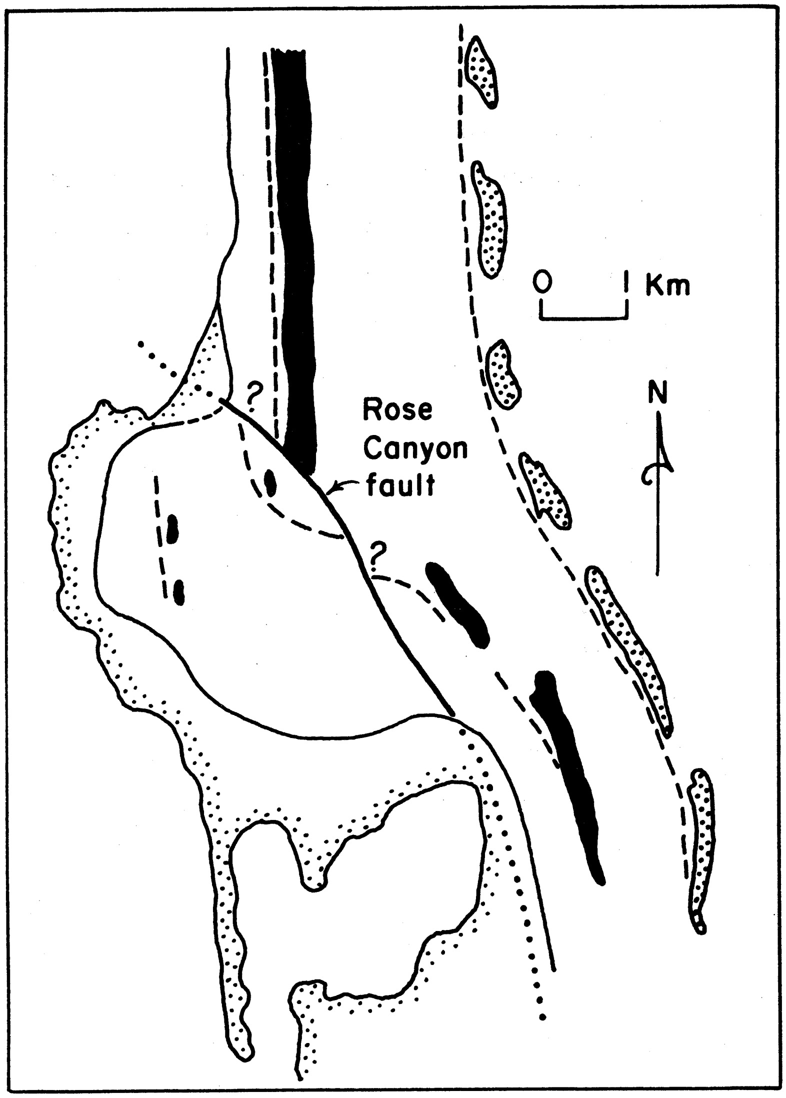


Figure 5. Diagrammatic representation of relation between beach ridges (from Peterson, 1970) and strike-slip movement along Rose Canyon fault.

POSSIBLE CONTINUITY BETWEEN THE ROSE CANYON AND SAN MIGUEL FAULT SYSTEMS

A number of authors have suggested the possibility of a connection between the Newport-Inglewood, Rose Canyon, and San Miguel fault systems (e.g. Wiegand, 1970; Kennedy, et al., 1975; Reyes, et al., 1975). The hypothesis that this system is part of the Pacific-North American plate boundary (Moore and Kennedy, 1975) would seem to require such a continuity. Bedrock exposures across this hypothetical fault, however, occur southeast of Presa Rodriquez (point R, Figure 6), and no northwest-trending fault trace is evident on air photographs. In August, 1978, an earthquake measuring 3.5 on the Richter scale had an epicenter in this exposed bedrock area (point E, Figure 5) (Brune, et al., this volume). Subsequently, Robert Washburn (unsubmitted senior report, SDSU), investigated the area of the epicenter for ground evidence of faults, modern or ancient, and found equivocal evidence for a significant northwest-trending fault.

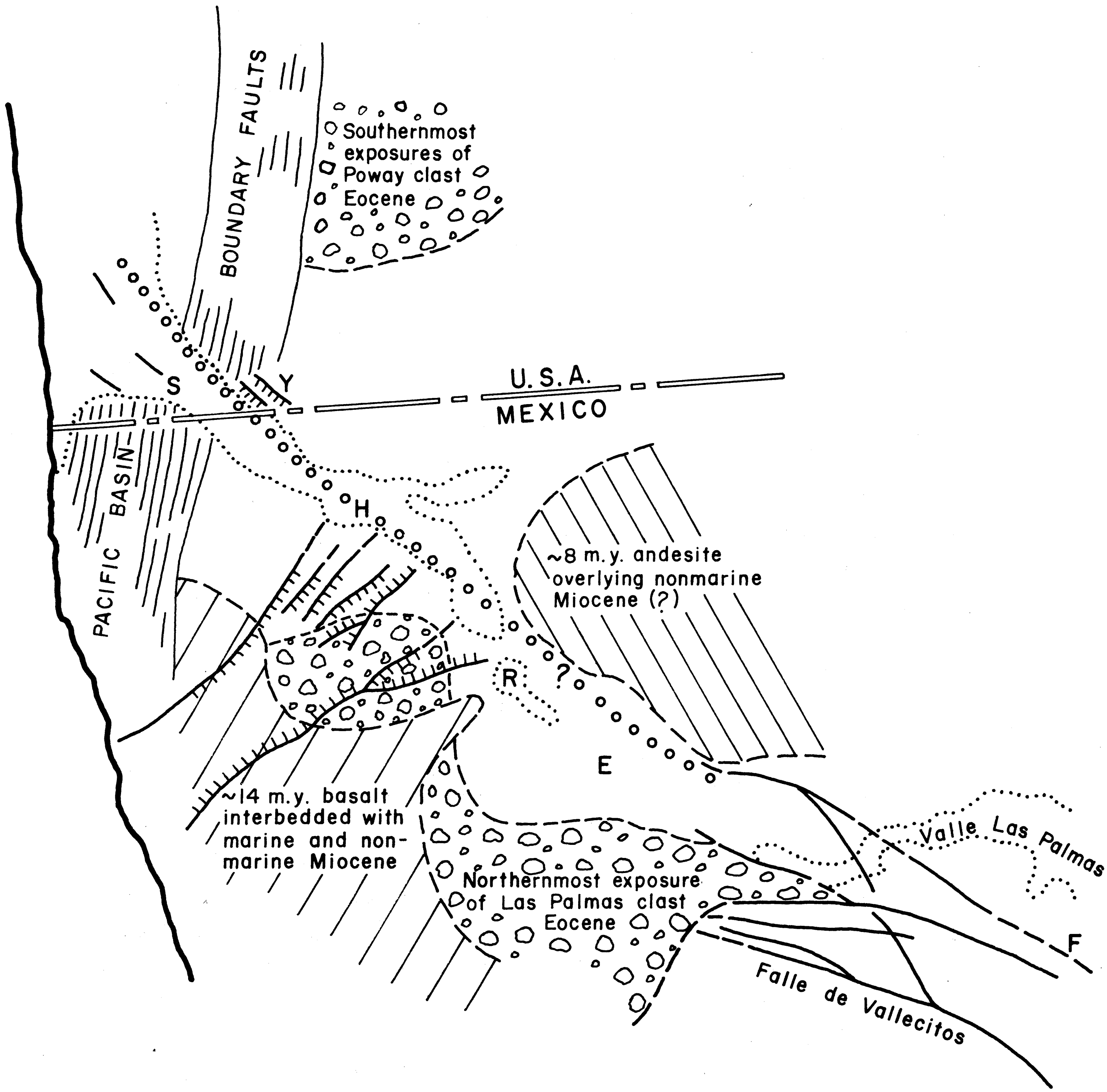


Figure 6. Evidence for the "Tijuana lineament." The lineament is shown by small circles; S = geophysically-determined faults and thermal wells; Y = surface faults; H = Agua Cliente hot springs; R = Presa Rodriguez; E = epicenter of August, 1978 earthquake; F = Holocene fault scarps.

However, several features are suggestive of a "lineament" through this area. First, there are northwest trending faults (or fault-like features) in the San Ysidro area (Kennedy, et al., 1975; points S and Y, Figure 6). Second, there are warm wells in the San Ysidro area (Herbert, 1977; point S, Figure 5) and a large hot spring at Agua Caliente (point H, Figure 5). Third, the northwest trend of Tijuana Valley. Fourth, the differences in Eocene stratigraphy between the north and south sides of the "lineament"; to the north are the Poway and La Jolla groups with the distinctive Poway-rhyolite clast population and to the south are the Delicias and Buenos Aires formations (Flynn, 1970) with the Las Palmas clast population (Minch, 1972). Also, to the south, basalt (circa 14 m.y.) is interbedded with marine and non-marine Miocene strata and to the north, andesite (circa 8 m.y.) overlies non-marine Miocene strata. No basalt occurs within the area of south of the lineament (Figure 5). Fifth, a set of faults (between points H and R on Figure 5) mapped by Flynn (1970) southwest of the lineament do not cross the lineament (Voorhees, 1975, Evans, 1976, Scheidemann, 1976, unsubmitted MS thesis, Higley, 1979). Finally the distribution of the Pacific boundary faults (Kennedy, et al., 1975, Vanderhurst, 1976, Kennedy, et al., 1975, Minch, 1972) south of the lineament suggest one or more kilometers of right-lateral separation.

It may be that the lineament is a recurrent structural feature dating back to the early Cenozoic with small Pleistocene and Holocene movement on a variety of individually minor but interconnected faults.

REGIONAL TECTONIC SIGNIFICANCE OF THE TRANSVERSE STRIKE-SLIP FAULTS

The concept that the right-lateral motion on scattered fault traces through northwestern Baja California is part of the plate boundary motion between the Pacific and North American plates, is hard-pressed to explain the apparent discontinuity of these fault segments. Specifically, why does the Agua Blanca fault show recent offset only along its western portion? Where is the connection between the Rose Canyon and Calabasas faults? What happens to the San Miguel fault to the southeast?

Apparently, recent fault motion is being superposed on much older, perhaps late Mesozoic, ruptures. The late Mesozoic lineaments exposed today (e.g. the Barrett Reservoir lineament of San Diego County; Merifield and Lamar, this volume) were deep in the crust at the time they formed. Thus, many of the features seen along them are the alignment of plutonic inclusion and gneissic textures, perhaps providing evidence of tectonic flow in the crystalline rocks. Where modern stresses within the wide and complex plate boundary involve the sialic crust of the San Diego-northern Baja California area, many of these old deformation zones provide zones of relative weakness for strain release. At present, strain of the peninsula may be widely distributed rather than concentrated on a narrow, transpeninsular fault zone.

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ROSE CANYON FAULT: AN ALTERNATIVE INTERPRETATION

by

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INTRODUCTION

Understanding of the geology of the San Diego area has been broadened significantly through the recent work of Kennedy and Moore (e.g. Kennedy and Moore, 1971; Kennedy, 1975). However, I register strong opposition to many of their interpretations of the structural geology of the Rose Canyon fault zone (e.g. Moore, 1972; Moore and Kennedy, 1975; Kennedy, et al., 1975; Kennedy, 1975).

The present paper is intended to show some fundamental problems with Kennedy and Moore's structural interpretations and to offer alternative interpretations. This discussion of the Rose Canyon fault zone is divided into three parts: (a) extent of the fault zone and its degree of continuity with the Newport-Inglewood fault zone to the northwest and with the San Miguel fault zone to the southeast; (b) sense and amount of slip; and (c) strain rate and evaluation of seismic risk.

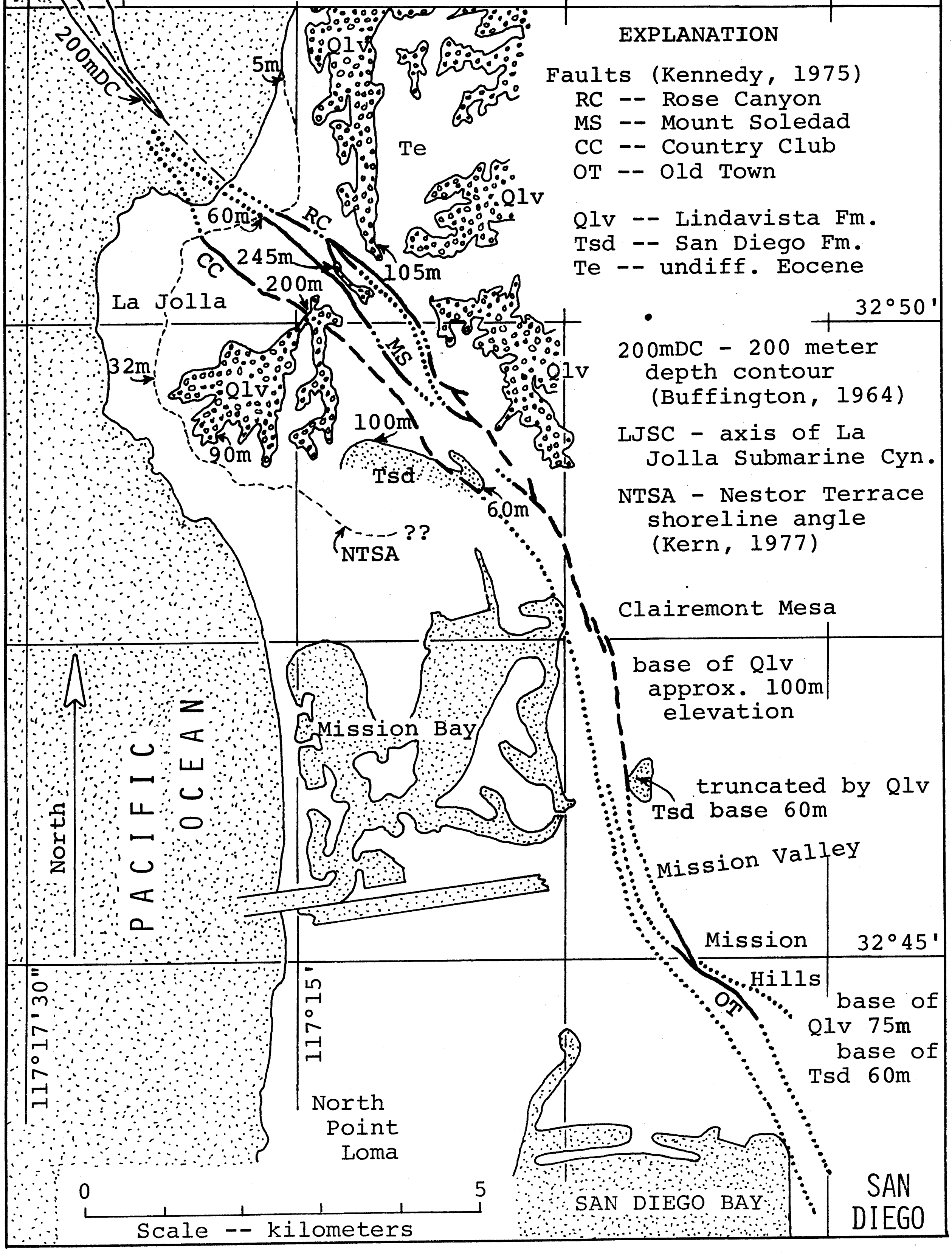
Figure 1, based primarily upon the mapping by Kennedy (1975), shows the location of generally acknowledged onshore geologic features that are significant tectonic elements in discussion of the Rose Canyon fault zone.

EXTENT OF THE ROSE CANYON FAULT ZONE IN THE SAN DIEGO AREA AND BEYOND

Moore (1972) published an interpretation of the offshore extension of the Rose Canyon fault northwest from La Jolla, and postulated a possible connection with the Newport-Inglewood fault zone to the north, and with the San Miguel fault to the south in Baja California. These interpretations carry implications of severe seismic risk for the San Diego area and should be examined critically.

Moore and Kennedy cited Ziony (1973) as support for an extension of the Rose Canyon fault zone "southeast of San Diego Bay" to a connection with the San Miguel fault. However, Ziony's map clearly does not extend the Rose Canyon fault zone any farther southeast than the northeast corner of San Diego Bay. Ziony's text does postulate a "through-going fault system in the base-

FIG. 1 TECTONIC SKELETAL ELEMENTS IN VICINITY OF ROSE CANYON FAULT ZONE, SAN DIEGO, CALIFORNIA



ment that would compare in length and trend with the Whittier-Elsinore and San Jacinto fault zones" -- a convenient sidestep of the lack of evidence for such continuity in the superjacent rocks in the San Diego region. The concept of continuity between the Rose Canyon and the San Miguel fault zones is contradicted by recent mapping of both basement and superjacent rocks in northwestern Baja California (Gastil, et al., 1971).

Moore's (1972) own work on a northwesterly, offshore continuation of the Rose Canyon fault apparently took liberties with the contemporaneous geologic maps by Kennedy and with implications of a bathymetric chart of the La Jolla submarine canyon (Buffington, 1964). Moore shifted the onshore coastal portion of the fault trace from the generally acknowledged northwest trend to a north-northwest trend offshore, completely ignoring the 6 km (3 miles) length of straight-line, fault-controlled La Jolla submarine canyon which trends northwest. Moore may have mapped merely the margin of the coastal shelf at about the 100 m (328 feet) depth contour, along with associated submarine slumping and landsliding, which could have been mistaken for tectonic features. By limiting geophysical traverses to a relatively narrow belt within 10-15 km (6 to 9 miles) of the coastline, Moore failed to evaluate the possibility of a northwesterly position of the Rose Canyon fault zone lying at, or beyond, the west end of his traverses. The faulting shown near the west end of his geophysical section C-C' is at least as convincing as the disruptions he chose for placing the fault much closer to shore.

An implication of Moore's (1972), abrupt bending (left-stepping) of the Rose Canyon fault trace past Mt. Soledad deserves comment here, in preparation for subsequent discussion. He states that uplift of Mt. Soledad "is believed to have resulted from compression there as a consequence of right-lateral strike-slip movement along the fault." While contemporaneous thinking on "the Palmdale Bulge" may have influenced Moore's development of a "model" for Mt. Soledad, introduction of a seemingly good hypothesis as scientific "evidence" is specious. As an alternative, draping of late Mesozoic and Cenozoic sedimentary rocks over a dip-slip horst block between the Rose Canyon fault and the Mt. Soledad fault to the southwest would be an equally satisfactory "model", in the absence of definitive evidence on the sense of slip on the Rose Canyon fault zone.

SENSE AND AMOUNT OF SLIP ON THE ROSE CANYON FAULT ZONE

The reason for my opposition to Moore and Kennedy's (1975) conclusions on sense and amount of slip on the Rose Canyon fault is their lack of understanding of the fundamental difference between separation and slip (Hill, 1959); especially when they repeatedly use the ambiguous term "displacement" (Kupfer, 1960), and introduce the completely meaningless terms "strike-slip separation" and "dip-slip separation". Confidence in their interpretations is further weakened by an obvious commitment to a "model" of right-lateral slip, on the basis of such vaguely supported statements as 1) "...features suggestive of strike-slip displacement, such as minor fault-bounded anticlines, chevron-shaped dilational synclines, and other complex folds that are not in harmony with dip slip drag." (Moore and Kennedy, 1975, p. 589), and 2) "...the Rose Canyon fault zone broadens and becomes *en echelon* at the San Diego basin...We believe that the basin is an area of tension at a junction between right-stepping strands of the right-lateral fault zone." (Moore and Kennedy, 1975, p. 589). I have no idea what kind of mechanical "model" might support the first contention. Termination in a zone of distributive *en echelon* faulting is not unique to strike-slip faults, in fact, the existence of such *en echelon* terminations is practically fatal, mechanically, for significant amounts of strike slip.

A source of misunderstanding by Moore and Kennedy (1975) may be their apparent equation of the present distribution of the Pliocene San Diego Formation and several Eocene formations with the configuration of "the San Diego basin". Several statements (p. 592, their Figure 3), appear to say they believe the line generated by the intersection of the Pliocene/Eocene unconformity surface and either, 1) the present topographic surface or, 2) the sub-Lindavista unconformity surface is equivalent to the shoreline of deposition of the San Diego Formation. They state that:

> "The north edge of the San Diego basin has been offset 6 km right laterally, as marked by the Eocene-Pliocene unconformity at Mission Bay..."

and use this as evidence of 6 km of right-lateral slip on the Rose Canyon fault. I can accept 6 km of right-lateral separation, as well as the necessary few hundred meters of down-to-the-west dip separation, based on the geometry of a regional unconformity that dips gently south and is broken by an essentially vertically-dipping fault. However, their associated statement

(1975, p. 593):

> "We believe that the larger part of the displacement on the fault zone is strike-slip, and that the generally more easily observed vertical displacement is an effect of it.",

demonstrates a naivete that cannot go unchallenged. They appear to be saying that either, 1) lateral separation causes dip separation, or 2) that strike slip can cause dip separation, but that dip slip cannot cause strike separation. A stronger case for not using the term "displacement" could not be imagined!

Reference to Mason Hill's (1959) block diagram and a simple consideration of the geometry of the normal projection of a fault plane, as shown in any elementary structural geology textbook, confirms that

$$ds = ls \times \tan \rho$$

where ds is dip separation, ls is lateral separation, and ρ is the rake (or pitch) of the trace of the marker bed or surface on the fault surface. Inasmuch as the dip of the Rose Canyon fault is acknowledged to be essentially vertical, the vertical separation is essentially equal to the dip separation. In the case of the east-striking surface of the Pliocene-Eocene unconformity, the rake of the trace of the unconformity on the fault would be essentially equal to the dip of the unconformity, and the dip separation would be approximately 10% to 20% of the amount of lateral separation. Both lateral separation and dip separation (and any other separation one cares to specify) are caused by slip, but Hill has shown clearly that the sense and amount of slip are infinitley equivocal in such a case. Drag is simply a variation of separation and gives no more or no less equivocation on sense of slip.

In view of the generally flat-lying attitudes of the Cenozoic strata in the San Diego region, as well as the northwest-striking attitudes of the late Mesozoic and Cenozoic strata that have been deformed in the vicinity of Mt. Soledad, the rake of marker beds on the northwesterly-trending Rose Canyon fault must be essentially 0°. Thus, any observed dip separation can have been produced only by a dip-slip component of the net slip; with the amount of lateral separation as meaningless as dividing by zero in mathematics and the amount of lateral-slip component of the net slip ranging from zero to "infinity", with complete equivocation.

One must be careful to avoid the specious equation of separation and slip. In fact, maddeningly, with certain combinations of rake of the marker bed and rake of the net slip, the sense of separation can be opposite to the sense of respective slip-component and grossly different in magnitude (Threet, 1973). Thus, the solution of sense of slip and amount of slip on a fault requires discriminating recognition of genuine evidence for separation versus slip.

Kennedy and Moore's other criteria for "displacement" must be looked at critically. Let us start with their statement that:

> "The 200-m depth contour has been offset about 4 km right laterally where the fault zone passes out to sea near Point La Jolla."

(Moore and Kennedy, 1975, p. 593). A literal, but nonsensical, meaning of this statement is that slip occurred after the USC&GS nautical chart was prepared. A probably intended meaning is that the configuration of the offshore bottom topography has shown no change, other than 4 km (2 miles) right slip on the Rose Canyon fault zone during the past 4,000,000 years, thereby providing the same sort of documentation of strike slip that was provided by the celebrated fence near San Francisco in 1906. I cannot conceive of anyone else taking this "evidence" seriously.

This initially more palatable statement must also be looked at critically:

> "The coast on opposite sides of the fault zone where it passes out to sea near Point La Jolla has rocks of similar resistance to erosion and a similar structural elevation of the Lindavista Formation. The southwest coast has been moved seaward right laterally about 1 km to form the point."

(Moore and Kennedy, 1975, p. 593). Differential erosion of the modern seacliffs at the seaward edge of the elevated Nestor Terrace (Kern, 1973, 1977) adequately explains the bight at La Jolla Cove and the 1 km misalignment of the N-S line of seacliffs on the west side of La Jolla and the N-S line of seacliffs at Black's Beach and Torrey Pines State Park, north of La Jolla. Why else would the late Quaternary Nestor Terrace be preserved as a rock—defended tread approximately 1 km wide on the hard Cretaceous sandstones of the La Jolla headland south of the fault, and be reduced to mere scraps of the shoreline angle just barely preserved in tiny pockets in the crumbling cliffs of soft Eocene shales and sandstones on the downthrown (northerly) side of the Rose Canyon fault zone? Kern's work clearly emphasizes these relationships, as well as the fact that the shoreline angle and back edge of the Nestor Terrace wrap around the northerly side of the La Jolla headland, documenting the prior existence of "Point La Jolla" and the absence of significant strike slip on the Rose Canyon fault during the past 100,000 years. As for Moore and Kennedy's claim of "similar structural elevation of the Lindavista Formation", I can only let the reader try to reconcile their (1975, p. 592) acknowledged 130-meter difference in elevation of the old wave abrasion platform at the base of the Lindavista Formation on opposite sides of the Rose Canyon fault at Mt. Soledad. I cannot accept this and preceding definitions of "similar".

Regarding "offset" of the late Pleistocene Bay Point Formation on the Nestor Terrace, Moore and Kennedy (1975, p. 593) and Kennedy (1975, p. 35) accept Kern's findings on the Rose Canyon fault at La Jolla, but Kennedy's accompanying geologic map inconsistently indicates that the Rose Canyon fault is concealed unconformably beneath the Bay Point Formation. Kern's work appears to be definitive for slip on the Rose Canyon fault during the past 100,000 years, inasmuch as he had based his conclusions on piercing points of a geologic line that provides genuine evidence on slip -- the vertex of the shoreline angle, a dihedral angle, at the landward edge of the Nestor Terrace abrasion platform.

Kern (1977) showed a minimum of 54 m of vertical separation of the shoreline angle of the Nestor Terrace, although he conceded that his vertical control north of the Rose Canyon fault must be projected about 2 km (1 mile) southerly to the fault. Nevertheless, the elevation difference of the very gently inclined shoreline angle vertex is probably not very sensitive to such projection, and whatever figure one accepts (on the order of 50 to 60 m) must be regarded as a direct measure of the amount and sense of dip-slip component of the net slip during the past 100,000 years.

In regard to the matter of lateral separation of the shoreline angle (which must also equal the lateral-slip component of the net slip in this special case), Kern (1977) acknowledges that his projection to the fault is subject to error, because the shoreline of 100,000 years ago also had a bight in it that was about as great as the present bight. This is indicated by the fact that the accurately mapped shoreline angle of the Nestor Terrace wraps around the north side of Point La Jolla, almost to the Rose Canyon fault. Kern's projection of the "shoreline angle" for 2 km southerly from the Scripps Pier (north of the Rose Canyon fault), admittedly had to depend on a somewhat vague geomorphic expression of the "back edge" of the terrace cover, rather than of the shoreline angle itself, approximately along the 25 m (80 ft.) topographic contour. Kern's choice of position shows a southwesterly-trending curve in such a way that the map position of the "shoreline angle" could be brought to the fault (from the north) at just about the same place that the directly mapped shoreline angle on the upthrown block (south of the fault) projects northeasterly and easterly to the fault. Kern interpreted a 150-meter right-lateral separation (although his Figure 8 inconsistently scales 230-240 m of right-lateral separation) of the "shoreline angle", which would mean 150 m (or 230-240 m) of right-slip component of the net slip. The acknowledged latitude in interpolating the position of the shoreline angle across the Rose Canyon fault could allow an interpretation of no strike slip since Nestor Terrace time. In other words, the amount of dip slip on the Rose Canyon fault during the past 100,000 years is rather accurately and unequivocally known to be several tens of meters, while the strike slip is much less definitively known and may range from zero to a few hundred meters.

STRAIN RATE AND EVALUATION OF SEISMIC RISK

The geometric consequences are that dip separation must equal dip-slip component of net slip with perhaps no strike-slip component, in this local case of predominantly flat-lying beds, or of northwest-striking beds raking essentially 0° on a northwest-striking fault. Thus, the differential amounts of dip separation of different rock units (800 m of post-Eocene, 130 m of post-Lindavista, and 50 m of post-Bay Point) from Moore and Kennedy (1975) and Kennedy (1975) yields a long-term rate of dip-slip strain on the order of 10^{-1} mm/yr. Moore and Kennedy used values for "strike-slip displacement" to assess seismic risk in the greater San Diego area, particularly with the further assumption of a "model" that the Rose Canyon fault zone is "related" to (continuous with?) the Newport-Inglewood and San Miguel faults. From this "model" Moore and Kennedy (1975) used:

(a) a rate of strain of 1 mm/yr, which may be an order of magnitude too high,

(b) Brune's (1968) "model" of seismic moment,

(c) Bonilla and Buchanan's (1970) work on length of historic fault rupture length versus earthquake magnitude, and

(d) the records of a few historic earthquakes remote from San Diego and of questionable relevance for the discontinuous and en echelon pattern of the minor league faults of the San Diego area.

Moore and Kennedy's (1975) conclusion was that "...strain for a larger earthquake may be accumulating." because of a hypothetical, gross deficiency of seismic events according to their "model". They estimate that a strong earthquake with a Richter magnitude of approximately 6.5 could be expected to have a recurrence interval of as little as 300 years in the San Diego area. Of course, if one considers:

(a) the essentially aseismic history of the San Diego area,

(b) one order of magnitude lower rates of strain that can be documented rather than merely postulated,

(c) a large difference in meaning between length of fault rupture and length of fault trace (especially in view of the tendency to extend and connect faults more or less indefinitely, despite local evidence of lack of continuity) and,

(d) the doubtful connection of the Newport-Inglewood-Rose Canyon-San Miguel faults and their supposed control of behavior by a "San Andreas system" (Moore, 1972),

then one might conclude that the seismic risk in San Diego is much lower than in many other areas of southern California and that a reasonable recurrence interval for strong local earthquakes soars up into the thousands of years. Published accounts indicate that both the documented geologic, long-term rate of strain, and the historic seismicity in the vicinity of the major league faults in southern California, are from two to three orders of magnitude as great as those which can be established firmly for the San Diego area.

CONCLUSIONS

It is my opinion that Moore and Kennedy have done a disservice to San Diegans and to consulting geologists who must provide objective evaluations of the character of the local faults and of the extent of seismic for the San Diego area. Instead of playing academic games with geologic "models" based on extrapolation of equivocal observations to the scale of global tectonics, we should be continuing to investigate and reason through multiple-working hypotheses, in a manner that is worthy of scientific credibility. Mark Twain's famous lesson from meander cut-offs on the Mississippi River and his sarcastically "scientific" conclusion is appropriate to remember often -- that model building may offer such a "wholesale return of conjecture for such a trifling investment of fact."

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View southeast of metropolitan San Diego, Mount Soledad in lower center. Note how it rises abruptly from the Linda Vista Terrace to the left (east). Linear canyons along left side of Mount Soledad are fault related. Photograph by Rozelle, San Diego, California in 1953.

GEOPHYSICAL SURVEY OF THE LA NACION FAULT ZONE, SAN DIEGO, CALIFORNIA

by

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INTRODUCTION

To better define the location, number of scarps and total throw, detailed detailed gravity traverses were made across the La Nacion fault zone. Results of these surveys and preliminary interpretations are presented herein. The gravity data used were collected as senior projects by San Diego State University students (Bair, 1976; Lothamer, 1978; Stoll, 1979).

LA NACION FAULT ZONE

GRAVITY SURVEY

Six, approximately E-W gravity traverses were made across the La Nacion fault zone as mapped by Kennedy, et al. (1975). The lines are spaced 2-7 km (1-4 miles) apart from Otay Valley on the south to Montezuma Road, 22 km (13 miles) to the north (Figure 1). Readings were taken at intervals of 150-300 m (500-1000 feet) over a 2-3 km (1 to 2 mile) length on either side of the fault zone. The instrument used for the southern two lines was the San Diego State University Worden gravimeter (E-132), and, for the northern four lines, the University of California, Riverside, La Coste-Romberg gravimeter. Data were corrected for elevation and latitude. Terrain corrections were found to be necessary only on the Montezuma Road traverse.

RESULTS

General. Gravity increases in a series of steps from west to east (Figure 2). This increase ranges from about 18 mgals along the southern traverses to only 1 mgal on the northern lines (Table 1). Similar gravity increases along these traverses were observed by Elliott (1970) in a regional gravity survey of the San Diego area. His combined gravity and well-log data showed the geology under southern San Diego to be that of a sedimentary basin, centered about 8 km (5 miles) southwest of the southern end of San Diego Bay. Underlying about 1830 m (6,000 feet) of Upper Cretaceous and younger sedimentary deposits at the center of the basin is the basement, probably Santiago Peak

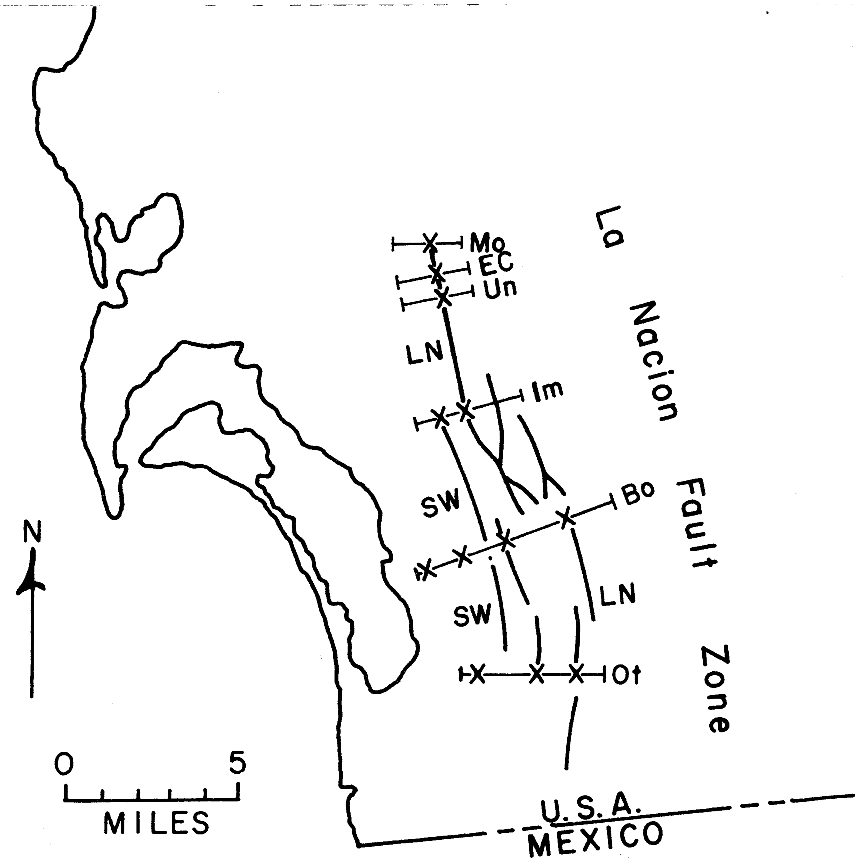

Figure 1. Location map of geophysical traverses. Mo, Montezuma Road; EC, El Cajon Boulevard; Un, University Avenue; Im, Imperial Avenue; Bo, Bonita Road-Sweetwater Valley; Ot, Otay Road. Fault traces generalized from Kennedy, et al. (1975). LN, main La Nacion fault trace; SW, Sweetwater fault. X, gravity-indicated positions of major scarps in basement.

Table 1. La Nacion Fault Zone Gravity Data

Line	Δ_g	T	S	$X_{1/4}$	Z	D_L	D_u	E_L	E_u	Δg_R	E_W	E_E	Δ_E
Mo	1.4	200	1	225	250	350	150	-50	150	0.3	-500	0	500
EC	0.8	100	1	275	330	400	300	0	100	0.8	-1000	-300	700
Un	3	500	3	300	375	600	100	-300	200	2	-1300	-500	800
Im	9	1400	3	--	--	--	--	--	--	6	-2700	-900	1800
Bo	18	2800	5	--	--	--	--	--	--	14	-4500	-500	4000
Ot	16	2500	3	--	--	--	--	--	--	14	-4000	-500	3500

Table 1. S, number of gravity-indicated scarps along the traverse; D_L and D_u, depth to the scarp base and top, respectively; E_L and E_u, elevation of scarp base and top, respectively. Δg_R - Δ_E are data taken along the present traverses from Elliott's (1970) regional gravity study. Δg_R, Elliott's gravity change; E_W and E_E, Elliott's estimated elevation of the west and east end of the traverse, respectively; Δ_E, the elevation difference between the traverse ends. All other symbols as in text. All distances in feet. Gravity in milligals.

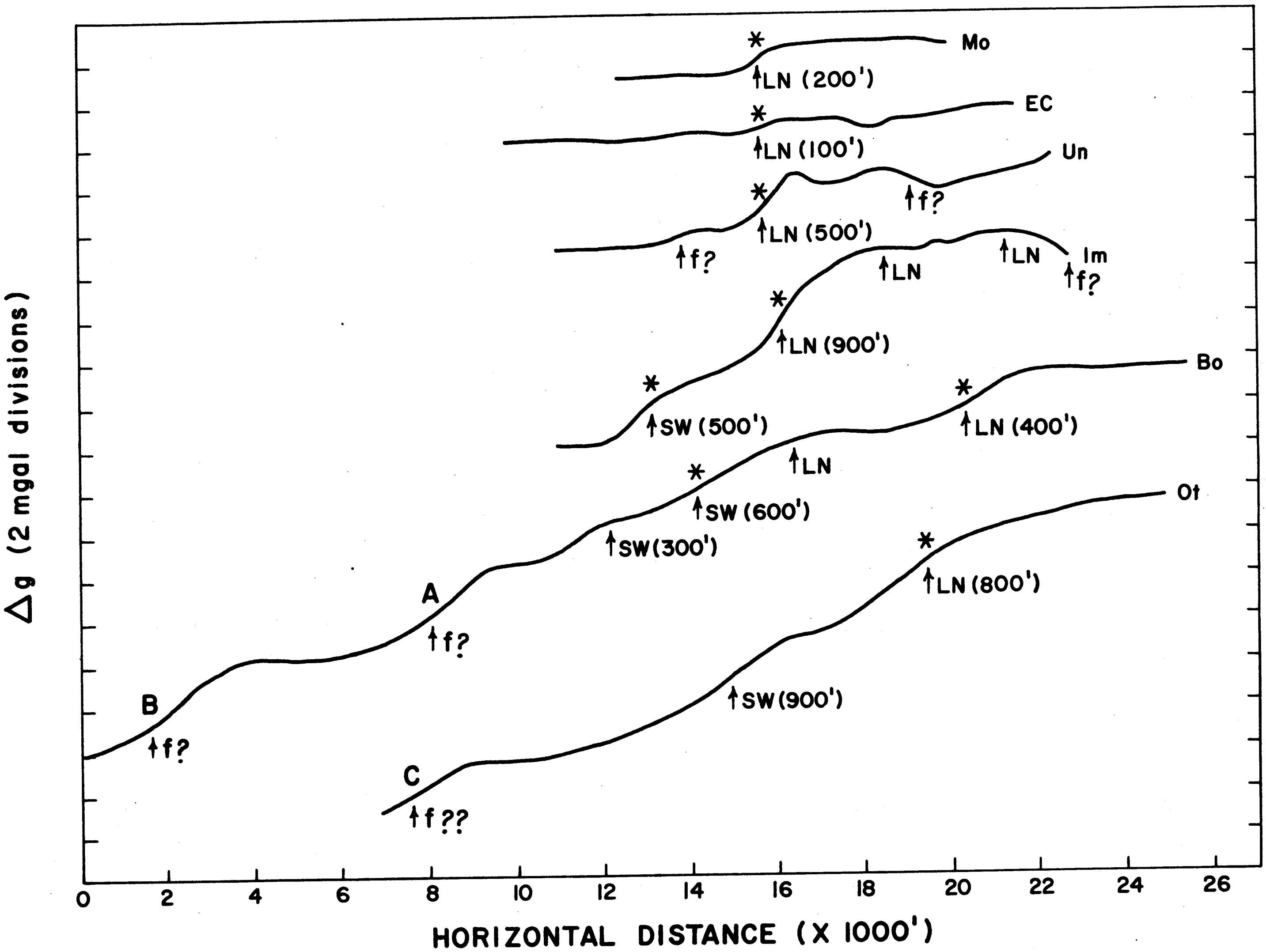

Figure 2. Gravity anomalies, Δg, over the La Nacion fault zone. Traverse locations and symbols as in Figure 1. LN and SW are traces of the La Nacion and Sweetwater faults, respectively, as mapped by Kennedy, et al. (1975). * Denotes appreciable post-Pliocene throw where mapped trace crosses the traverse. Number in parenthesis is the geophysically-estimated throw. f denotes the geophysically-indicated position of a fault (see text).

metavolcanic rocks, which shoals northward and eastward and outcrops several miles east of the present study area. Steps in the detailed gravity profiles, however, suggest that this eastward shoaling of the basement is largely accomplished by steps or scarps. That these scarps are fault related is further suggested by correspondence between inflection points on the gravity profiles and traces of the La Nacion fault zone, an en echelon series of high angle, down-on-the-west, normal faults (Artim and Pinckney, 1973; Kennedy et al., 1975).

Gravity changes observed in this study agree fairly well with those found in the regional study by Elliott (1970, Table 1). The gravity-computed total relief on the southern four lines is also somewhat similar in the two studies. However, the relief across the northern two lines as well as the depth to basement in the northern three lines is considerably greater in Elliott's study. The present estimation of throw is based on an assumed density contrast, $\Delta\rho$, of 0.5 gm/cc. Since sediments overlying basement in the northern part are conglomeratic, the actual basement-sediment density contrast probably is lower than 0.5 gm/cc. Increasing the conglomerate density from 2.3 to 2.5 gm/cc, for example, would reduce $\Delta\rho$ to 0.3, almost doubling the throw estimates and increasing the depth to basement values as well. On the other hand, the elevation changes and depth to the basement observed in Elliott's study may be unrealistically large due to the lack of well control in this area.

Steps in the Profiles. Assuming that the steps in the gravity profiles are due to scarps in the basement where denser metavolcanic rocks have been faulted against less dense sedimentary rocks, gravity data can be used to help define basement fault location, throw, and depth. Fault location is the map position of the point of inflection of S-shaped steps in gravity profiles, i.e., the point on the step where the value of gravity is midway between the lower value at the base of the step and the higher value at the top of the step. Relief on the scarps, or throw (T), is given by T (in feet) = Δg (change in gravity due to the individual scarp)/$0.013\Delta\rho$, where $\Delta\rho$ is the density contrast across the scarp. Densities of 2.8 gm/cc for metavolcanic basement and 2.3 gm/cc for sedimentary rocks were assumed for this study, giving a $\Delta\rho$ of 0.5 gm/cc. Assuming a single, vertical scarp, the depth to the midpoint on the scarp, Z, is indicated by the slope on the S-shaped gravity steps, as measured by the horizontal distance ($X_{1/4}$) between the inflection point and the point on the S-shaped step where the value of gravity has changed by $\Delta g/4$. For scarps where $T \ll Z$, $Z = X_{1/4}$; when $T \approx Z$, i.e., the upthrown basement side is close to the ground surface, $Z \approx 1.2X_{1/4}$.

The Three Northern Profiles. The geophysically-indicated position of west-facing basement scarps beneath the northern three lines coincides very closely with the position of the trace of the La Nacion fault as mapped by Kennedy, *et al.* (1975). The increasing number of other steps and curves in the gravity profiles to the south of Montezuma Road suggests that the basement topography becomes more irregular, possibly due to other east- and west-facing fault scarps. The gravity-indicated throw on the single La Nacion fault is 30 m (100 feet) beneath El Cajon Boulevard and increases slightly to 60 m (200 feet) beneath Montezuma Road, the northern limit of the mapped trace (Table 1). South of El Cajon Boulevard, the throw increases rapidly to 150 m (500 feet) beneath University Avenue. The slope, or gradient, of the gravity profiles suggests that the depth to the midpoint on the scarp increases southward from about 75 to 120 m (250 to 400 feet) over this 3.2 km (two mile) distance.

The Imperial Avenue Profile. South of University Avenue, the *en echelon*, multiple strands of the La Nacion fault zone are mirrored in the multiple steps of the gravity profiles (Figure 1). The gravity-indicated positions of the two large basement scarps on the Imperial Avenue line closely match the traces of the main La Nacion fault and a break to the west, the Sweetwater fault. Two fault traces east of the main La Nacion fault apparently are not associated with any detectable basement scarps. The two western traces crossing the Imperial Avenue line are the only traces associated with significant basement relief, a total of 460 m (1400 feet), as well as appreciable throw on the San Diego Formation at the surface (Gastil, *et al.*, this volume). Depth to basement along the Imperial Avenue traverse, as well as that along the two traverses to the south, cannot be directly computed using the formula given above. Its use requires either a single scarp or scarps so widely spaced that the steps on the gravity profile are totally independent of each other. Despite the fact that the position of the inflection point is probably affected by the close spacing of the two faults, their geophysically-indicated position is within several hundred feet of the fault traces, suggesting the faults are high angle.

The 8 km (5 mile) long traverse across Chula Vista, along Bonita Road and up Sweetwater Valley (Bo) suggests that basement there is offset by at least five scarps having a total relief of almost 900 m (3000 feet). The total displacement in the geologically-mapped fault zone, about 400 m (1300 feet), is quite similar to the 430 m (1400 feet) observed in the zone to the north, as well as to the displacement of 520 m (1700 feet) along line Ot to the south (Figure 2). The agreement between the geophysically-indicated position of basement scarps and surface traces is not nearly as good as along the traverses to the north--which is not surprising given the complexity of the surface faulting. However, major displacements of the basement seem to shift to the eastern branches; the eastern breaks show the most displacement of the San Diego Formation. Traverse Bo has many basement scarps, partially because it is at least twice as long as the other traverses. When lines Im and Ot are extended, they too will probably detect other basement scarps. Since the basement trough shoals to the north, the northerly lines, when extended, should show fewer scarps with less relief. Line Bo suggests the presence of two faults (A and B), as yet unmapped, in Chula Vista (Figure 2). Assuming the faults are nearly vertical, the eastern fault (A) would lie in an area centered approximately midway between F and G Streets and First and Second Avenues. The western fault (B) would lie in an area centered on Broadway, 150 m (500 feet) north of H Street. Since traverse Bo does not extend west far enough to define the entire S-shaped gravity curve, the location of proposed fault B is more uncertain than that of fault A. Interestingly, possible fault B lies almost directly on line with a series of faults mapped and inferred from photographic evidence by Kennedy, et al. (1975), several miles to the north in National City.

The Otay Valley Profile. Principal basement scarps on the Otay Valley traverse appear to coincide with the main La Nacion fault trace on the east (Kennedy, et al., 1975) and with their extension (with the aid of photographic evidence) of the Sweetwater fault to the west. The two fault traces lie about 300 m (1000 feet) to the east of the geophysically-suggested position of the basement scarp. This discrepancy is probably due to a combination of the westerly dip of the faults, an error in the geophysical position caused by the close spacing of the two faults, or the basement scarps actually being zones of multiple, stair-step faults extending 300-600 m (1000-2000 feet) west of the two surface traces. Although the Otay Valley traverse did not extend far enough west to define its position accurately, the gravity profile suggests a basement scarp, which, if associated with a vertical fault (C), would intersect Main Street roughly in the vicinity of Hermosa Avenue. This scarp is situated almost due south of the eastern of the two Chula Vista faults (fault A) proposed above. It also appears to be located about 300 m (1000 feet) west of the extension of a short fault trace, mapped by Kennedy, et al. (1975), south of Otay Valley along Beyer Way.

CONCLUSIONS

The limited gravity data presented here suggest that the style of faulting in the basement rocks along the La Nacion fault zone parallels that in the overlying sedimentary rocks (Figure 3). Fault spacing decreases and the amount of throw generally increases from north to south. Basement scarps are apparently *en echelon* and, with exception of a few possible scarps at the eastern end of the northern traverses, basement is down to the west. Relief, or throw, on the mapped part of the fault zone increases from 60 m (200 feet) at the north end to about 520 m (1700 feet) along Otay Valley. Fault planes appear to be almost vertical, although the exact position of basement scarps along the southern lines is obscured by closely spaced, multiple faulting. Inflections in gravity profiles suggest the existence of at least two, as yet unmapped, faults or fault zones in the western Otay Valley-Chula Vista area.

The multiple, down-to-the-west, basement scarps suggested by the gravity data agree with the proposal (Kennedy, *et al.*, 1975) that the San Diego basin is a multi-stepped graben. That the basin is still subsiding is suggested by the parallelism of the structural contours on the Pleistocene Lindavista terrace (Moore and Kennedy, 1975) with the basement contours (Elliott, 1970). Additionally, Moore and Kennedy (1975) point out a submerged Sangamon barrier beach, south of Coronado, in the center of the basin. Faults forming this nested graben not only cut Quaternary sediments, but apparently cause much of the local seismicity (Moore and Kennedy, 1975). Aside from the faults bordering the Coronado escarpment, 15 km (9 miles) west of San Diego, the currently most seismically active region in the San Diego area is the southern end of San Diego Bay (Simons, 1977).

Dip-slip movement on the graben faults may be genetically associated with possible strike-slip motion on the Rose Canyon fault, which trends southeasterly from La Jolla approximately through the center of the graben (Kennedy, *et al.*, 1975, Moore and Kennedy, 1975). How much of the current seismicity is due to strike-slip and how much to dip-slip motion is unknown because seismograph distribution is not yet adequate to compute focal mechanisms. Whether wrench tectonics caused the graben to form, or whether possible strike slip simply inherited some of the older dip-slip fault planes, is unknown. If the basin is possibly as old as Cretaceous (Elliott, 1970), it may simply be the easternmost extensional feature of the southern California Borderland.

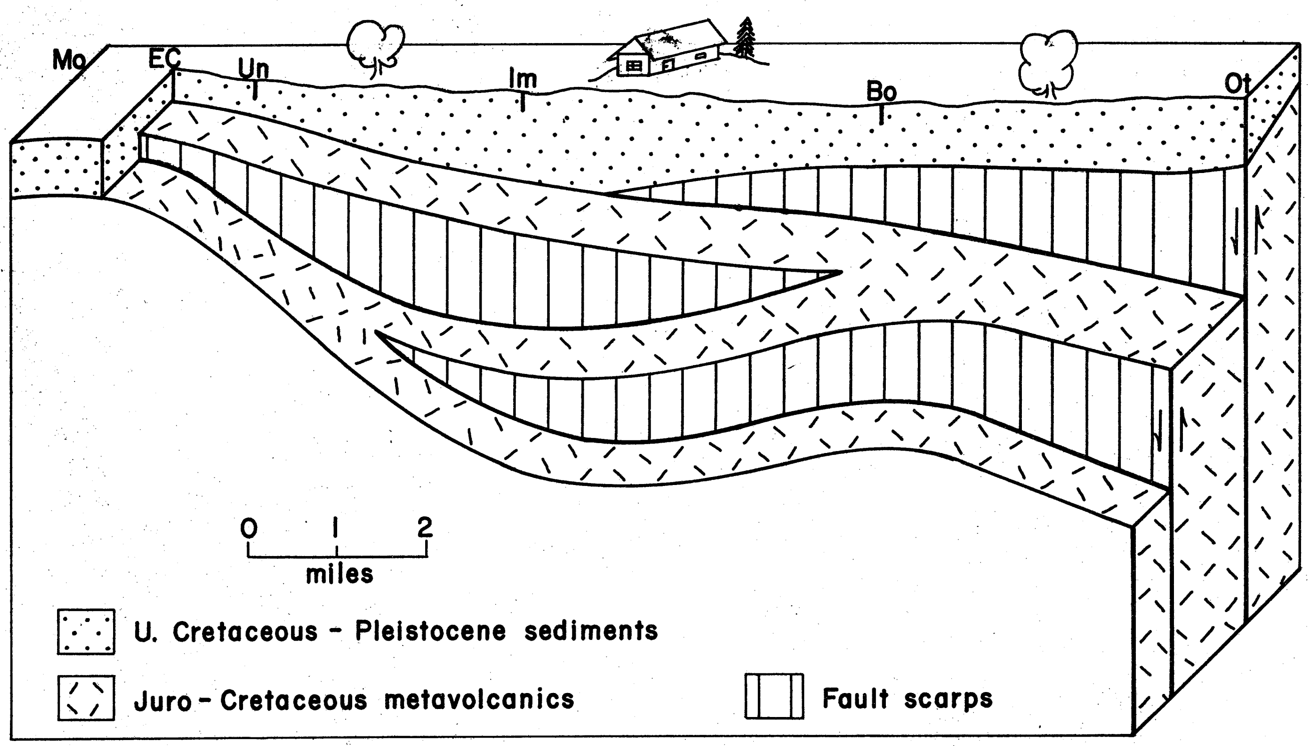

Figure 3. Schematic, block diagram of the basement scarps along the La Nacion fault zone. View looking eastward. Scarp relief and en echelon style generalized from gravity data.

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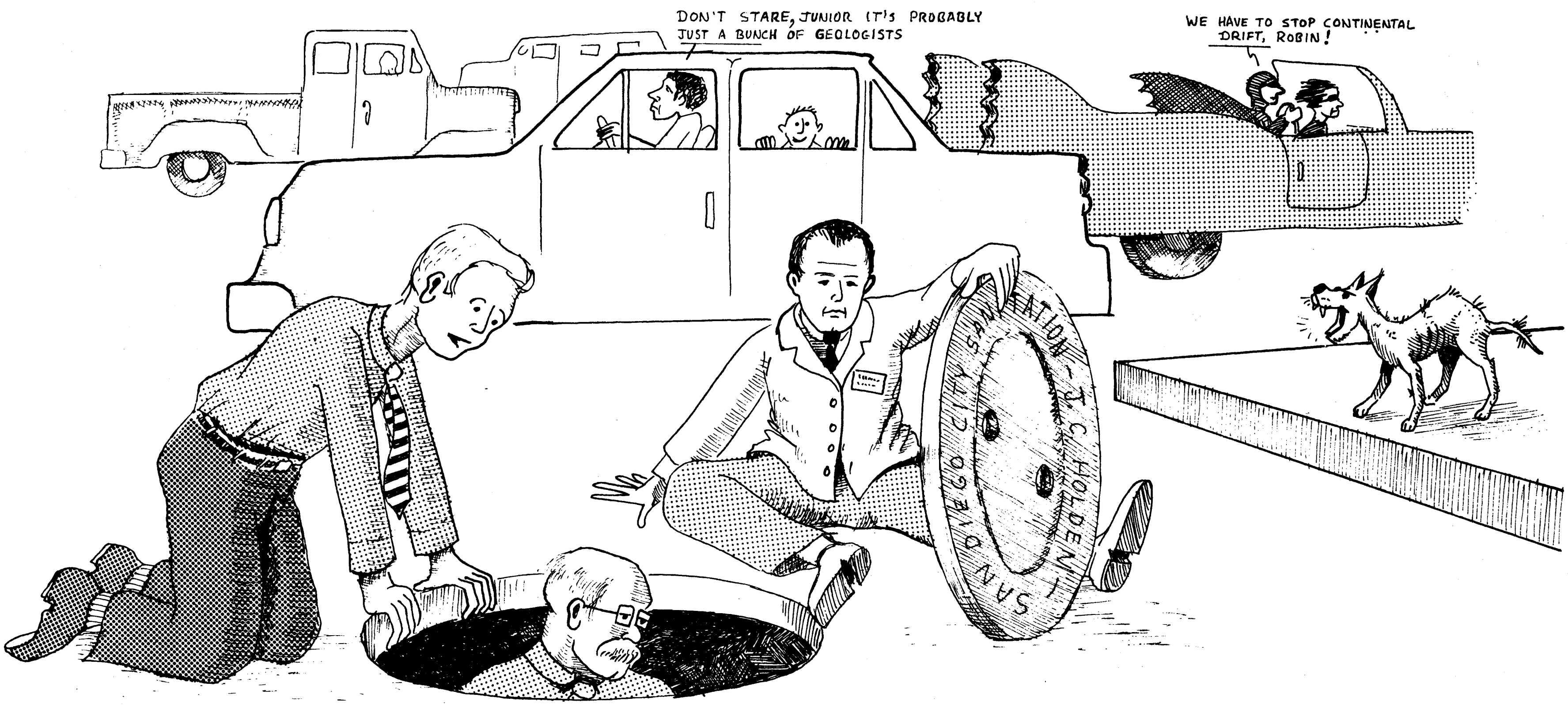

"There! Right between the two conduits - that's the type area for the San Diego Formation. It was more accessible two weeks ago before they built the subdivision here..."

SEISMICITY AND FAULTING IN NORTHERN BAJA CALIFORNIA

by

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TECTONIC SETTING

The seismicity of northern Baja California is related to the numerous faults of the San Andreas system, which represent the boundary between the Pacific and North American Plates (moving right-laterally at a rate of about 6cm/yr.). The main plate boundary at present appears to be represented by the San Andreas and Brawley faults near the Salton Sea, the Imperial fault at the International Border, and the Cerro Prieto fault south of Cerro Prieto, with connecting zones of spreading (Figure 1).

Although an idealized transform fault-spreading center system appears to be a fair representation of the tectonic framework of the Salton trough and northern Gulf of California, it does not explain the abundant seismic activity west of the trough, nor the numerous active faults which continue northwest from transform faults within the trough and which, in the idealized pattern, should not be present (e.g. - the Agua Blanca, San Miguel, Laguna Salada, Elsinore and the San Jacinto fault zones). All of these are active right-lateral faults which diverge westward from the axis of the northern Gulf and Salton trough; there is no analogous system to the east. Lomnitz, et al, (1970) gave a tectonic explanation for this, i.e., that the present-day spreading rates on individual ridge segments decrease progressively northward, resulting in a continuation of north-westerly trending, right-lateral faults on the west side of the Gulf. Why the spreading rate should decrease northward is unknown, but it was suggested that this might be the result of the interference to through-going fault movements caused by the Transverse Ranges of southern California.

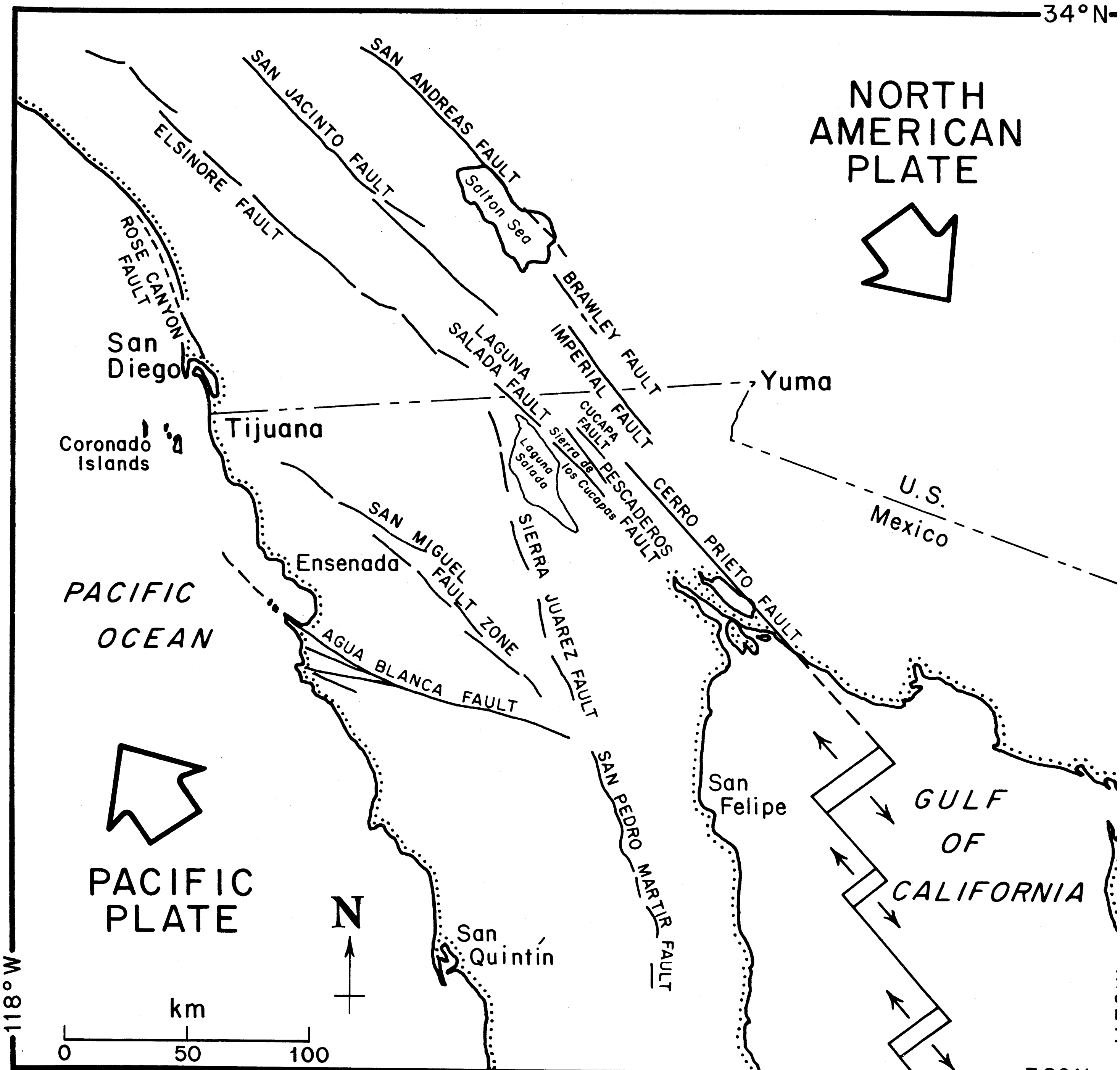

Figure 1. The major faults of southern California and northern Baja California.

The tectonic significance of the branch faulting west of the main fault boundary is important in understanding earthquake hazards in the southern California - northern Baja California area, because a significant amount of the right-lateral plate motion between the Pacific and North American plates may be shunted offshore from southern California and connect up again with the main plate boundary, either in the Transverse Ranges or farther north along the Hosgri-San Simeon fault system.

MAJOR FAULTS

The major faults are shown in Figure 1. The following paragraphs describe each of them briefly.

1) The Imperial fault strikes southeast, 15 km east of Calexico, and extends at least 30 km into Baja California, as observed from displacements that occurred during the magnitude 6.7 Imperial Valley earthquake of 1940.

2) The Cerro Prieto fault, formerly called the San Jacinto fault, extends from Cerro Prieto, an old volcanic remnant, southeast for 150 km to a point near El Golfo. Earthquakes larger than magnitude 6.0, believed to have been associated with this fault, occurred in 1915, 1934, 1963, and 1966. The magnitude 7.1 earthquake in 1934 was the apparent cause of surface faulting near the head of the Gulf of California which was observed in subsequent aerial photographs (Biehler, et al., 1964).

3) The Laguna Salada and Sierra Juarez faults. The Laguna Salada fault extends southeast from the Elsinore fault zone, cutting across the Sierra de los Cucapas Range. This region also is occupied by a series of smaller sub-parallel faults, including the Cucapa and Pescaderos. The estimated epicenter of the 1934 magnitude 6.5 earthquake is about 10 km southwest of the Laguna Salada fault. The Sierra Juarez fault is a zone of high seismic activity on the western edge of Laguna Salada. In 1975-1976 it was the most active zone in the region, with many events between magnitudes 4 and 5.

4) The San Miguel fault zone trends northwest as a series of en echelon faults, from the southern end of the Sierra Juarez fault to the vicinity of Tijuana (Gastil, et al., 1975). Four large earthquakes, magnitude 6.1 through 6.8, occurred along this fault zone in 1956 near the town of San Miguel; surface faulting associated with this earthquake was observed to extend more than 20 km (12 miles) (Figure 2). Relocation of

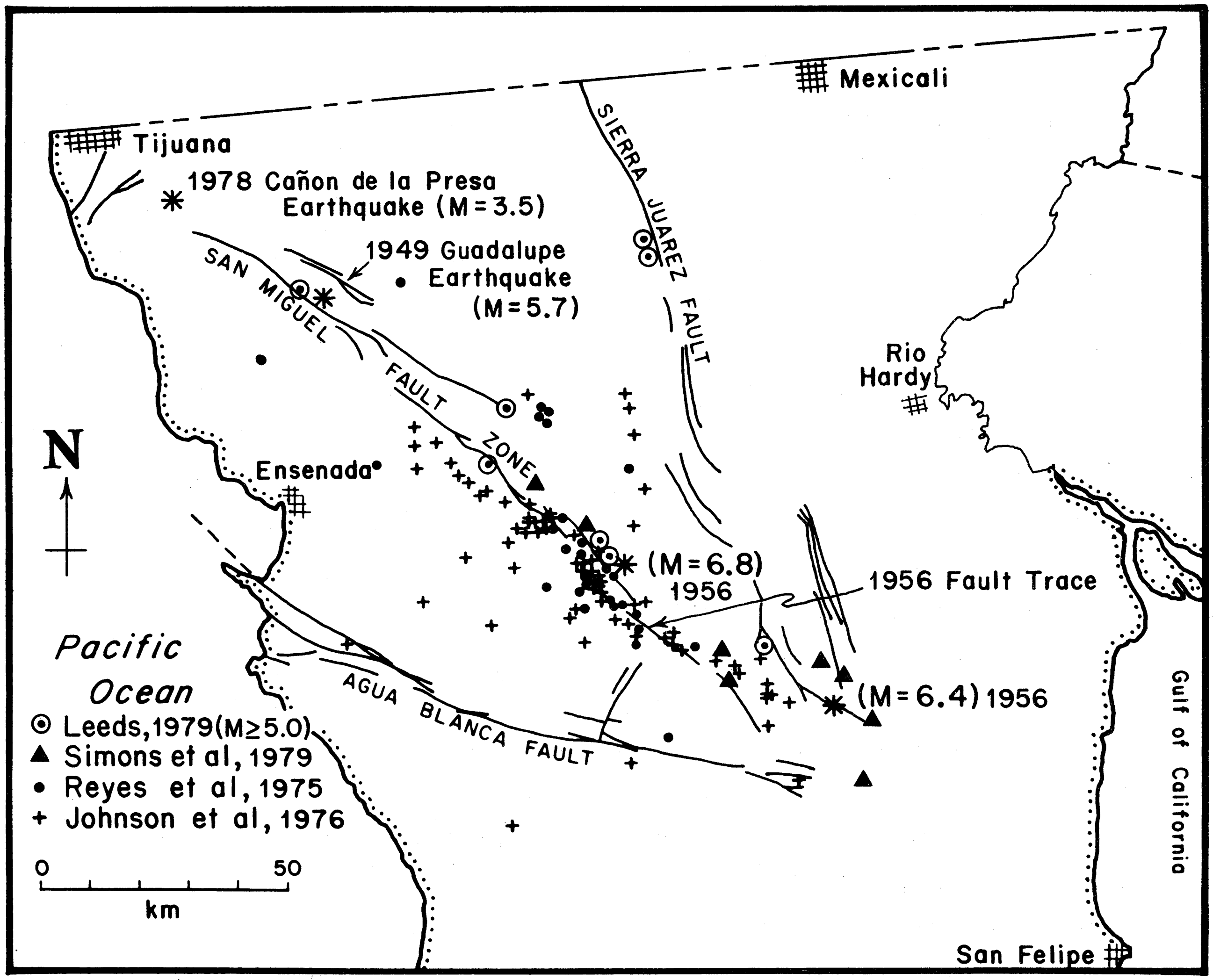

Figure 2. Some recent large earthquakes and microearthquake activity along the San Miguel fault, Baja California norte, Mexico.

the magnitude 6.0 and 6.3 earthquakes of 1954 indicates that they also were located along the San Miguel fault zone near the northern end of the surface faulting observed by Shor and Roberts (1958). Tectonic, geologic and seismic evidence suggest that the San Miguel fault is part of a through-going fault zone capable of generating at least moderate-sized earthquakes (M > 6 ½). This zone includes the Newport-Inglewood fault zone to the northwest, site of the 1933 Long Beach earthquake (M = 6.3), the Rose Canyon fault zone (Figure 1), and offshore fault zones in the vicinity of San Diego, in addition to the San Miguel fault zone. However, the exact relationships between these fault zones have not been established.

5) The Agua Blanca fault cuts west-northwesterly across the Baja California Peninsula from near Valle Trinidad to the Pacific Ocean, 15 km south of Ensenada (Allen, et al., 1960). It continues northward offshore, sub-parallel to the coastline, possibly connecting with either the San Diego trough or the Coronado Banks fault zones (Legg and Ortega, 1978). The 6.0 and 6.3 magnitude earthquakes described above, previously located on this fault, are now thought to have occurred on the San Miguel fault, hence, no large earthquakes are known to have occurred along the Agua Blanca fault.

6) The San Pedro Martir fault zone extends southeast from the projected intersection of the San Miguel and Agua Blanca faults (Figure 1). It lies at the base of the spectacular fault-scarp face of San Pedro Martir Mountain, which rises to an elevation of nearly 3,050 m (10,000 feet) above San Felipe Valley. Impressive recent fault scarps exist in this zone and have recently been shown to be older than 300 years (R. Gordon Gastil, personal communication).

GENERAL SEISMICITY

Northern Baja California is an area of extremely high seismicity. At least 13 earthquakes of magnitude greater than 6 have occurred since 1900 (Table I). The large 1892 earthquake originated in this area, but has not yet been identified with a particular fault. The Caltech earthquake catalogue (since 1932) shows considerably higher seismicity for this area than for the area north of the border, even though the percentage of earthquakes located is smaller because of the lack of seismograph

TABLE I

Earthquakes of Magnitude 6.0 and Greater in Northern Baja and Northwestern Sonora, Mexico between 1912 and 1971.

DATE	LAT.	LONG.	MAG.	REGION	FAULT	AUTHORITY
11-21-15	32.0	115.0	7.1	Colorado Delta	Cerro Prieto	Eq. Hist. #
12-30-34	32.25	115.5	6.5	Colorado Delta	Laguna Salada	Leeds +
12-31-34	32.1	114.9	7.1	Colorado Delta	Cerro Prieto	Leeds
2-24-35	32.0	116.0	6.0	Sierra Tinaja	San Miguel	Leeds
5-19-40	32.7	115.5	6.7	Imperial Valley, Calif.*	Imperial	Caltech ʘ
12-7-40	31.7	115.1	6.0	Colorado Delta	Cerro Prieto	Caltech
10-24-54	31.7	115.9	6.0	Santo Tomas	San Miguel	Leeds
11-12-54	31.7	115.9	6.3	Santo Tomas	San Miguel	Leeds
2-09-56	31.7	115.9	6.8	San Miguel	San Miguel	Caltech
2-09-56	31.7	115.9	6.1	San Miguel	San Miguel	Caltech
2-14-56	31.5	115.5	6.3	San Miguel	San Miguel	Caltech
2-15-56	31.5	115.5	6.4	San Miguel	San Miguel	Caltech
8-07-65	31.8	114.5	6.3	Colorado Delta	Cerro Prieto	Caltech

* Surface faulting extended about 30 km into Baja California.

\# Earthquake History of the United States Publication 41-1
U. S. Department of Commerce
NOAA/EDS

\+ Leeds, A. L., 1979, Relocation of M $\geq$ 5.0 northern Baja California earthquakes using S-P times: Masters Thesis, University of California, San Diego.

ʘ 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, Pasadena, California.

stations south of the border. Older epicenter locations in the Caltech catalogue show a wide scatter because of a lack of local station control. Lomintz, et al.,(1970), using data from a seismograph station at Rio Hardy (Figure 2), have shown that most of the epicenters fall along active faults. More recent Caltech locations show less scatter because of improved station coverage.

The paper by Hileman (this volume), contains a discussion of the general seismicity of this region. In the following sections only specially-located earthquakes and earthquake swarms will be described.

EARTHQUAKES AND EARTHQUAKE SWARMS

SAN MIGUEL FAULT ZONE

Micro-earthquake activity in the San Miguel fault region is very high. Reyes, et al., (1975) operated high gain portable seismographs at 22 sites within this region. Results were reported in terms of normalized rates of micro-earthquakes per day. Very high rates, exceeding 100 events/day, were observed near the southeast end of the San Miguel fault (Figure 2). Sixteen of the 22 sites recorded rates exceeding 20 events/day. The overall micro-seismicity was higher than along most of the San Andreas fault in southern California. At two sites, arrays were operated to obtain accurate locations. Hypocenter locations near the southeast end of the San Miguel fault were near the fault trace and at depths of 8 to 14 km. Relatively high micro-earthquake rates were observe at a site 70 km from Tijuana, suggesting that the north-western San Miguel fault zone is active and might pose a significant seismic hazard to the cities of Tijuana and San Diego.

Johnson, et al., (1976) studied the micro-seismicity of the San Miguel and Agua Blanca fault zones. Five micro-earthquake instruments were operated for two months in 1974, in a small mobile array deployed at various sites. An 80 km (50 mile) long section of the San Miguel fault zone was found to be seismically active, producing the vast majority of recorded earthquakes (Figure 2). Very low activity was recorded on the Agua Blanca fault. Hypocenters on the San Miguel fault ranged in depth from 0 to 20 km although two thirds were shallower than 10 km. A composite focal mechanism study showed a mixture of right-lateral and dip slip, east side up, similar to a solution obtained for the 1956 San Miguel earthquakes, and consistent with observed surface deformation.

In an unpublished 1979 study, R. S. Simons, A. Nava, and J. N. Brune relocated eight earthquakes in this region based on readings from two stations in Baja California (Rio Hardy and San Felipe) plus stations of the Caltech network to the north in southern California. The earthquakes occurred between September, 1969 and January, 1970. Six of the events were clustered about the southern end of the San Miguel (and Sierra Juarez) fault zone; the other two originated in an area near the middle of the San Miguel fault (Figure 2).

In a study relocating northern Baja California earthquakes with magnitudes greater than 5.0, using S-P times, A. L. Leeds (1979) found 5 events in the San Miguel fault zone (Figure 2).

1974 PINO SOLO EARTHQUAKE

The Pino Solo earthquake (M = 5.0) occurred on July 8, 1974 between the San Miguel and Sierra Juarez fault zones (Figure 3). The epicenter was located by using stations in the Caltech array and in northern Baja California to obtain better epicenter control than would result from just using the Caltech array. The location of this event is important for calibrating epicenter locations in this region because its location was confirmed by using a small local array to pinpoint aftershock locations. The aftershock region was located between the San Miguel and Sierra Juarez fault zones (hatched area, Figure 3) at depths between 4 and 18 km. The aftershock zone extends in a west-northwest--east-southeast direction (A. Nava, in prep., 1979).

There are no known through-going, major faults in the epicentral region, although some small faults are shown on the map by Gastil, et al., (1975). The earthquake probably resulted from the complex stress system between the San Miguel and Sierra Juarez fault zones.

THE AUGUST 19, 1978 CAÑON DE LA PRESA EARTHQUAKE

On August 19, 1978, an earthquake of approximate magnitude 3.5 occurred in an area midway between the southernmost known extension of the Rose Canyon fault in San Diego and the northernmost trace of the San Miguel fault zone in Baja California (Simons, 1979) (Figure 4). The location was obtained using stations in the San Diego area, the Ensenada station, and selected stations of the Caltech network. The locale of this event is distinguished by a sharp

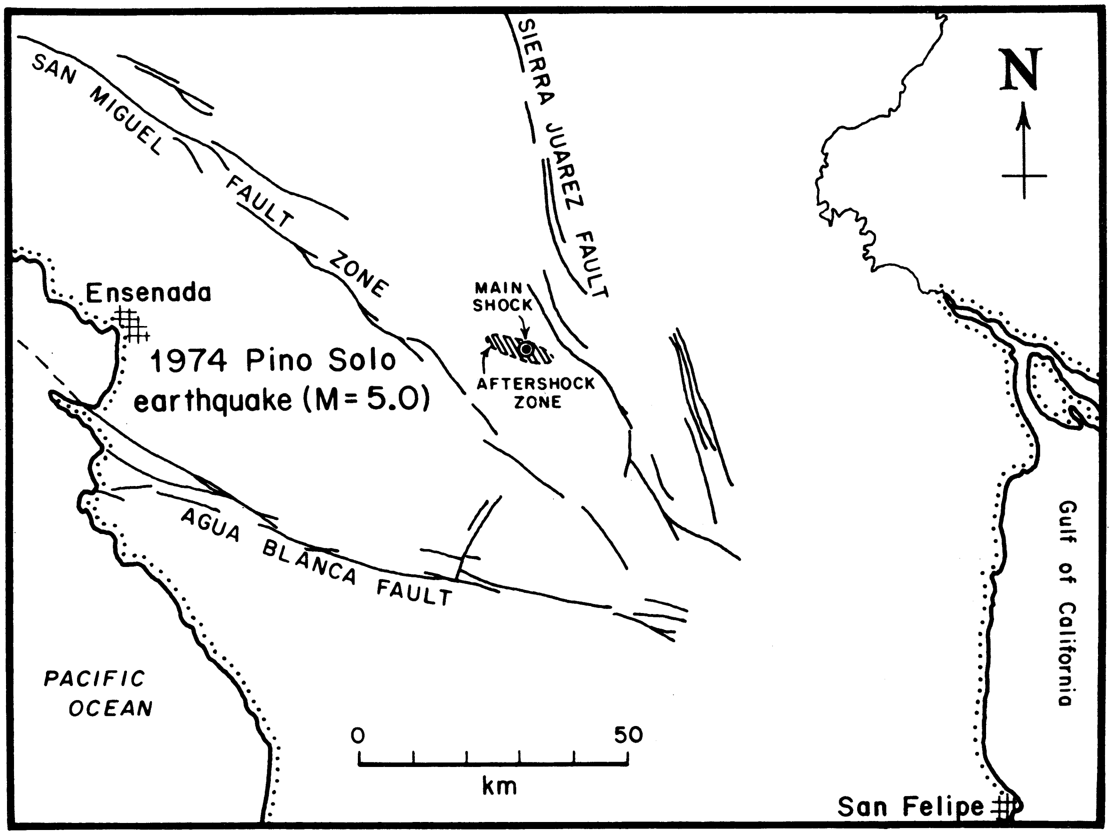

Figure 3. Location of the 1974 Pino Solo earthquake and its aftershocks (A. Nava, in preparation, Doctoral Thesis, UCSD).

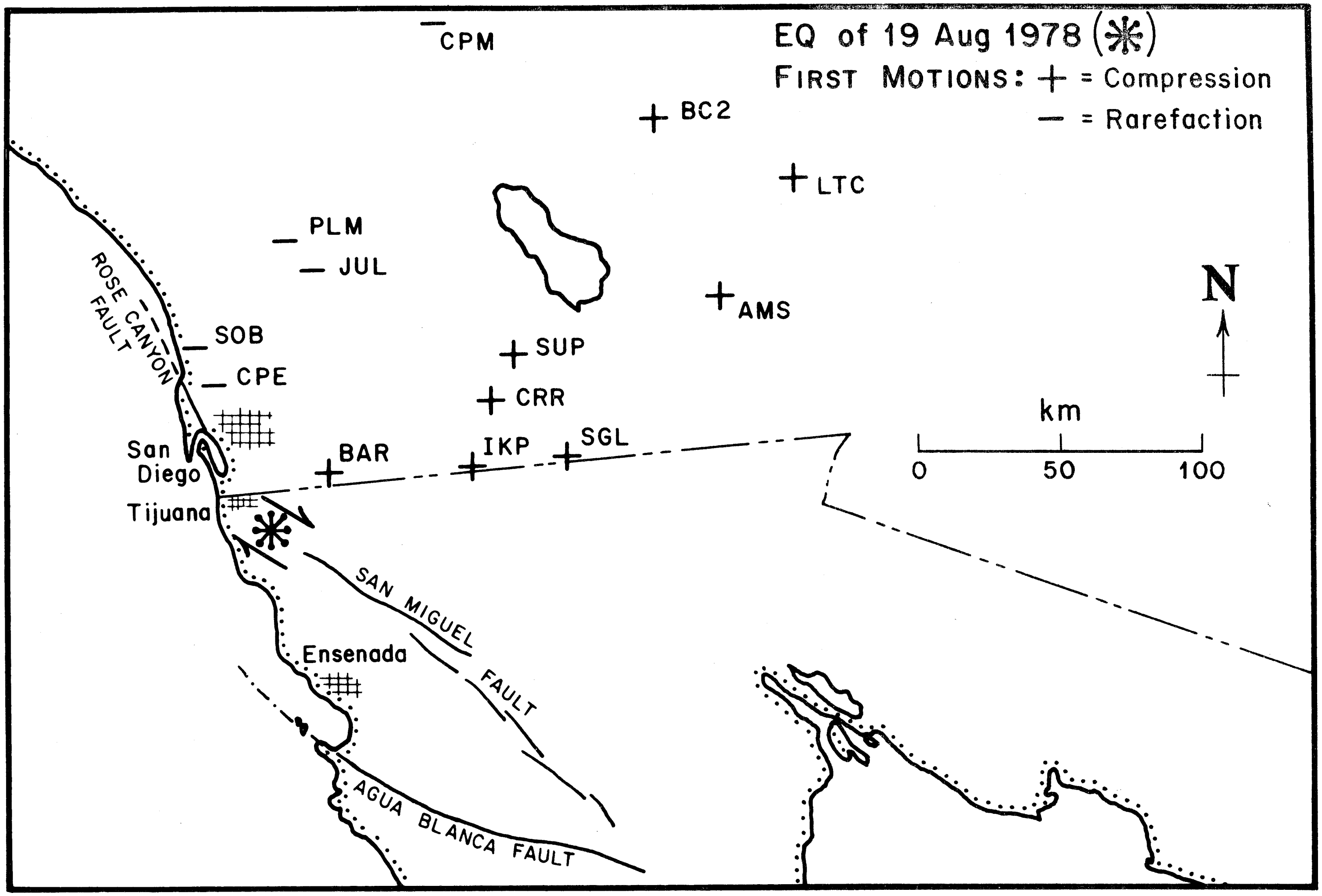

Figure 4. Location of the 19 August 1978 Cañon de La Presa earthquake southeast of Tijuana. First motion data suggests right-lateral strike-slip movement as indicated by arrows (Simons, 1979).

topographic feature trending northwest-southeast (Cañon de la Presa) All available first motion data are consistent with right-lateral strike slip movement (Figure 4). Robert Washburn of San Diego State University (personal communication) has reported evidence of recent landslides in Cañon de la Presa and for strike-slip faulting in the Cañon. The geological and the seismological observations both suggest that Cañon de la Presa may delineate an active fault between (and possibly connecting) the Rose Canyon and San Miguel fault systems.

LOCATION OF THE 1954 NORTHERN BAJA CALIFORNIA EARTHQUAKES

A series of earthquakes occurred in northern Baja California in late 1954 (October 17, 5.7; October 24, 6.0, 5.4; November 12, 6.3, 5.0; November 14, 5.4; and numerous smaller events). The Caltech Bulletin placed the epicenters for these events a few km from the Agua Blanca fault (the epicenters were taken from USGS locations). These locations have been taken as evidence for activity of the Agua Blanca fault. However, the earthquakes of 1956 were clearly not on the Agua Blanca fault, but on the San Miguel fault farther north; for example, ground breakage was reported by Shor and Roberts (1958).

Evidence for the locations of the 1954 earthquakes has been reexamined by Leeds and Brune (1979). Richter (1958) stated that the accuracies of the USGS locations for the 1954 events is about ± 1/4 degree, (i.e., ± 28 km). Within these limits of error, all the events (with the exception of the October 17 event) could have occurred on the San Miguel fault, rather than on the Agua Blanca fault. Comparison of S-P times for the numerous 1954 aftershocks with S-P times for the 1974 Pino Solo earthquake aftershocks (for which there is an accurate location based on local aftershock recordings), indicates that the 1954 events were only 10-20 km south of Pino Solo, i.e., on the San Miguel fault and not on the Agua Blanca fault (actually farther north than the 1956 events). International Seismological Centre locations for these 1954 events are also near the same location on the San Miguel fault. This new location of the 1954 events is consistent with micro-earthquake studies of Reyes, et al., (1975) and Johnson, et al., (1976); they found no micro-earthquake activity on the Agua Blanca fault but high activity on the San Miguel fault.

REGION OF THE CERRO PRIETO GEOTHERMAL FIELD

Albores, et al., (1979) reported results of seismicity studies in the region of the Cerro Prieto geothermal field (Figure 5). These studies were conducted with local, short-period seismic arrays during 1974-75 and 1977-78. During the latter period, horizontal seismometers were used for better control on S-wave arrival times. Locations were obtained for about 200 events and composite fault plane solutions were obtained for five groups of events. The seismic activity is characterized primarily by swarms of relatively small events, although one swarm had events with magnitudes as high as 5.0.

Epicenter locations indicate a broad distribution connecting the Cerro Prieto and Imperial faults (Figure 5). Within this distribution there are indications of trends both parallel, and oblique to, the Cerro Prieto-Imperial transform fault system. Composite fault-plane solutions indicate right-lateral strike-slip faulting along the northwest-southeast trending faults (A and E, Figure 5) and dip-slip faulting along at least some of the oblique faults (B, C and D, Figure 5).

Most of the events near region E (Figure 5) occurred during the Victoria, Baja California earthquake swarm of March 9 to March 20, 1978. The largest event of the swarm had a magnitude of 5.0.

CERRO PRIETO FAULT REGION

The Cerro Prieto fault, southeast of the Cerro Prieto volcano and steam field, is the main locus of slip between the Pacific and North American plates, and consequently, seismic activity is very high. Three moderately large historic earthquakes have occurred along this fault (1934, M = 7.1; 1940, M = 6.0; 1966, M = 6.3). The most recent of these events has been studied by Ebel, et al., (1978).

Smaller earthquakes and earthquake swarms along the Cerro Prieto fault have been located in special studies. Lomintz, et al., (1970) found a concentration of events along the fault during 1969 (Figure 6). The 1976 Mesa de Andrade earthquake occurred on this fault and the aftershocks were located by Centro de Investigación Cientifica y Educación Superior de Ensenada (CICESE) in Ensenada (Figure 7).

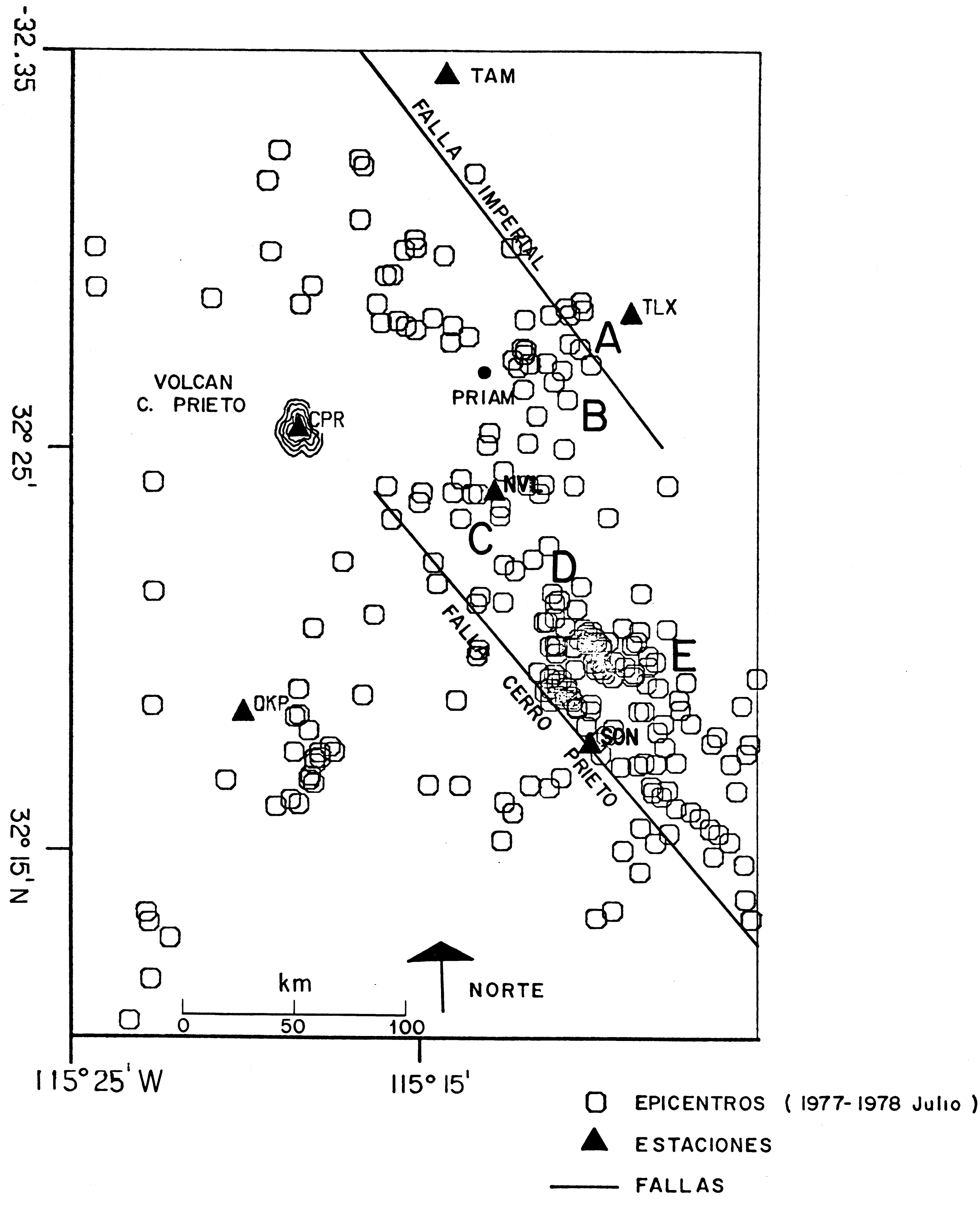

Figure 5. Seismicity in the region of the Cerro Prieto geothermal field (From Albores, *et al.*, 1979).

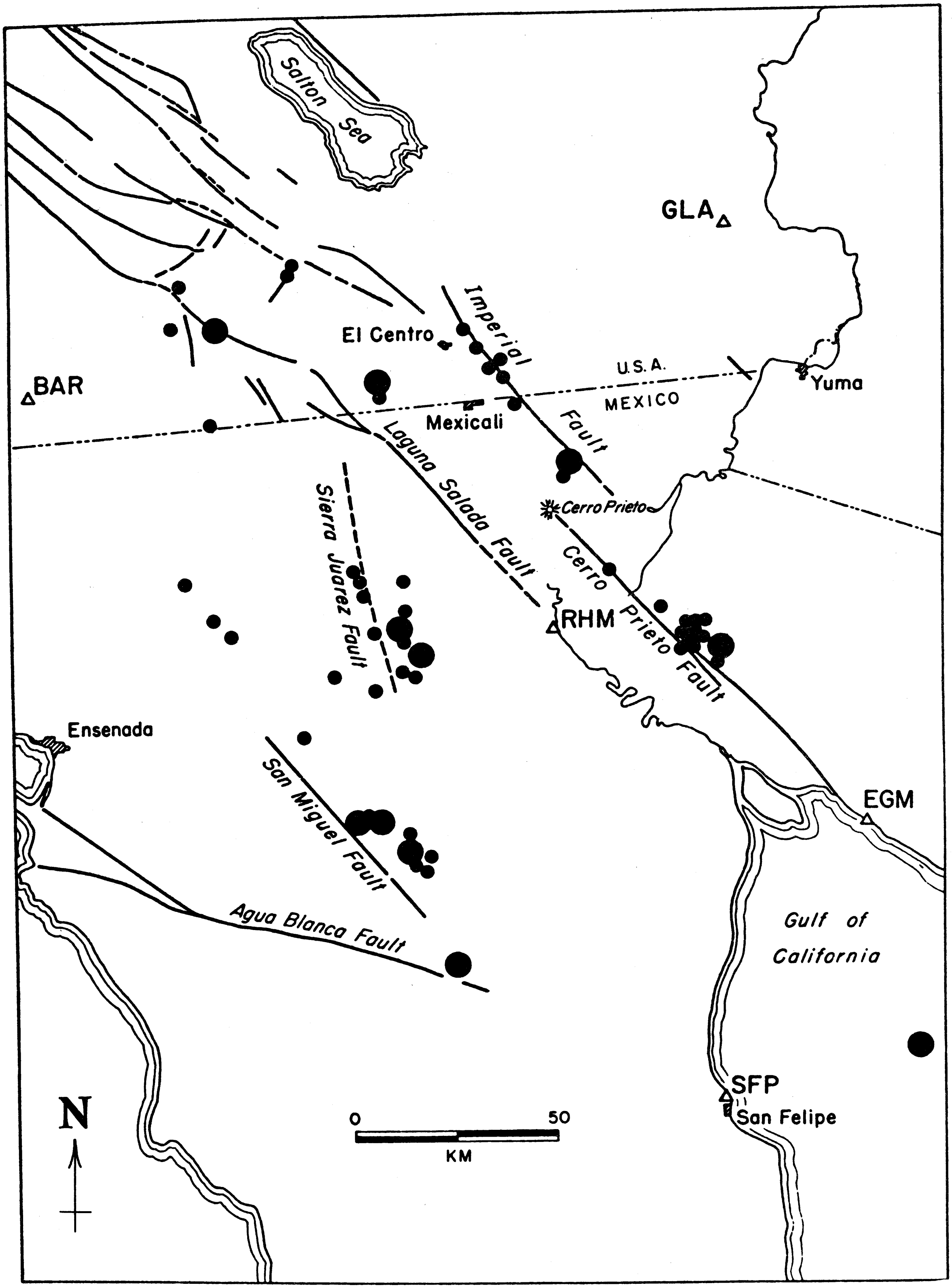

Figure 6. Epicenters of earthquakes that occurred during April and May of 1969 (from Lomnitz, *et al.*, 1970).

SIERRA JUAREZ FAULT ZONE

Local array studies of the Sierra Juarez fault zone have not been carried out. Caltech epicenter catalogues show that this is one of the zones of highest earthquake activity in the region. Numerous magnitude 4 to 5 earthquakes were reported in 1975-1976. The activity has decreased considerably since the first part of 1978. Epicentral control on these events will be greatly improved once readings from Mexican stations are included with the epicenter location calculations. Leeds (1979) has located 3 earthquakes with magnitudes greater than 5 in the Sierra Juarez fault zone. Two of them are in the northern portion of the zone; the other is at the southern end near its confluence with the San Miguel fault zone (Figure 2).

BAHIA DE SAN RAMÓN

On September 13, 1975, an earthquake of magnitude 5.2 occurred in the vicinity of Bahia de San Ramón, approximately midway between Punta Colnett and Cabo San Quintín (Figure 8). It was followed by an exceptionally high level of seismic activity having the characteristics more of a swarm than a typical aftershock sequence. Using portable seismographs deployed 2 days after the initial event, seismologists from the CICESE detected as many as 164 events in a period of 48 hours. The epicenters were clustered in a fairly limited area centered just offshore (Figure 8). The depths of the events lay principally between 14 and 20 kilometers. The swarm continued at least through January, 1977, with a gradually decreasing rate of seismicity, although there was a return to relatively high levels of activity during April 5-19, 1976.

The vicinity of Bahia de San Ramón contains no mapped faults of any consequence, and has sustained no previous known seismic activity (with the possible exception of a poorly located event in 1942). The principal geologic characteristics of the area consist of a sequence of inactive volcanoes both onshore and offshore, with remnant flows of Quaternary basalt (Rebollar, 1977).

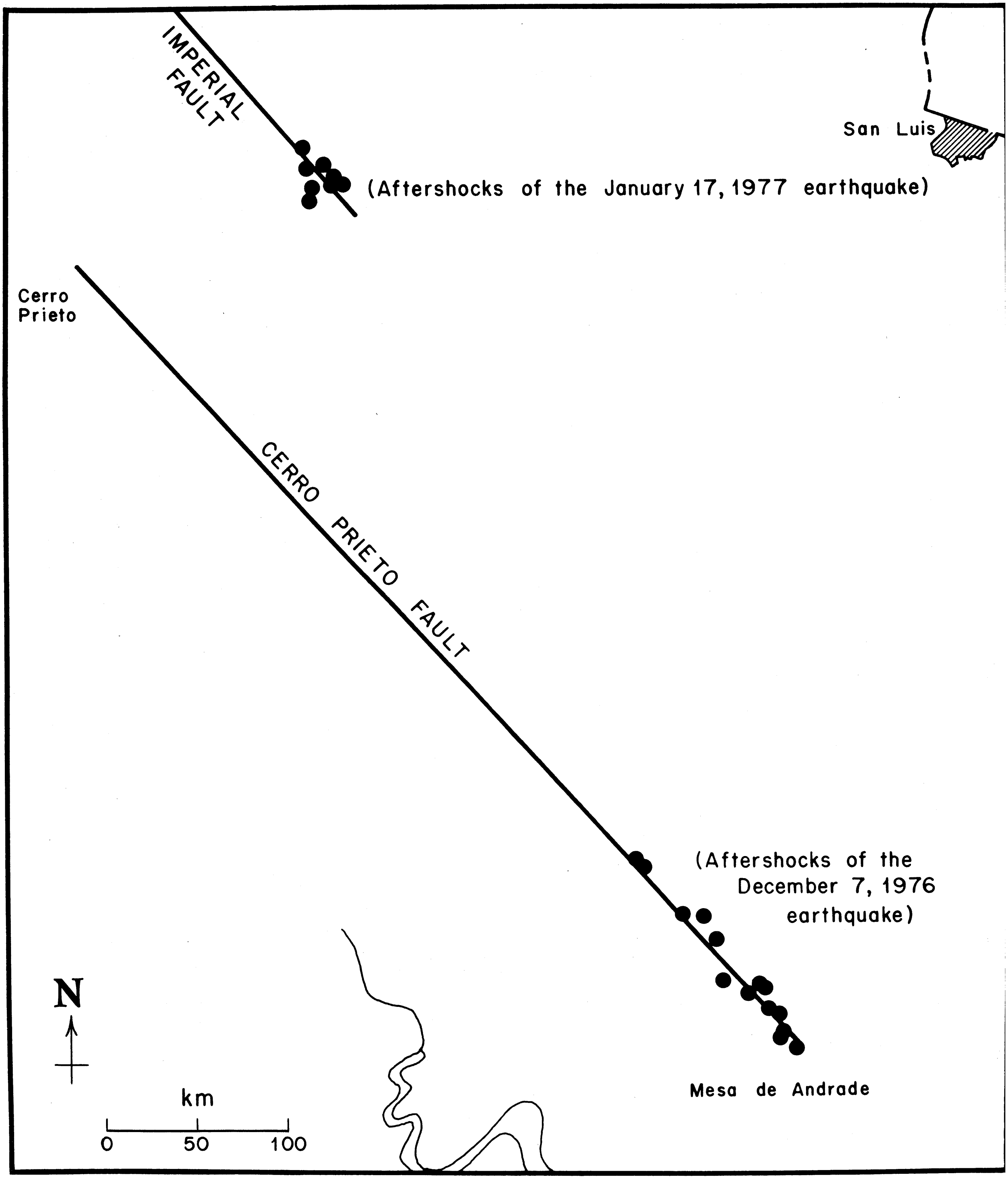

Figure 7. Aftershocks of the 17 January, 1977 earthquake on the Imperial fault and the earthquake on the Cerro Prieto fault (located by CICESE in Ensenada).

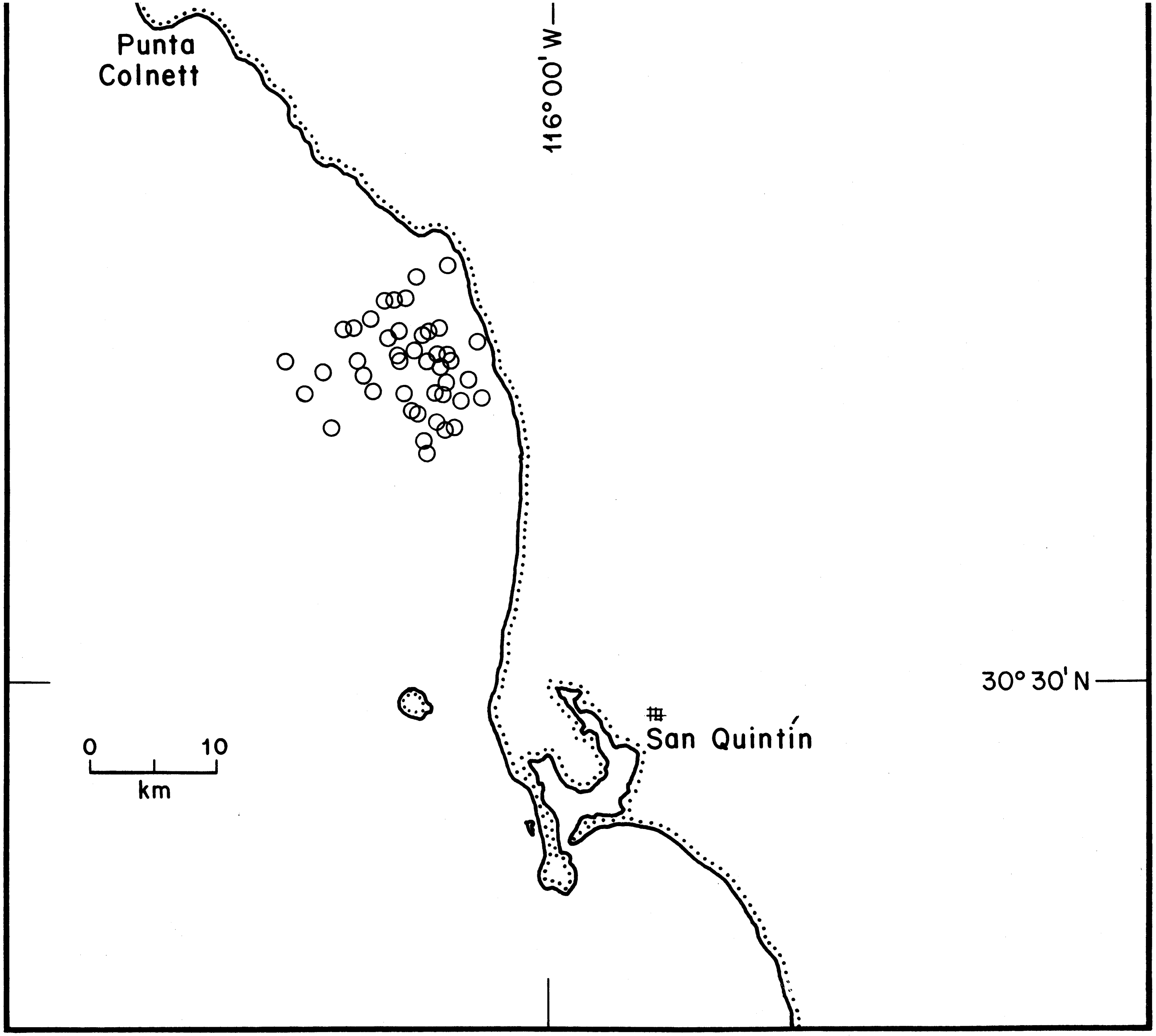

Figure 8. Epicenters of some earthquakes that occurred during the September, 1975, swarm near Bahia de San Ramon (Rebollar, 1977).

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INSTRUMENTAL SEISMICITY OF THE SAN DIEGO AREA 1934-1978

by

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In a previous paper (Simons,1977), twelve quarry explosions within the City of San Diego were used to determine a crustal velocity model for the surrounding region. Parameters for this model are:

$h_1 = 1.5$ km	$\alpha_1 = 3.50$ km/sec	$\beta_1 = 1.90$ km/sec
$h_2 = 26.5$ km	$\alpha_2 = 6.35$ km/sec	$\beta_2 = 3.65$ km/sec
$h_3 = \infty$	$\alpha_3 = 8.00$ km/sec	$\beta_3 = 4.60$ km/sec

A computer program embodying this model was used to recalculate epicenters of all events previously located in the San Diego area by work at the Seismological Laboratory at Caltech from 1934 through 1974. Over 70 percent of these epicenters had been established by pre-computer, graphical techniques, and the velocity models used for the computer-determined epicenters were not appropriate for this region. The 1977 relocations benefited from readings from several new stations in the vicinity (beginning in 1964), not available to scientists at Caltech. Also, a great deal of care was taken to identify and eliminate quarry blasts, which were numerous.

The purpose of this paper is to summarize and update the previous paper (Simons, 1977) by applying the same model to locate earthquakes from 1975 through 1978. Since 1975, epicenter control within the San Diego area has been improved by the addition of new stations to the Caltech-USGS network. Those most critical to San Diego are Vista (VST), Camp Pendleton (CPT) and Julian (JUL). These stations are shown in Figure 1, along with others normally utilized for locating events in the San Diego area. Data continues to be available from the three non-Caltech stations in the area (SOB, SND, and BBP).

Epicenters for the period 1934-1978 are shown in Figure 2. Although 37 earthquakes are charted for the original 41-year period, a total of 15 are shown representing the past four years. This apparent upwelling in seismicity is, of course, the result of lowering the network's detection threshold by adding more and closer stations. Whereas the entire 1934-1974 period turned up no more than six events of magnitude 2.5 or

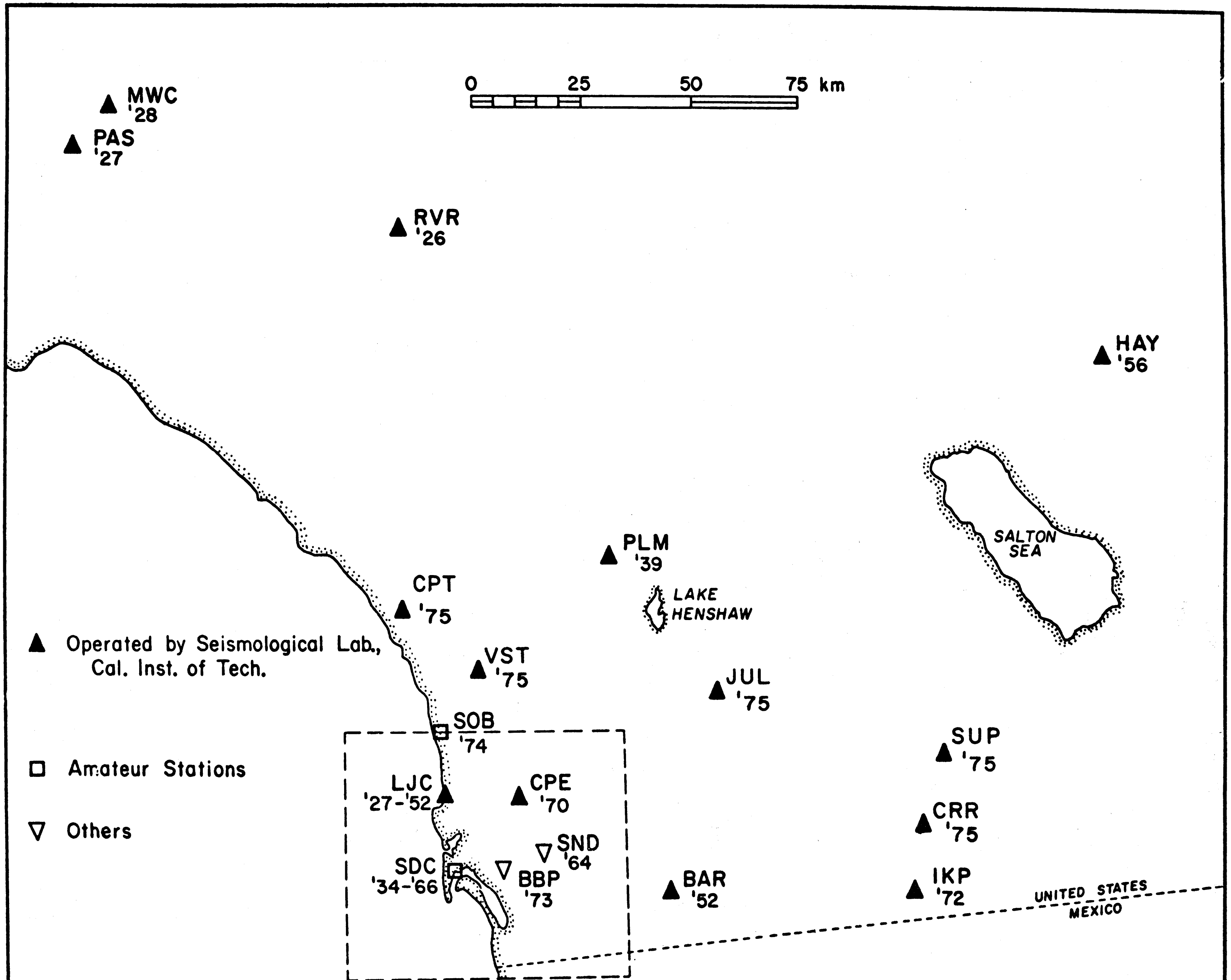

Figure 1. Principal seismic stations monitoring the San Diego area, 1934-1978.

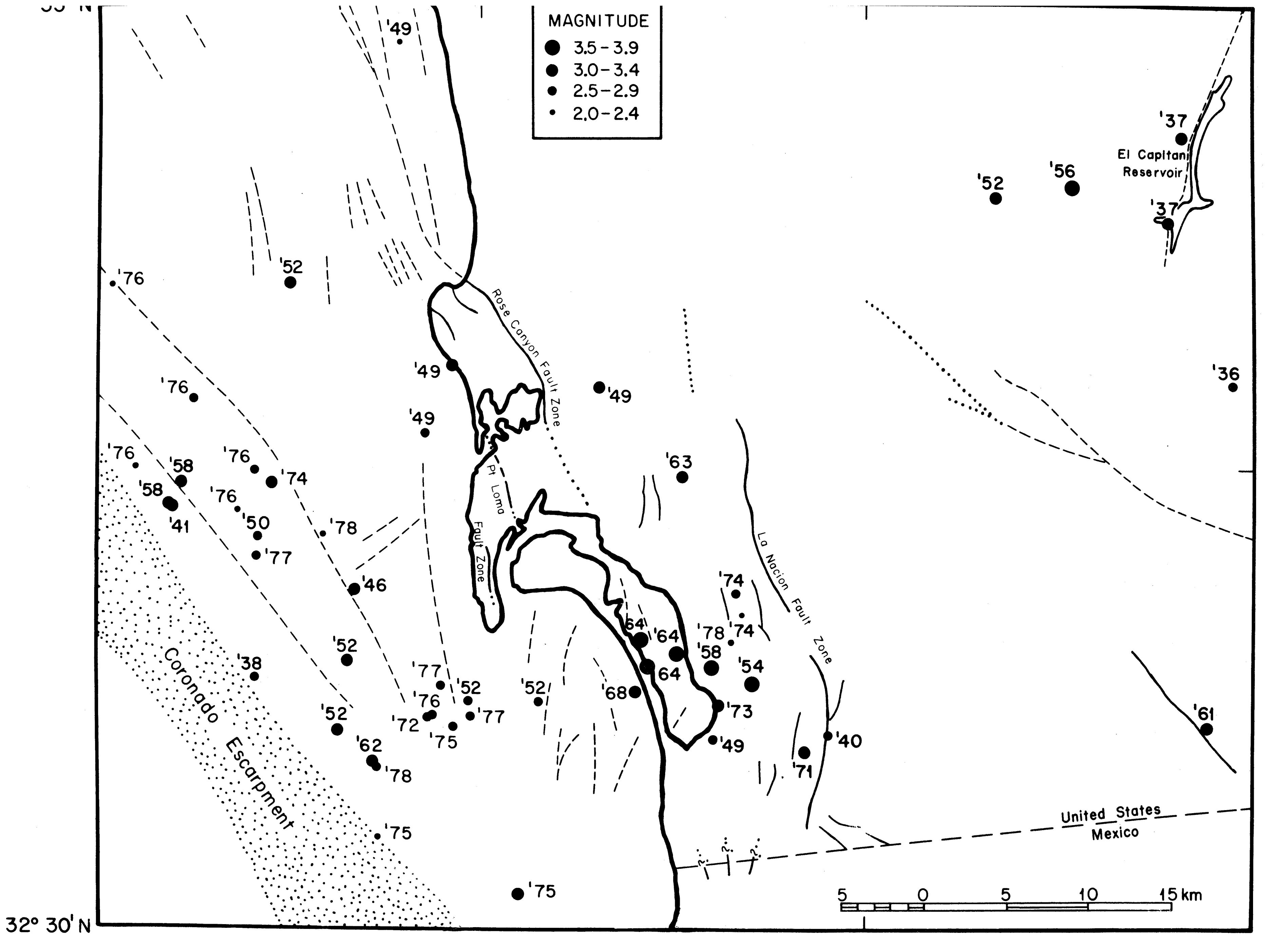

Figure 2. Seismic activity in San Diego area, 1934-1978. Depths held at 4 km.

less, the number of similar events reported for 1975-1978 is eight. The number of earthquakes of magnitude 3.0 or greater during 1975-1978 (one), is actually lower than the average rate for similar events during 1934-1974 (approximately 0.6 per annum).

Coordinates, origin times and magnitudes of all the relocated earthquakes are provided in Table 1. Magnitudes given are those originally determined at Caltech. The largest events (magnitude 3.7) occurred in 1958 and 1964. The depths of all events have been constrained to 4 km, because a well-located subset of the 1934-1974 events suggested this depth as a good median choice.

As shown in Figure 2, the general pat ern of seismicity around San Diego since 1934 has consisted of a broad scattering of events either offshore or less than 10 km inland, plus a handful of events more than 25 km inland. Within the limits of location accuracy, most of the epicenters shown can be associated with either submarine topographic features paralleling the Coronado Escarpment or the broad area of fracturing which constitutes the Rose Canyon fault zone. The concentration of activity around the south end of San Diego Bay is conceivably associated with a series of underwater faults discovered there by Moore and Kennedy (1975) by means of acoustic profiling. The faults are reported to have definitely displaced Holocene sediments.

Little is known about the earthquakes in the eastern part of the study area except that, on the whole, they are not well located. It is perhaps noteworthy that the El Capitan Reservoir was completed in 1934; the two events located near there in 1937 may be related to subsequent filling of the reservoir.

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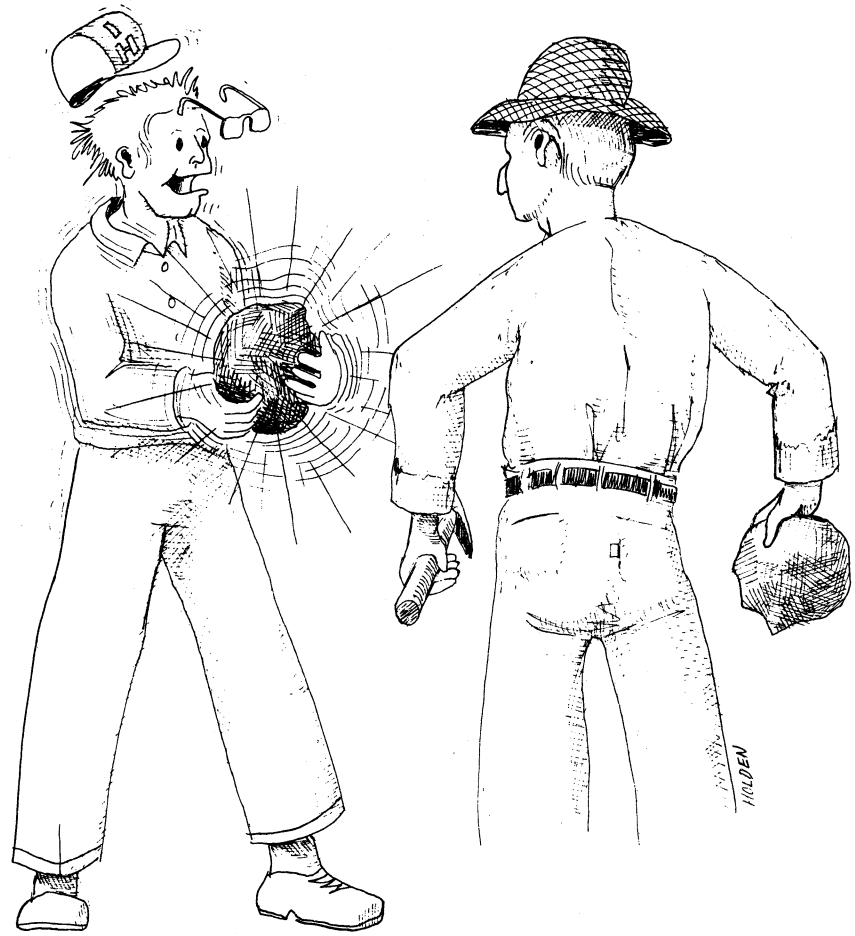
TABLE 1

Earthquakes in the San Diego Area (32.5° - 33.0°N, 116.75° - 117.5°W), 1934-1978

DATE	TIME (UTC) HR MIN SEC	LOCATION LAT.(N)	LONG.(W)	MAG.	N*	P+	Q#
5 JUN 1936	05 38 54.1	32.798	116.764	2.5	4	6	B
11 OCT 1937	04 55 07.5	32.886	116.805	3.0	3	6	B
25 OCT 1937	10 28 27.4	32.932	116.797	3.0	3	6	B
27 SEP 1938	17 18 07.2	32.639	117.401	2.5	4	8	B
11 JUL 1940	13 34 45.2	32.608	117.027	2.7	3	5	C
14 SEP 1941	13 50 52.6	32.732	117.455	3.0	5	8	B
1 JAN 1946	23 56 32.2	32.687	117.335	3.3	5	10	A
20 JUN 1949	18 35 30.1	32.808	117.272	3.0	4	8	A
21 JUN 1949	19 39 35.9	32.772	117.290	2.9	3	6	C
25 JUN 1949	02 13 18.8	32.796	117.175	3.1	4	7	C
4 AUG 1949	01 24 30.5	32.605	117.102	2.5	3	6	B
5 OCT 1949	02 52 10.1	32.981	117.307	2.3	3	6	B
13 MAY 1950	12 11 36.0	32.716	117.399	2.9	5	9	B
20 APR 1952	18 01 43.4	32.648	117.340	3.2	4	6	A
20 APR 1952	21 12 27.3	32.610	117.347	3.2	4	6	A
11 JUN 1952	08 01 58.2	32.852	117.378	3.0	4	5	C
12 JUN 1952	12 45 43.1	32.627	117.262	3.4	3	5	B
12 JUN 1952	12 54 39.4	32.626	117.216	2.6	4	6	A
4 NOV 1952	19 07 31.3	32.899	116.919	3.2	3	5	C
21 DEC 1954	07 11 12.5	32.636	117.076	3.5	5	9	B
7 JUL 1956	12 41 53.2	32.905	116.868	3.5	6	12	A
14 JAN 1958	14 05 41.6	32.644	117.102	3.7	6	12	A
13 NOV 1958	09 09 01.8	32.733	117.456	3.4	4	7	A
23 NOV 1958	21 04 00.3	32.745	117.449	3.4	5	9	A
30 MAY 1961	22 01 38.1	32.612	116.779	3.0	4	7	C
4 AUG 1962	06 37 26.9	32.593	117.324	3.2	4	8	B
14 DEC 1963	02 48 14.3	32.748	117.123	3.1	4	8	B
21 JUN 1964	15 32 52.1	32.652	117.126	3.7	6	11	A
23 JUN 1964	04 54 37.5	32.659	117.148	3.6	5	10	A
15 JUL 1964	03 11 05.6	32.645	117.144	3.5	5	9	A
3 MAY 1968	07 21 54.4	32.631	117.153	3.5	6	11	A
9 APR 1971	23 00 29.0	32.598	117.043	3.3	5	10	A
18 DEC 1972	01 59 37.0	32.617	117.288	2.5	4	8	A
15 APR 1973	03 18 06.4	32.624	117.099	3.2	5	10	A
12 JUN 1974	23 48 19.8	32.684	117.088	2.7	8	15	A
14 DEC 1974	04 01 23.0	32.745	117.389	3.1	5	10	B
22 DEC 1974	15 16 30.0	32.672	117.084	2.3	4	8	B
27 JAN 1975	02 07 21.5	32.519	117.227	3.1	6	10	B
18 MAY 1975	04 42 51.6	32.610	117.269	2.5	8	13	A
1 NOV 1975	12 28 45.2	32.550	117.317	2.1	5	9	B
19 FEB 1976	08 34 15.6	32.728	117.409	2.3	7	13	A
11 MAR 1976	18 12 16.3	32.749	117.398	2.6	7	13	A
13 JUN 1976	01 19 42.5	32.617	117.283	2.7	10	17	B
10 JUL 1976	17 20 57.6	32.788	117.438	2.9	8	12	B
27 JUL 1976	16 25 55.3	32.849	117.492	2.4	7	13	A
3 DEC 1976	10 59 37.5	32.752	117.476	1.7	5	10	A
29 JUL 1977	18 25 45.5	32.704	117.397	2.7	6	10	A
22 SEP 1977	04 27 26.2	32.616	117.257	2.7	8	16	B
20 NOV 1977	02 44 16.7	32.633	117.277	2.5	8	13	A
29 JUN 1978	06 55 57.8	32.715	117.353	2.4	9	15	A
17 JUL 1978	17 25 59.4	32.656	117.088	0.0	5	9	B
26 DEC 1978	02 33 33.0	32.589	117.319	2.7	9	17	A

* No. of stations used in solution; + No. of phases used in solution;
# Estimated accuracy of solution: A=Probably within 2 km; B=Probably within 4 km; C=Uncertain, easily beyond 4 km. (Depths of all events constrained to 4 km).



"Look! A fossil earthquake... and it's at least a 5.5 on the Richter Scale!"

PROBABILITY OF EARTHQUAKE GROUND ACCELERATIONS IN SAN DIEGO

by

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INTRODUCTION

Probabilities that various earthquake accelerations on firm ground will be exceeded in San Diego in a 50-year period and the average return periods of these accelerations have been computed. The analytical model used for the calculations was similar to standard models currently used for seismic risk analyses of this type. Inputs to the analysis consisted of: (1) the location and geometry of seismic source areas in the region surrounding San Diego, (2) recurrence curves giving the rate of occurrence of earthquakes of a given magnitude within each seismic source area, and (3) an attenuation relation to predict peak accelerations on firm ground in San Diego from future earthquakes in the region.

ANALYSIS

Analytical Model

The basic assumption of the analytical model for this, and many other seismic risk studies, is that the occurrence of earthquakes within a particular seismic source area are random and can be approximated as a Poisson process. Previous studies of seismicity in southern California (Gardner and Knopoff, 1974) have shown this assumption to be reasonable. It is recognized that the Poisson assumption may not be appropriate for certain seismic sources such as the San Andreas fault. However, for this application, the San Andreas fault is far enough from San Diego that its impact on the probabilities would be small, regardless of the assumption made on the occurrence of earthquakes on this fault.

The mathematical model for this study was adapted from publications by Cornell (1968), Der Kiureghian and Ang (1975) and Benjamin and Cornell (1970). Under the assumption of a Poisson process, it can be shown that this model is represented by the following equation:

$$p(a>A) = 1 - \exp\left(-t \sum_{j=1}^{n} \sum_{i=1}^{m_j} (v_{ij}\, p_{ij})\right) \qquad (1)$$

where $p(a>A)$ is the probability that a given ground acceleration will be exceeded in San Diego in t years (t = 50 years was assumed in this study). The symbol p_{ij} is the probability that one earthquake in some small magnitude range (i) occurring in some seismic source (j) produces a peak ground acceleration in San Diego, (a) exceeding a given acceleration level (A). The basis for computing p_{ij} is to assume that earthquakes can occur anywhere within the seismic source area. The value of p_{ij} is a function of the attenuation of the peak ground acceleration with magnitude and distance, and the geometry and location of the seismic source area, with respect to San Diego. Details of the method to compute p_{ij} can be found in Cornell (1968) or Der Kiureghian and Ang (1975). The symbol, v_{ij}, represents the mean recurrence rate of an earthquake of a given magnitude (M_i) in a particular seismic source (j) and is computed from the recurrence curves.

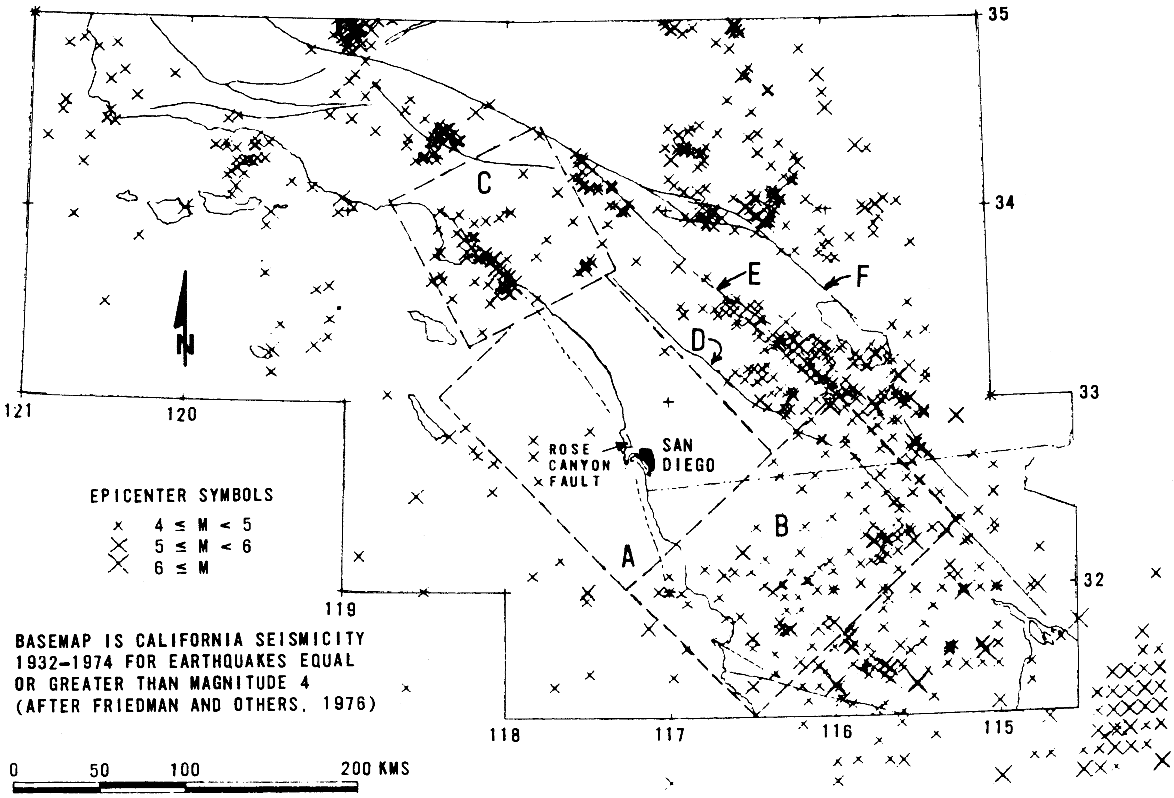
The average return period (T) of the event (a>A) is:

$$T = 1/\left(\sum_{j=1}^{n} \sum_{i=1}^{m_j} v_{ij}\, p_{ij}\right) \qquad (2)$$

Inputs to Analysis

The seismic source areas considered in the probabilistic analysis are shown in Figure 1. A seismic source is defined as an area where the seismicity characteristics and potential for earthquakes are reasonably uniform. The selection of the seismic sources for this analysis was based on the distribution of seismicity, recognized geologic provinces or major fault zones, and general understanding of the tectonics of southern California. A reasonable simplification of the geometry was to consider the sources as rectangles. The San Andreas, San Jacinto and Elsinore fault systems were approximated as long, narrow rectangles. The Rose Canyon fault, which passes through San Diego, was not included in the analysis because of the lack of historic seismicity associated with this feature. Preliminary calculations indicated that other possible seismic source areas not shown in Figure 1, such as a source area to the west of the Peninsular Ranges/Continental Borderlands and northern Mexico, had a negligible effect on the probabilities.

Interval recurrence curves for each seismic source considered in the analysis are shown in Figure 2. These curves indicate the average number of earthquakes per year per unit area for magnitude intervals of one-half unit. For example, the recurrence curve (Figure 2) for the San Jacinto fault indi-



SEISMIC SOURCES

A. PENINSULAR RANGES / CONTINENTAL BORDERLANDS
B. NORTHERN MEXICO
C. LOS ANGELES BASIN
D. ELSINORE FAULT
E. SAN JACINTO FAULT
F. SAN ANDREAS FAULT

FIGURE 1. SEISMIC SOURCES IN THE REGION SURROUNDING SAN DIEGO

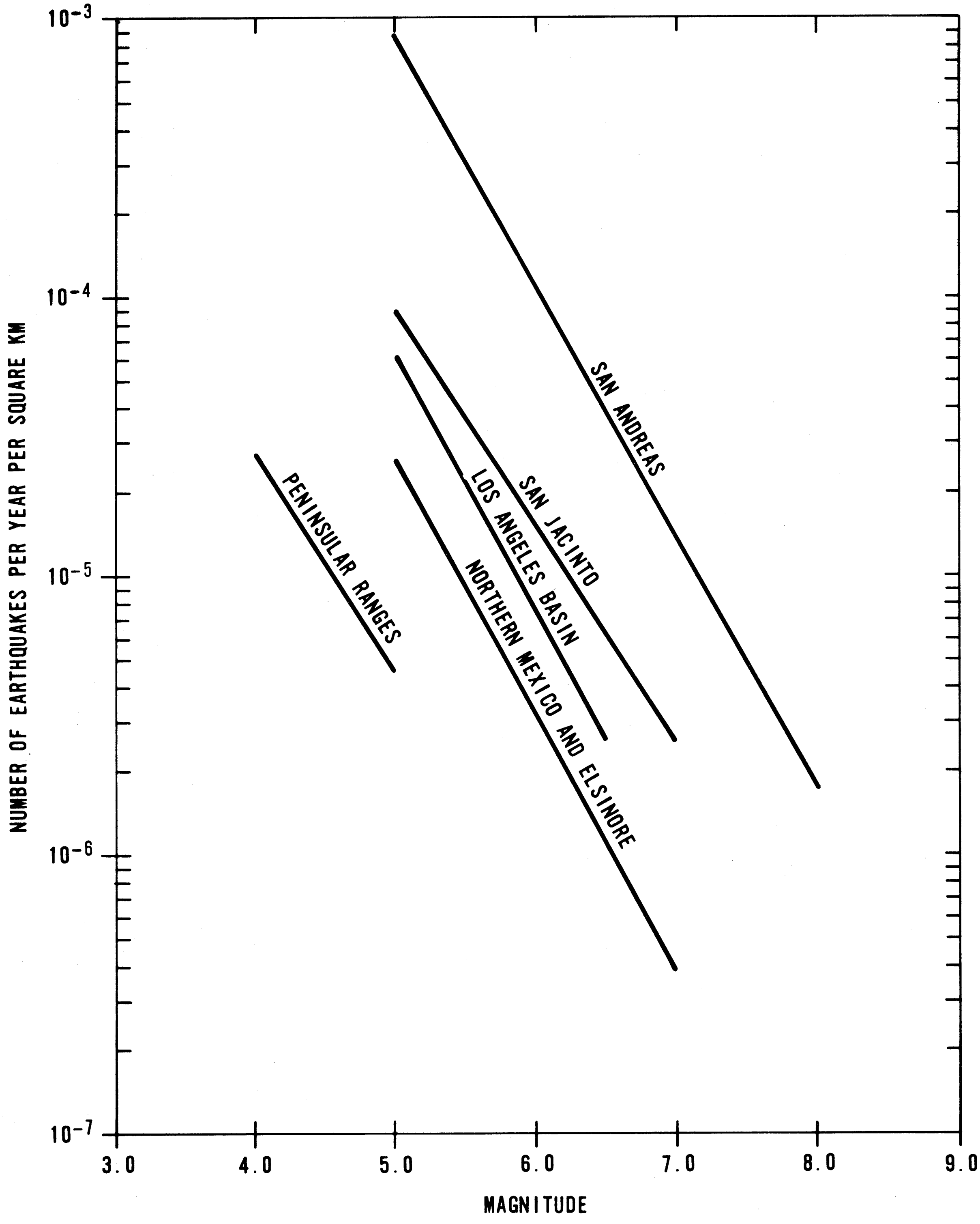


FIGURE 2. EARTHQUAKE RECURRENCE CURVES OF INTERVAL TYPE

cates about 10^{-5} earthquakes per year per square km for the magnitude interval 6.0 to 6.5. The values of v_{ij} used in equations (1) and (2) were obtained from the recurrence curves.

An attenuation equation by Donovan (1973) was adopted for the study to approximate the peak accelerations in San Diego on firm ground from earthquakes in the surrounding region. This equation was:

$$a = 1080 \ (\exp \ (0.5M)) \ (R + 25)^{-1.32} \tag{3}$$

where a is the peak ground acceleration in cm/sec/sec, M is earthquake magnitude and R is the hypocentral distance in km. This equation was obtained by a regression analysis of peak ground accelerations recorded during previous earthquakes. Since a significant portion of the regression data came from southern California, reasonable estimates of the accelerations in San Diego can be obtained from equation (3). Equation (3) and the associated uncertainty in the estimated accelerations were used to compute p_{ij} in equations (1) and (2).

RESULTS AND DISCUSSION

Results of the analysis, shown in Figure 3, indicate that the probability of significant ground accelerations in San Diego is relatively low compared to other regions in southern California. The main reason for this is that the more active seismic sources such as northern Mexico, the San Jacinto fault, and the Los Angeles basin, are too far from San Diego to appreciably affect the probabilities. The Peninsular Ranges/Continental Borderlands, the seismic source area containing San Diego, had by far the greatest contribution to the probabilities even though the recurrence of earthquakes in this region (Figure 2) is the lowest of all the seismic sources considered in the analysis. Whether or not the low historic seismicity is representative of the long-term seismic activity for this region is unclear, due to the relatively short time period over which seismicity has been recorded. Geologic maps (e.g. Jennings, 1975) show a few Quaternary faults within San Diego, such as the Rose Canyon and La Nacion faults. Although the potential earthquake activity in the immediate future of these or other capable faults in the San Diego vicinity is not presently known, engineers should consider the possibility of moderate to large earthquakes produced by these faults in the aseismic design of important or critical facilities.

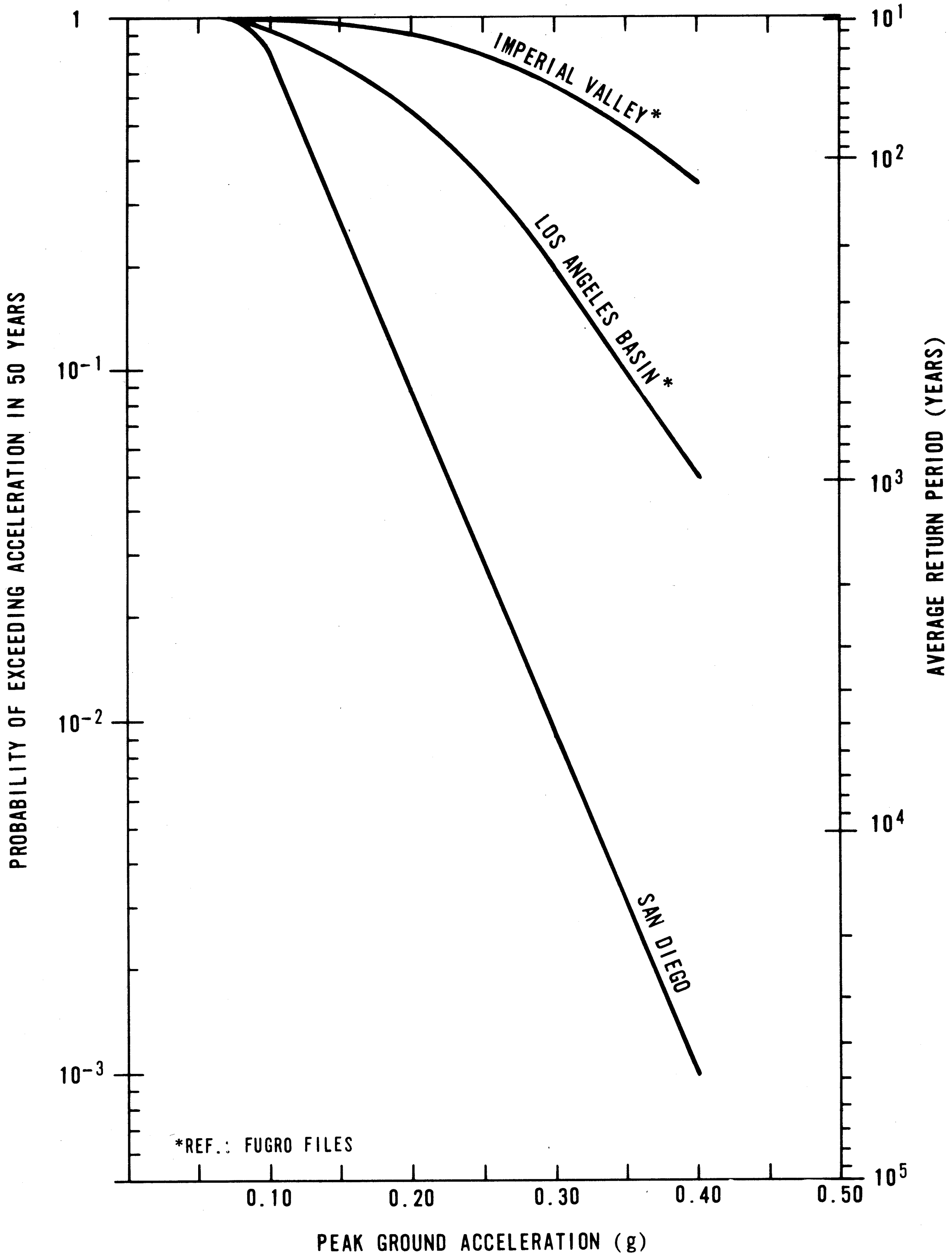


FIGURE 3. AVERAGE RETURN PERIODS AND PROBABILITIES OF EXCEEDING GROUND ACCELERATIONS IN 50 YEARS

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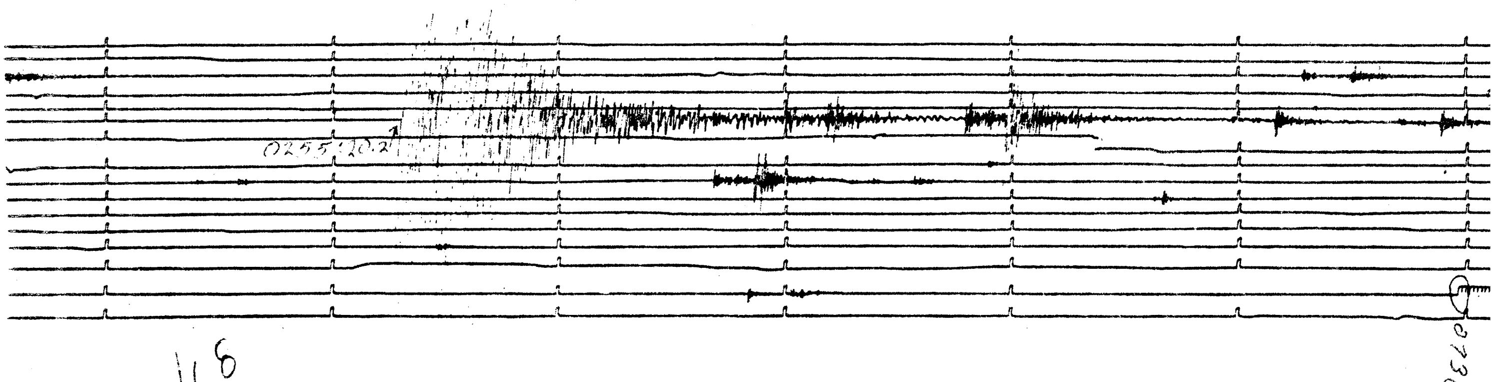
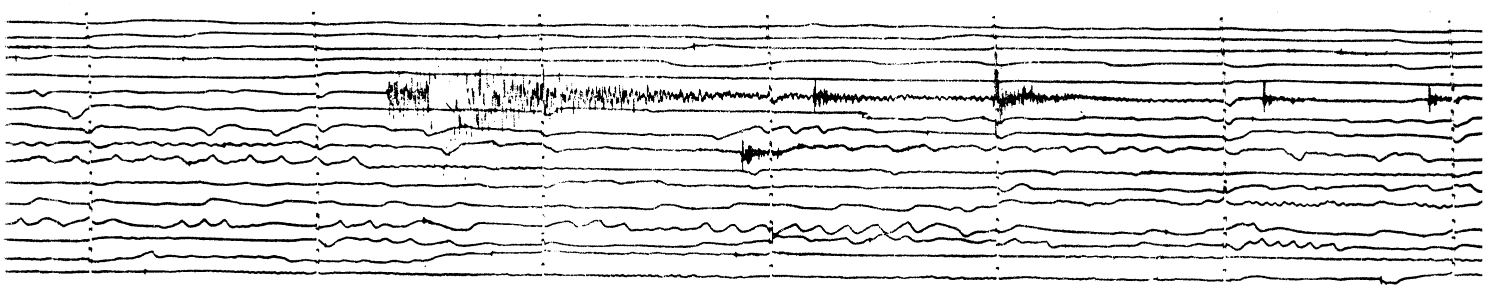


Short Period. Horizontal. N-S.



Short Period. Horizontal. E-W.

Some aftershocks from 6.5M Ocotillo Wells earthquake of April 8, 1968. Epicenter located about 60 miles northeast of Town & Country Convention Center in San Diego. Records from Department of Geological Sciences, San Diego State University.

THEORETICAL ASPECTS OF TSUNAMIS ALONG THE SAN DIEGO COASTLINE

by

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If one were asked to pick the safest place in the Pacific Margin from the standpoint of geologic hazards from tsunamis, San Diego County would be a top contender. Of the five greatest tsunamis occurring in this century, not one of them produced effects readily apparent even to a skilled observer walking along the seacoast (Table 1). The greatest single excursion of sea level (1.0 m) was recorded at La Jolla for the tsunami of May 22, 1960, which was produced by the largest earthquake ever recorded (Richter Magnitude 8.5). The strong alternating currents engendered within San Diego Bay by this same tsunami ripped loose a few hundred feet of rotted wharfage, and caused the Coronado Ferry to discontinue service for several hours for the first time in 80 years of operation.

Table 1. Maximum Recorded Local Tide Gauge Excursions Δh(cm) for Five Major Tsunamis (USC&GS Reports)

	Tsunami Date Source Location	4-1-46 Aleutians	11-2-52 Kamchatka	7-1-57 Aleutians	5-22-60 Chile	3-28-64 Alaska
Δh	San Diego (Broadway Pier)	37	70	46	137	110
Δh	La Jolla (SIO Pier)	43	24	61	100	76

Because the above tsunamis have originated from all representative directions where tectonically active tsunamigenic sources are thought to exist around the Pacific, it is considered unlikely that new surprises may alter present confidence in San Diego's immunity from tsunami damage. The physical reasons underlying this confidence are, however, more associative than theoretical.

(1) It has long been recognized that major tsunamis originate from vertical dislocations of large crustal blocks (10^5 km^2) by a meter or so, and that such dislocations are primarily confined to the Pacific trench system and have

recurrence intervals of several hundreds of years.

(2) Recent numerical calculations of the resulting patterns of water waves suggest that most large tsunamis are very similar in deep water, and that their local intensity depends mainly on source orientation, distance, and angle of approach to a remote point.

(3) Nature has providentially arranged matters so that waves from currently active foci approach southern California from nearly glancing incidence; further protection is afforded by wave transformation and/or reflection at the margin of our broad coastal shelf.

Thus, calculations of regional effects serve only to confirm historical precedent as regards remotely generated tsunamis.

As regards local generation, the prognosis is similarly optimistic, but for different reasons.

(1) Relative motion of the Pacific crustal plate, vis-a-vis the continental plate off California, is principally horizontal. Hence, local earthquakes along the San Andreas fault system are prone to strike-slip motions. This circumstance is the strongest argument against the occurrence of a major tsunamigenic earthquake in this sector of the Pacific.

(2) Relatively minor local tsunamis have been produced by small earthquakes on the continental shelf north of Point Fermin, and there is at least a verbal description of a three-foot wave in San Diego Bay associated with the earthquake of May 27, 1862, the only positive evidence for significant thrusting of any magnitude is the possible connection of an offshore escarpment with the Agua Blanca fault (Legg and Kennedy, this volume).

(3) Given the dimensions of the above fault zone, one could assume a maximum credible areal dislocation, and use present numerical methods to estimate the magnitude of shoreline effects along the San Diego coastline.

So far, this has not been done. Thus, one can conjecture that (1) it would be highly unlikely that a destructive tsunami could be produced by any reasonable dislocation (1 m) along this fault zone, and (2) that the most likely result would be minor flooding of the low-lying areas in Imperial Beach and Mission Beach, if it happened to coincide with a high tide.

TSUNAMI HISTORY OF SAN DIEGO

by

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The purpose of this paper is to list the available records of tsunamis at San Diego. For remote tsunamis the historical record is quite extensive; for local tsunamis data are essentially nonexistent.

A remote tsunami is one observed more than a few wavelengths from its point of generation. Large runup from remote tsunamis usually occurs when the offshore topography concentrates the tsunami energy. This does not seem to have happened at San Diego. Tide gauge records for San Diego bay extend from 1854 to 1872 and from 1906 to the present. In the 92 years of record, at least 19 tsunamis have been recorded. Most have been only a few tenths of a meter in height; for comparison, the diurnal range of tide at San Diego is 1.7 meters. The largest one was caused by the Chilean earthquake of May 1960. In San Diego it had a maximum range (peak-to-trough) of 1.5 meters, and produced strong currents which caused some damage to piers and which temporarily halted ferry service to Coronado.

In its recorded history (since the late 1700's) San Diego has experienced only one tsunami caused by a local earthquake. It was associated with the earthquake of May 27, 1862, which caused the most intense shaking known for San Diego (Legg and Agnew, this volume). Because the tide gauge was being repaired at the time, there is no quantitative record of the event, but an eyewitness account by the tidal observer, Andrew Cassidy, has been preserved*. At the time of the

*In a memorandum dated May 27, 1862, pasted on page 711 of the "Emigrant Notes" compiled by Benjamin Hayes (manuscript CE 62, Bancroft Library, Berkeley).

earthquake Cassidy was on the beach at La Playa, about 2 kilometers north of Ballast Point, on the east side of Point Loma. He wrote that, "The water in the Bay did not appear to be much agitated notwithstanding the sea run up on the beach between 3 and 4 feet, and immediately returned to its usual level." The value of 3 to 4 feet probably refers to the horizontal distance along the beach; the wave height would have been much less. Cassidy also noted falls of earth in the banks between La Playa and Point Loma. If one of these were large enough it might have caused a single wave in San Diego Bay similar to, but much smaller than, that caused by a rockslide in Lituya Bay, Alaska, in 1958 (Miller, 1960). In light of this possibility it would be premature to use this observation to conclude that tsunamigenic earthquakes can occur near San Diego. Such a conclusion, and any estimates of risk from local tsunamis, would have to come from a combined study of earthquake recurrence rates and types of faulting in the offshore area, together with model studies of tsunami generation, propagation, and runup. All the historical evidence shows is that damaging local tsunamis have not occurred at San Diego in the last two centuries.

The following list, which is based on that of Joy (1968), is limited to those tsunamis for which there is some evidence of a record at San Diego. For each date, the list gives the location and magnitude of the causative earthquake, followed by the size of the tsunami at tide gauges near San Diego. Where possible, earthquake magnitudes have been given according to the M_w scale introduced by Kanamori (1977). Three terms have been used to specify tsunami size. "Range" is the maximum value from peak to trough, also called "maximum rise or fall". "Height" (taken from Iida _et al_, 1967) is the maximum positive departure from normal sea level. "Amplitude" is used when the definition of size in the original source is unclear. Though it is tempting to estimate a period for a tsunami record, it may not be too meaningful. Detailed analysis of the 1960 tsunami as recorded at La Jolla showed a broad spectrum (Miller _et al_, 1962). Tsunami records from San Diego harbor give the general impression that the predominate periods are in the range of one-half to one hour.

Unless otherwise specified, the sources of information for this list are as follows. Earthquake locations before 1900 are from Iida _et_ al (1967); from 1900 to 1954 locations are from Gutenberg and Richter (1954), and M_s magnitudes are from Geller and Kanamori (1977) and Geller et al (1978); after 1954 locations and M_s magnitudes are from epicenter lists published by the U. S. Coast and Geodetic Survey and its successor agencies. M_w magnitudes are either from Kanamori (1977) or have been computed from moment estimates. Tsunami information is from Iida et al (1967). Other references are given in the individual listings.

TSUNAMIS AT SAN DIEGO
1854-1975

1854 July 24. No source is known, but the tidal observer at San Diego noted that on this date, "Water rose & fell nearly a foot in 10 minutes - currents set up also, harbor calm." (Andrew Cassidy, "Miscellaneous Notes on the Tide Gauge & Tidal Observations at San Diego - Cal: 1853-1854". Cassidy Papers, Serra Museum Library, San Diego).

1854 December 23. Japan, 34° N, 138° E. Range 0.1 m at San Diego (Bache 1855).

1856 August 23. Japan, 42° N, 141° E. Recorded on the coast of California (Joy, 1968).

1862 May 27. Earthquake at San Diego caused a small tsunami in San Diego Bay. See text for details.

1868 April 2. Hawaii, 19.3° N, 155.3° W (Wood, 1914). Height 0.1 m at San Diego.

1868 August 13. Chile, 18.5° S, 71° W. Amplitude 0.8 m at San Diego (Hilgard, 1869).

1872 August 23. Davidson (1872) said that on this date a tsunami was recorded at San Diego, San Francisco, and Astoria. He used relative arrival times to infer a source in the northwest Pacific.

1906 January 31. Off the coast of Ecuador, 1° N, 81.5° W. $M_w = 8.8$. Recorded at San Diego.

1917 May 2. Kermadec Islands, 29° S, 177° W. $M_s = 7.9$. Recorded on the west coast of the U. S. (Heck, 1947).

1917 June 25. Tonga, 15.5° S, 173° W. M_s = 8.4. Recorded on the west coast of the U. S. (Heck, 1947).

1919 April 30. Tonga, 19° S, 172.5° W. M_s = 8.2. Recorded in California (Heck, 1947).

1922 November 10. Central Chile, 28.5° S, 70° W. M_w = 8.5. Height 0.2 m at San Diego.

1923 February 4. East coast of Kamchatka, 54° N, 161° E. M_w = 8.3. Height 0.2 m at San Diego.

1923 April 14. East coast of Kamchatka, 56.5° N, 162.5° E. M = 7.2 (Gutenberg and Richter, 1954). Height 0.1 m at San Diego.

1927 November 4. Off Point Arguello, California, 34.5° N, 121° W. M_w = 7.3 (Hanks et al, 1975). Range 0.006 m at La Jolla (Byerly, 1930).

1933 March 2. East of Honshu, 39.2° N, 144.5° E. M_w = 8.4. Height less than 0.1 m at La Jolla.

1944 December 7. Near Honshu, 33.7° N, 136° E. M_w = 8.1. Height 0.1 m at San Diego.

1946 April 1. Southern Alaska, 52.75° N, 163.5° W. M_w = 8.4 (Kanamori, 1972). Range 0.43 m at La Jolla, 0.37 m at San Diego (Green, 1946; Symons and Zetler, 1960).

1952 March 4. Hokkaido, Japan, 42.5° N, 143° E. M_w = 8.1. Range 0.02 m at La Jolla (Munk, 1953).

1952 November 5. Off east coast of Kamchatka, 52.7° N, 159.5° E. M_w = 9.0. Range 0.24 m at La Jolla, 0.7 m at San Diego (Zerbe, 1953).

1957 March 9. Rat Islands, 51.3° N, 175.8° W. M_w = 9.1. Range 0.6 m at La Jolla, 0.45 m at San Diego (Salsman, 1959).

1960 May 22. Coast of central Chile, 39.5° S, 74.5° W. M_w = 9.5. Range 1 m at La Jolla, 1.5 m at San Diego (Symons and Zetler, 1960; Miller et al, 1962). Some damage to piers and moorings in San Diego Bay.

1964 March 27. Southern Alaska, 61° N, 147.8° W. M_w = 9.2. Range 0.7 m at La Jolla, 1.1 m at San Diego (Spaeth and Berkman, 1964).

1968 May 15. East of Honshu, 29.9° N, 129.4° E. M_w = 8.2. Amplitude 0.1 m at La Jolla (Joy, 1968).

1975 November 29. Hawaii, 19.3° N, 155° W. M_s = 7.1. Amplitude 0.3 m at La Jolla, 0.12 m at San Diego, 0.37 m at Imperial Beach (Spaeth, 1976).

Acknowledgements. I should like to thank B. D. Zetler for help and comments.

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EARTHQUAKE HISTORY OF SAN DIEGO

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The San Diego area is sometimes taken to be relatively safe seismically, at least compared with other major population centers in California. Instrumental records since 1931 show the San Diego area to be relatively free from earthquakes, but this is a very short time on which to base a seismicity estimate. Our purpose here is to give a more complete picture of the local seismicity, by presenting a partial listing of earthquakes felt in the San Diego area in the last 180 years.

Though we have made no explicit division, different classes of earthquake are included for different periods. Before 1900, we have included every earthquake reported as felt within the present boundaries of San Diego County. Most of these were small and unimportant, and have been included only for completeness. Although 1900 is a somewhat arbitrary cutoff, after this date the existing lists are much more complete. Between 1900 and 1931 we have included only those earthquakes for which shaking of intensity VI or above (on the Modified Mercalli scale) was reported within the county. More extensive lists for this period are those of Toppozada, et al (1978) and Townley and Allen (1939); the latter has been ably indexed by Clark (1944). After 1931 instrumental locations are available in Hileman, et al (1973) and additions to it issued by the California Institute of Technology. For the immediate San

Diego area Simons (1977 and this volume) should be consulted instead. Intensity data from 1928 to the present are available in the annual publication United States Earthquakes, published by the U. S. Department of Commerce. There seems little point in republishing this information, and we have therefore limited our list to earthquakes that caused shaking of intensity VI in the metropolitan San Diego area.

Because of the imperfect nature of the historical record this catalog is also incomplete before 1900, but for earthquakes of damaging intensity at San Diego it is probably complete from 1850 on. The record from the Spanish and Mexican periods is very scanty, though from about 1780 to 1830 some mission records are available. In 1850 a U. S. Army post was established at San Diego. Daily weather records kept there sometimes report earthquakes. In 1851 a weekly newspaper, the San Diego Herald, began publication, which continued until 1859 (Dawson, 1950). Though the files of this newspaper are not complete, they still provide a valuable record. The San Diego Union began publication in 1869 and is still in existence. There is a good index to both of these newspapers in the San Diego Public Library. The lack of a local newspaper in the 1860's is to some extent remedied by the notes compiled by Judge Benjamin Hayes in about 1870, and now in the Bancroft Library. For the years from 1870 to 1900 our most important sources have been the San Diego Union and the catalog of Townley and Allen (1939), which for this period is mostly based on that of Holden (1898). This in turn drew on a variety of sources; an important one was the reports of weather station observers at such places as Campo.

Few of the earthquakes listed here caused any damage. Usually the only description of them is as being "light", "heavy", "severe", or some similar adjective. Because the use of these terms does not seem to correlate very well with intensity, we have not given an intensity unless other information was available. A mention of a place means that the earthquake was felt at that place. If no location is given, the earthquake was reported from San Diego only. The times given are taken from the reports, and so are either local or Pacific Standard (and in any case not very accurate). The times for earthquakes for which epicentral coordinates are given are the origin times, again Pacific Standard. These coordinates and times, and the local magnitudes, are from

Richter (1958) and Hileman, _et al_ (1973). The times are to the nearest minute, and coordinates to the nearest tenth of a degree.

During the time covered by this catalog, San Diego has suffered from several damaging earthquakes, but none have been very destructive. The earthquakes that have caused the strongest shaking before 1900 were those in 1800, April 1852, September 1856, May 1862, February 1892, and October 1894. The first two are inadequately documented. Of all the earthquakes in this list, the one in 1862 seems to have produced the strongest shaking, of about intensity VI-VII in San Diego (Legg and Agnew, this volume). The pre-1900 part of this list also includes at least three large earthquakes that clearly were located in the Salton Trough: November 1852, November 1875, and July 1891. In the last 50 years the strongest shaking in San Diego has come from earthquakes along the San Jacinto fault zone or in northern Baja California.

CATALOG OF SAN DIEGO EARTHQUAKES

Abbreviations used for references cited often in the catalog are given here. All newspapers are cited according to month, day, and year, followed by page and column number.

CMS - MS recollections of Herbert L. Crouch, Serra Museum Library, San Diego.

CR - Climatological Records of the Weather Bureau, Record Group 27, U. S. National Archives. (Microfilm number T907. If no name is given, the records are those for San Diego or New San Diego).

GD - Extracts from the diaries of Dr. Hiram W. Gould, Serra Museum Library, San Diego.

H - Holden (1898).

HEN - Benjamin Hayes, "Emigrant Notes", Bancroft Library CE 62, Berkeley. (The pagination used in the references is that added after the MS was written).

McD - Extracts from the diaries of Dr. George McKinstry, Serra Museum Library, San Diego.

PD - Extracts from the diaries of Theron Parsons, Serra Museum Library, San Diego.

R78 - Rockwood (1878).

SD - Extracts from the diaries of Mrs. Theodore Steinmeyer, Serra Museum Library, San Diego.

SDH - San Diego Herald.

SDU - San Diego Union.

SFAC - San Francisco Alta California.

TA - Townley and Allen (1939).

USEQ - United States Earthquakes (Annual publication of the Coast and Geodetic Survey).

1800 November 22. 1:30 P.M. At San Juan Capistrano, threw down walls of mission church (then under construction). At San Diego, several buildings considerably cracked (VI?). - Bancroft (1888), v. 1, p. 654, 659; Engelhardt (1920), p. 154.

1803 May 25. San Diego, mission church slightly damaged. - Bancroft (1888), v. 2, p. 106.

1812 December 8. Mission church at San Juan Capistrano destroyed. No evidence of damage at San Diego, or even that the earthquake was felt. - Bancroft (1888), v. 2, pp. 200-201.

1843 June 23. Coast of California - H.

1849 August 16. At night, at Palm Spring oasis, 11 km SE of Vallecito. - Bloom (1945).

1849 September 16. Santa Ysabel, felt by few. - Whipple (1850).

1849 September 22. South of Carrizo Creek, felt by few. - Whipple (1849), Couts (1932).

1850 August 4. San Diego and the Gila River.- H.

1850 August 15. San Diego and the Gila River. - H.

1852 April 12. Midnight. "Very severe", duration 30 seconds, an adobe house "destroyed". - SDH, 4/17/52, 2:1. (Intensity possibly VII, but it is odd that no other damage is mentioned.)

1852 November 29. About noon. A large earthquake, probably in the region of the Colorado River delta. Intensity about V at San Diego. - Balderman, et al (1978); Agnew (1978).

1852 November 30. 8 A.M. Aftershock of the above, felt in San Diego. - CR.

1853 June 26. 8:30 A.M. - CR.

1856 September 20. 11:25 P.M. At San Diego windows rattled, small objects upset (V). At Santa Ysabel and San Felipe trees shaken severely, some cracking of adobe walls (VI-VII). Felt at El Cajon, Vallecito. Not felt at Yuma. - CR; SDH 9/27/56, 2:3; HEN, pp. 889-900.

1857 January 9. 8:30 A.M. The great Fort Tejon earthquake, felt in San Diego with intensity V. - Agnew and Sieh (1978).

1859 January 26. 11 P.M. - McD 1/27/59.

1859 March 21. 6 A.M. Buildings creaked (IV-V?). Several more felt that day. - McD 1/21/59; SDH 3/26/59, 2:4.

1859 March 25. Severe, with ground cracking near Ballena. - McD 3/25/59. (Possibly the same as the next shock).

1859 March 26. 2 P.M., sensibly felt. - SDH 4/2/59, 2:4. Possibly also at Mesa Grande. - McD 3/26/59.

1859 March 30. 10 A. M., slight. - McD 3/30/59.

1859 August 2. 10 A.M. - McD 8/2/59.

1860 January 14. 7:23 P.M., "violent", lasted about 10 sec. - CR; Meteorological Journal of Andrew Cassidy (Cassidy Papers, Serra Museum Library).

1860 August 2. 5 A.M., Mesa Grande. - McD 8/2/60.

1860 August 15. 1:30 & 4:30. - McD 8/15/60. (Mesa Grande?).

1862 April 15. Carrizo Creek stage station, all frightened. - Los Angeles Semi-Weekly Southern News 4/23/62.

1862 May 27. About noon. In San Diego, objects upset, buildings cracked, cracks formed in wet ground (VI-VII). At Temecula and Aguanga plates rattled and objects upset (V). Generally felt throughout San Diego County, from the ocean to the desert. Felt at Anaheim and Los Angeles. Not felt at Yuma. - Legg and Agnew (this volume).

1862 May 28. Several, "slight". - CR.

1862 May 29. 10 A.M. "Violent" at San Diego. Felt San Ysidro and Anaheim. - CR; HEN, p. 691.

1862 May 30. 3 A.M. - HEN, p. 691. 3 P.M. - CR

1862 May 31. 1-2 P.M. Temecula and San Diego. - CR; HEN, p.691.

1862 June 1. 11 A.M. - CR.

1862 June 2. In the night. - CR.

1862 June 3. 4 A.M. - CR.

1862 June 4 & 5. "Light shocks at San Diego". - HEN, p. 691.

1862 June 6. Midnight. - HEN, p. 691.

1862 June 7. 5 P.M. - CR; HEN, p. 691.

1862 June 8. 5 A.M. - CR.

1862 June 13. 10:30 A.M. "Violent" at San Diego. Another about 2 P.M. - CR; HEN p. 697.

1862 June 14. 2 P.M., 10 P.M. - CR; HEN, p. 697.

1862 June 15. 9:50 P.M. - CR.

1862 June 19. Noon. - CR.

1862 June 27. 10 P.M. "Violent". - CR.

1862 July 11. 9:27 P.M. - CR.

1862 August 18. 2 A.M. - CR.

1862 October 21. 6 A.M. Many frightened and ran outdoors, no "serious damage" (V?) - Clipping from SFAC, pasted on p. 562 of HEN.

1863 January 25. 2:20 P.M. No damage, many frightened (IV?) - SFAC, 2/11/62, 1:8.

1863 about June 25. 1:11. Lasted 30-40 seconds, buildings creaked, no damage (IV). - SFAC 7/7/63, 1:5.

1865 April 15. 12:39 A.M. Many awakened, liquids splashed. - CR; SFAC 4/26/65, 1:6.

1867 February 1. 6:45 A.M. - SFAC 2/18/67, 1:6.

1869 October 21. At New River stage station (near Mexicali), many alarmed. - San Diego Weekly Bulletin 11/6/69, 2:2.

1869 October 30. "Severe" in the desert, 100 km east of San Diego. - SDU 11/4/69, 2:1.

1871 October 27. 10 P.M., Temecula and San Juan Rancho. - McD; SDU 11/14/71, 2:2.

1872 March 26. 2:46 A.M. The Owens Valley earthquake, marginally felt in San Diego (intensity II-III). - SDU 4/2/72, 3:3.

1873 March 23. 3 A.M. Cholla Valley (now southeast San Diego). - SDU 3/25/73, 3:1.

1873 October 12. 1:15 A.M. - H.

1875 November 15. 2:30 P.M. Earthquake probably centered in the Imperial Valley or Colorado River delta. Destroyed adobe buildings at Indian Wells and Gardner's Wells, near Mexicali (VIII), at Campo upset furniture and threw dishes off the shelves (VI), at San Diego frightened some and stopped clocks whose pendulums swung EW (IV). Also felt at Yuma and Maricopa Wells, Arizona. Six more shocks were felt at Campo in the next 2 days. - SDU 11/16/75, 3:2; 11/19/75, 3:2 & 3:1.

1877 January 13. Noon, 70 km southeast of San Diego. - R78.

1877 August 17. 7:30 P.M., Campo and Agua Caliente. - CMS, R78.

1877 September 4. Agua Caliente. - CMS.

1877 September 29. 2:30 P.M. Campo and Agua Caliente. - CMS, R78.

1877 October 23. Agua Caliente? - CMS.

1877 November 30. San Luis Rey? - CMS.

1878 July 2. About 6 P.M. Two shocks felt in the mountains east of San Diego, in some places strong enough to break crockery and upset things (V). - SDU 7/9/78, 1:3.

1878 December 17. 4 P.M. Campo and Yuma. - H.; Fort Yuma CR.

1880 August 29. 1:10 P.M. - SDU 8/31/80.

1880 December 19. 3:40 P.M. Felt by some in San Diego, and noticed along the coast to Los Angeles. - SDU 12/23/80, 4:4; 12/24/80, 4:3.

1880 December 21. 11 P.M. San Diego and Campo. - SDU 12/23/80, 4:4; 12/25/80, 4:3.

1880 December 22. 3:22 A.M. Campo, all awakened (V?). - SDU 12/25/80, 4:3.

1881 January 7. 6:15 A.M. Campo, slight. - H.

1881 February 15. 6:20 A.M. "Light". - GD.

1881 June 30. 8 A.M. Campo, sharp. - H.

1881 October 2. 9 A.M. Campo, sharp. - H.

1882 February 1. 3 o'clock. Warner's ranch. - SDU 2/11/82, 3:1.

1882 March 11. 4 P.M. Poway, slight at San Diego. - H.; SDU 3/12/82, 3:1.

1882 September 30. 11 A.M. Campo and Warner's ranch. - H.; SDU 10/11/82, 3:1.

1882 October 8. 2 A.M. "Very heavy" at Warner's ranch. In San Diego, windows and crockery rattled (IV); another felt at 5:30 A.M. Felt at Spring Valley, National City. - SDU 10/11/82, 3:1, 3:2; GD; diary of F. A. Kimball, National City Public Library.

1883 February 6. 4:30 P.M., slight. - H.

1883 March 11. 11 A.M. Campo and Tijuana. - SDU 3/13/83, 3:1.

1883 April 4. 1:30 A.M. Warner's ranch. - SDU 4/7/83, 3:1.

1883 November 11. 6:15 P.M. Poway, slight. - H.

1883 December 16. 3 P.M. Poway, slight. - H.

1884 July 24. 4:20 P.M. Pala. - SDU 7/27/84, 3:1.

1884 August 26. 11 P.M. "Severe" at Jacumba, still stronger south of the border. - SDU 9/3/84, 3:2.

1885 April 1. 3 A.M. Agua Caliente. - SDU 4/3/85, 3:2.

1885 August 19. 1 P.M., not felt by all. - SDU 8/20/85, 3:1.

1885 September 5. 1 P.M. - CR.

1885 September 13. 4:30 A.M. Many awakened (V). Felt in Los Angeles and San Bernardino. - SDU 9/15/85, 3:1; GD; H.

1885 December 1. 1:40 A.M., light. - SDU 12/2/85, 3:1.

1886 September 29. 11:05 A.M., felt by few. - SDU 9/30/86, 3:2.

1886 October 8. 3:30 A.M., 4 A.M. Many awakened (V). - SDU 10/9/86, 3:1; GD.

1886 December 4. 2:40 A.M. Rattled windows and doors (IV). - SDU 12/4/86, 3:1; GD.

1887 April 29? 3:30 A.M. Campo, rattled dishes (IV). 4 A.M. National City. - SDU 5/4/87, 4:2; PD. (The date of the Campo shock is uncertain; we have assumed that it coincided with that reported from National City).

1887 June 28. 11 P.M., some frightened. - SDU 6/30/87, 5:1.

1887 August 24. 6 A.M., light. - SDU 8/25/87, 3:3.

1888 March 7. 7:54 A.M. Earthquake centered near Pasadena, intensity II in San Diego. - H.

1888 August 19. Morning, National City. - PD.

1888 October 4. 11 P.M. - H.

1889 February 6. 9 A.M., National City. - PD. (Possibly an error for the shock of 9:20 P.M., felt strongly in San Bernardino.)

1889 June 25. Midnight. - H.

1890 February 5. 10:15 P.M. In San Diego and National City, many awakened, crockery rattled, no damage (V). - SDU 2/6/90, 4:1 & 5:1; PD.

1890 February 9. 4:06 A. M. Earthquake probably in the San Jacinto mountains, felt in San Diego, Lawson Valley, and National City. - SDU 2/18/90, 4:3; PD; SD; H.

1890 February 21. Lawson Valley. - SD.

1890 April 3. Evening. Several light shocks at Tijuana. - SDU 4/4/90, 6:2.

1890 June 10. 3 P.M. Buildings creaked, felt by many, lamps swayed. Also Coronado, National City. - SDU 6/11/90, 6:2 & 8:4; PD.

1890 September 22. 8:05 P.M. Chandeliers swung, rattled glass (IV?). Also El Cajon, National City. - SDU 9/23/90, 8:2; PD.

1890 late November. Two shocks felt "last week" at Campo. - SDU 12/8/90, 5:2.

1891 January 5. 8:25 P.M. Some awakened in National City. Also San Diego, Linda Vista. - PD; SDU 1/8/91, 5:2.

1891 January 6. 4:55 P.M. - SDU 1/8/91, 5:2.

1891 January 13. 3 A.M., few awakened. - SDU 1/14/91, 5:1.

1891 March 17. 7:45. At Campo, strong, no damage. Slight at National City. - SDU 3/23/91, 8:1; PD.

1891 July 30. 6:10 A.M. Earthquake probably centered in the Colorado River delta. In San Diego, clocks stopped, china rattled, furniture moved, many awakened (V). - SDU 7/31/91, 5:3. Also National City. - PD. In Ensenada, many awakened, no damage. - Ensenada Lower Californian 7/31/91, 1:2. In Yuma, all frightened and ran outdoors, clocks stopped, windows and crockery rattled, houses creaked, some adobe cracked (VI). - Yuma Arizona Sentinel 8/1/91, 3:4. At Colonia Lerdo, men thrown down, buildings collapsed, ground cracked (VIII). - Yuma Arizona Sentinel 8/8/91, 3:3; San Francisco Examiner 8/13/91, 3:5. (This earthquake seems to have inspired a great many sensationalized newspaper accounts, and it is difficult to make out just what did happen.)

1892 February 20. 9:15 A.M. "Sharp" at Julian. - Elsinore Press 2/27/92, 1:3.

1892 February 23. 11:20 P.M. One of the largest earthquakes to have produced strong shaking in the San Diego area. It was felt from San Quintin (Baja California) to Visalia and Santa Barbara (II-III), and as far east as Needles and Yuma. In San Diego, many were awakened and ran outdoors, clocks stopped, crockery was upset, and much plaster was cracked though little fell (VI). In Paradise Valley, two buildings on stilts collapsed; at Jamul, a stone kiln was cracked; at Julian, some light objects were upset; at Campo, some adobe walls were cracked but goods were not thrown off shelves; at the Carrizo stage station adobe buildings were damaged. There are reports of landslides or falling rocks from Campo, Dulzura, Inkopah, and other places in the mountains east of San Diego. In Escondido, some objects were overturned and goods thrown off shelves (V). The shock was "severe" but apparently caused no damage in Ensenada. The intensity seems to have been IV-V throughout the Los Angeles area; reports from Anaheim, Santa Ana, Los Angeles, Pasadena, San Bernardino, Ontario, Redlands, and Riverside all say that many were awakened and ran outside, that some clocks were stopped, but that there was little or no damage. Many accounts from San Diego and places nearby mention a very large number of aftershocks, over 100 in the first day; shocks were still being felt in the mountains east of San Diego as late as May. We have listed only the more important of these. [This earthquake and its aftershocks are the subject of a forthcoming Master's thesis by Carl Strand, which will contain full references.]

1892 February 24. 5 A.M. At Campo caused an adobe wall to collapse and goods to fall off shelves. Also felt at Rancho Bernardo, and possibly Julian, though the time there is given as 6:30. - SDU 2/25/92, 5:2; 2/29/92, 5:2; San Diego <u>Sun</u> 2/25/92, 5:3.

1892 February 24. 9:30 P.M. Julian, Rancho Bernardo, Ontario, Santa Ana, Los Angeles.

1892 February 25. 2 A.M. San Diego, Julian, Beaumont, Ontario, Santa Ana, Los Angeles.

1892 March 1. 3:20 P.M. Ensenada, San Diego, Campo, San Bernardino. - Ensenada <u>Lower Californian</u> 3/4/92, 1:1; San Diego <u>Sun</u> 3/1/92, 5:2; 3/2/92, 5:2; <u>Monthly Bull. Cal. Weather Service</u> vol. 1, no. 7, p. 136.

1892 March 22. 9:10 A.M. "Light" at San Diego, National City. - SDU 3/23/92, 5:1; PD.

1892 March 23. 7:50 A.M. National City - PD.

1892 April 5. 4:45 A.M. Campo, strong. - SDU 4/7/92, 5:2.

1892 April 19. Morning. Ensenada. - Ensenada <u>Lower Californian</u> 4/22/92, 1:1.

1892 April 25. San Diego. - El Cajon <u>Valley News</u> 4/30/92, 2:2.

1892 May 28. 3:20 A.M. Felt in Spring Valley, strongest in San Bernardino. - El Cajon <u>Valley News</u> 4/30/92, 2:2; H.

1892 June 14. 5:25 A.M. Felt in San Diego, strongest in San Bernardino and Riverside. - H.

1893 April 4. 11:40 A.M. Newhall earthquake, intensity II in San Diego. - H.

1893 May 18. 4:35 P.M. Earthquake centered near Ventura, felt as far south as San Diego. - TA.

1893 August 9. 11:02 A.M., 4:07 P.M. - H.

1894 July 29. 9:12 A.M. Earthquake centered near Mojave, felt in Escondido. - TA; SDU 7/30/94, 5:4.

1894 October 23. 3:03 P.M. In San Diego, people frightened and ran outside, buildings creaked, some cracks and fallen plaster (VI). At Otay and Buckman Springs, rocks fell off hillsides (VI+?). - SDU

10/24/94, 5:4; San Diego Sun 10/23/94, 5:4. In National City, all frightened and ran out, no damage reported. - National City Record 10/25/94, 3:1. In San Juan Capistrano, clocks stopped, windows broken, crockery overturned (VI). No damage at Oceanside. In Santa Ana, people frightened and ran outside. - SDU 10/24/94, 1:5. Felt strongly at Escondido and Valley Center. - Escondido Times 10/25/94, 3:2; 11/1/94, 3:4. Also felt at Coronado, Campo, Los Angeles, Riverside, San Bernardino, Needles, Ensenada. - SDU 10/24/94, 5:4; 10/28/94, 5:2; Riverside Daily Press 10/23/94, 3:2; Needles Eye 10/23/94, 2:1; Ensenada Lower Californian 11/2/94, 2; TA. Most aftershocks felt in the mountains east of San Diego. - SDU 10/30/94, 5:4. The exact location of the epicenter of this earthquake is unclear; it seems to have been in the Peninsular Ranges, probably near the Mexican border.

1894 October 26. 5 A.M. "Strong" in Lakeside and Alpine, felt in Ensenada. - SDU 10/28/94, 5:2; Ensenada Lower Californian 11/2/94, 1.

1894 October 27. 11 P.M. In San Diego, windows rattled and lamps swung (IV). Felt in Los Angeles, and strongly to the east of San Diego. - SDU 10/28/94, 5:4; 10/30/94, 5:4.

1894 November 17 5 P.M. Campo. - H.

1894 November 19. 10 A.M. Felt on upper stories in San Diego (II). Also Julian, Rancho Bernardo. - SDU 11/20/94, 5:4; H.; Escondido Times, 11/22/94, 3:2.

1895 September 18. 8:25 P.M. Campo, sharp. - SDU 9/23/95, 5:1.

1896 April 12. Jamul, light. - SDU 5/1/96, 2:2.

1896 July 3. 9:27 P.M. - H.

1896 September 30. Descanso. - H.

1897 February 16. Descanso. - TA.

1897 February 25. Descanso. - TA.

1897 May 15. About 4 A.M. - TA.

1897 May 22. 6:55 A.M. "Very distinct". - SDU 5/23/97, 5:1.

1897 September 6. Descanso. - TA.

1897 October 27. 9:07 A.M. "Slight" in San Diego. Also Morena Dam, Campo. - SDU 10/28/97, 5:1.

1897 November 12. Descanso. - TA.

1897 November 22. Descanso, Escondido, Fallbrook. - TA.

1898 March 3. 2:30 A.M. Descanso, light. - TA.

1898 April 21. Descanso. - TA.

1898 June 23. 1:44 P.M. Descanso. - TA.

1898 June 24. 2:45 P.M. Descanso. - TA.

1899 April 14. Cuyamaca. - TA.

1899 June 1. Morena Dam. - TA.

1899 July 21. 4:45 P.M., no damage. - SDU 7/22/99, 6:2.

1899 July 22. 12:32 P.M. Cajon Pass earthquake, "quite strong" in San Diego, but no damage (IV). - TA; SDU 7/23/99, 7:4.

1899 July 27. Campo, heavy. - SDU 8/3/99, 7:1.

1899 August 21. - SDU 8/22/99, 6:2.

1899 October 28. Morena Dam. - TA.

1899 December 25. 4:25 A.M. San Jacinto earthquake. In San Diego, many awakened and ran outdoors, clocks stopped, some glass broken (V). - SDU 12/26/99.

1915 November 20. 4:15 P.M. Near Cerro Prieto, Baja California (32° N, 115° W, M_L = 7.1) Intensity V-VI in the San Diego area. - TA.

1918 April 21. 2:32 P.M. Near San Jacinto (33.75° N, 117° W, M_L = 6.8). In San Diego, many frightened, some clocks stopped, a few small objects upset (V). Intensities V-VI in San Diego County, largest in the northeast. - SDU 4/22/18, 2:5-6; Townley (1918).

1919 December 31. 6:35 P.M. At Warner Springs, adobe walls cracked (VI). Felt strongly (intensity about IV) in San Diego, El Cajon, Julian, Elsinore, Hemet, Corona. - TA.

1920 October 5. 9:48 A.M. At Warner Springs, trees shaken, all frightened and ran outdoors (VI). Also Aguanga, Hemet, San Diego. - TA.

1927 August 14. 6:48 A.M. Epicenter near Barrett reservoir. Intensity V+ at Alpine and Jacumba. Felt San Diego, Oceanside. - Carnegie Institution of Washington Yearbook, 27, 419; TA.

1929 December 2. 3:24 A.M. Epicenter near Ensenada. Intensity V+ in San Diego. Also felt Jamul, Escondido. - USEQ.

1934 December 31. 10:45 A.M. Colorado Delta (32° N, 114.8° W, M_L = 7.1). Intensity V-VI throughout San Diego County. In San Diego, some cracks in buildings, fallen plaster, broken windows. Slight damage also reported from Alpine, Coronado, Lemon Grove (V). Intensity IV reported along the coast from Solana Beach north, also Ramona and Escondido. - USEQ.

1942 October 21. 8:22 A.M. Borrego Valley (33° N, 116° W, M_L = 6.5). Maximum acceleration .026 g at San Diego. Intensity VII in Carrizo Gorge. Intensity VI (cracked plaster and broken glass) in Campo, Lakeside, Miramar, San Diego, Santa Ysabel, Warner Springs. Intensity V reported from Aguanga, Anza, Escondido, Mesa Grande, Mount Laguna, Oceanside. Intensity IV reported generally along the coast. - USEQ.

1949 November 4. 12:42 P.M. Northern Baja California (32.2° N, 116.5° W, M_L = 5.7). Maximum acceleration .017 g at San Diego. Intensity V-VI in San Diego, La Jolla, Campo (some plaster cracking, trees and bushes shaken, dishes rattled). - USEQ.

1951 December 25. 4:47 P.M. Near San Clemente Island (32.8° N, 116.3° W, M_L = 5.9). Maximum acceleration .014 g at San Diego. In Del Mar and San Diego, goods fell off shelves, some plaster cracked, trees and bushes shaken (VI). Intensity V reported from Barrett Dam, Mount Laguna, Pala. Intensity IV at Alpine, Campo, El Cajon, Escondido, Jamul, Julian, Leucadia, Oceanside, Santa Ysabel. - USEQ.

1954 March 19. 1:54 A.M. Santa Rosa Mountains (33.3° N, 116.2° W, M_L = 6.2). Maximum acceleration .016 g at San Diego. Intensity VI (some broken glass and cracked plaster) in Boulevard, Jamul, La Jolla, La Mesa, Warner Springs. Intensity V in Aguanga, Campo, Chula Vista, Del Mar, Descanso, El Cajon, Escondido, Julian, Leucadia, Oceanside, Pala, Ramona, San Diego, San Ysidro. - USEQ.

1956 February 9. 6:32 A.M. El Alamo, Baja California (31.7° N, 115.9° W, M_L = 6.8). Maximum acceleration .013 g at San Diego. Intensity VI (cracked plaster reported) in Campo, Chula Vista, El Cajon, Imperial Beach, La Jolla, La Mesa, National City, San Diego, Santee. (In many of these places the damage, though present, was described as "slight"). Intensity V reported from Cardiff, Carlsbad, Del Mar, Escondido, Lake Hodges, Leucadia, Pala, Poway, San Marcos, San Ysidro. - USEQ.

1964 December 22. 12:54 P.M. Northwest of Ensenada (31.8° N, 117.1° W, M_L = 5.6). Maximum acceleration .034 g at San Diego. Intensity VI at Imperial Beach, La Mesa, National City, San Diego. Intensity V at Campo, Chula Vista, El Cajon, La Jolla, San Ysidro. - USEQ.

1968 April 8. 6:29 P.M. Borrego Valley (33.2° N, 116.1° W, M_L = 6.4). Maximum acceleration .029 g at San Diego. Intensity VII in the Borrego Mountain - Ocotillo Wells area. Intensity VI at Alpine, Borrego Springs, Campo, Chula Vista, Del Mar, El Cajon, Encinitas, Escondido, Julian, Lakeside, Leucadia, Ramona, San Diego, San Ysidro. Intensity V in La Jolla. - USEQ.

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THE 1862 EARTHQUAKE IN SAN DIEGO

by

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The earthquake of May 27, 1862, is of special importance in making seismic risk estimates for San Diego. Most earthquakes that have caused damage in San Diego have been located in the Imperial Valley or northern Baja California. Although its location is not completely determinable, the 1862 earthquake seems to have been closer to the San Diego metropolitan area. This earthquake serves as a good example of the fragmentary nature of the historical record of California earthquakes: despite its size, it has received almost no mention in earthquake catalogs. The purpose of this paper is to give a brief description of the earthquake, based on contemporary documents. A list of these is given at the end of the paper; the numbering of that list will be used in the citations.

The main shock occurred at about noon on May 27, 1862. Two accounts (1,2) say that there were two shocks separated by some minutes, the second being the stronger. In San Diego (the present Old Town) this shock stopped clocks and upset bottles and tumblers (1,2,4,6) so that "many sets of crockery were demolished" (2). The bell at the Army depot was set ringing (2). Understandably enough, all the people ran outside in fright (1,2,4), and many slept outside because they feared further earthquakes (1,7). There apparently were no injuries, and no buildings were destroyed. However, many of the accounts (1,2,4) mention damage to buildings, primarily cracking; it should be remembered that in 1862 most buildings in San Diego were either adobe or poor masonry. The newspaper reports say that "various adobe houses" (4) were "cracked through and through". Some specific examples were the Pico adobe, which sustained several cracks, one passing through the wall; the Bandini adobe; and the 2-story Fitch adobe, which was "much sprung on its side wall" (1). Of masonry buildings, the Whaley house cracked in several places, and the lighthouse tower suffered several cracks, one going through the wall (1,4). However, the light was not thrown out of adjustment, nor was any glass broken (1). Some frame buildings were racked so that windows and doors were loosened in their frames (1), and windows and door hinges were broken. Several accounts (1,2,4) mention cracks in low ground near the San Diego River, which washed over its banks (1,4). At La Playa (on Point Loma), cracks formed on the beach, water came out of the sand on the tidal flats, and a piling that had just been driven into the mud was shaken loose. Some bluff banks on the east side of Point Loma collapsed (1, p. 711, 4).

This shock was felt in Los Angeles, where it was termed "light" (5) and in Anaheim (1). At Temecula and Aguanga it rattled plates on the shelves; at Aguanga it also caused a pile of sacks to fall over (1). At Mesa Grande it seemed to last about 10 seconds, and caused the building roof to creak (1). It was also felt at Lake Henshaw, El Cajon, Carlsbad, Rincon del Diablo, Vallecito, San Luis Rey, San Dieguito, San Felipe, and the Cuyamacas (1,4). It was not felt at Fort Yuma (4).

There are two lists of aftershocks (1,6). These show that earthquakes were felt every day at San Diego up to June 8, 12 days after the first shock, and relatively frequently for the rest of June (see Agnew et al., this volume). An aftershock at 10 a.m. on May 29 was described as "violent" at San Diego (6), and was felt at San Ysidro and Anaheim (1). One in the afternoon of May 31 was felt at San Diego (6) and Temecula (1). A relatively large aftershock occurred at 10:30 a.m. on June 13; it was strong at San Diego (1,6) and also felt at Penasquitos (1), but was not generally felt in Los Angeles or San Bernardino (1).

Based on the descriptions given here, we estimate that this earthquake caused shaking in San Diego of about intensity VI to VII on the Modified Mercalli scale. The upsetting of small objects and the extent of building damage (cracking but no serious damage) both suggest intensity VI, although the damage seems to have been greater than that associated with intensity VI shaking from more recent earthquakes, such as the 1968 Borrego Mountain event. Ground cracking is usually associated with intensity VIII, but this is certainly too high, judging by the effects on buildings. It is possible that this reflects higher intensity on marshy ground. There is not enough information to estimate intensities elsewhere, except that they were lower, possibly IV-V, in the Temecula-Aguanga area, and lower still in Los Angeles.

The distribution of intensities suggests that San Diego was closer to the epicenter than any other place for which we have reports. This seems to be confirmed by the aftershock records, though there is an obvious bias because San Diego is the only place for which there is a continuous record. That the earthquake was not felt at Fort Yuma would seem to rule out a source in the Imperial Valley. On the whole, a location south or west of San Diego seems most likely; in the absence of more information we can say little else.

SOURCES

(1) Benjamin Hayes, "Emigrant Notes", MS CE-62, Bancroft Library, Berkeley. (In the Bancroft Library pagination, pp. 690-697 are transcripts of a diary for May-June 1862; pp. 709-710 is an account of the 1862 earthquake; p. 711 is a memorandum from Andrew Cassidy describing the effects of the earthquake at La Playa).

(2) San Francisco Daily Alta California, June 17, 1862, p. 2.

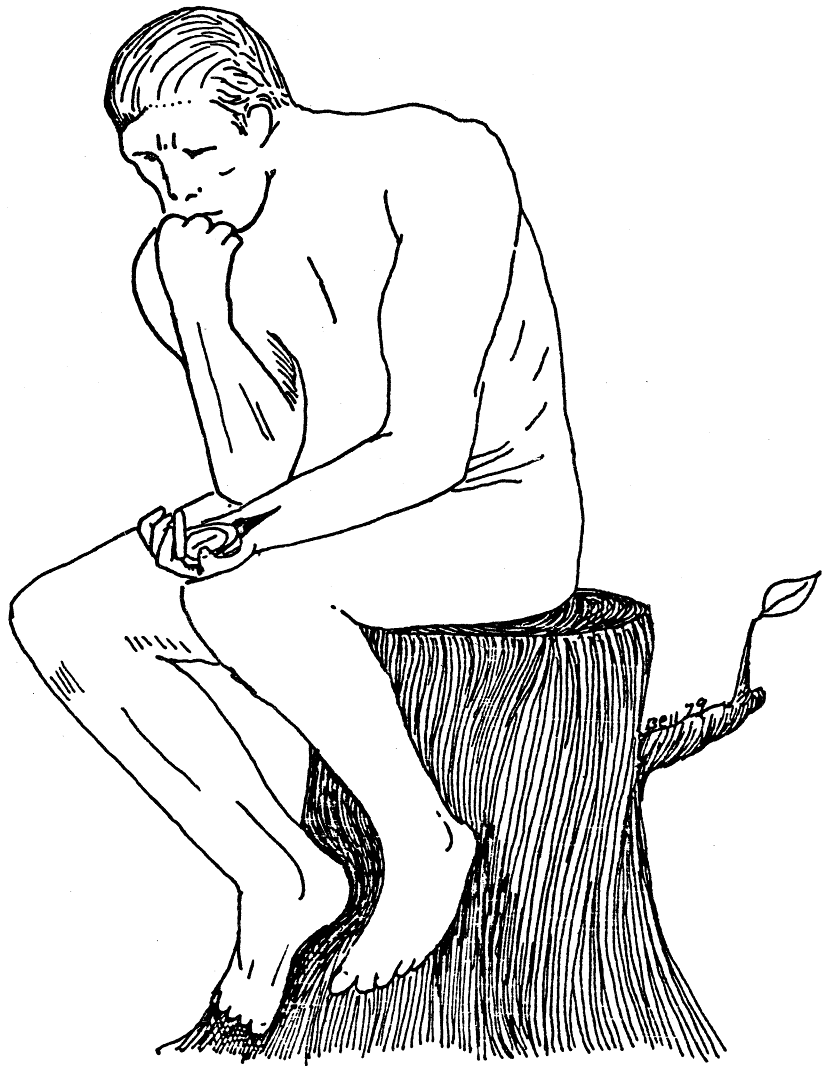
(3) San Francisco Daily Alta California, June 18, 1862, p. 1, col. 3.

(4) Los Angeles Star, June 21, 1862, p. 2, col. 2.

(5) Los Angeles Semi-Weekly Southern News, May 28, 1862, p. 2, col. 2.

(6) Weather Records, New San Diego. (In the Climatological Records of the Weather Bureau, Record Group 27, U. S. National Archives).

(7) Letter of Augustus Ensworth to Cave Couts, May 28, 1862, San Diego. (Couts Collection, Huntington Library, San Marino).



REGIONAL METEOROLOGY

by

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Geologic hazards such as flooding, landslides, silting, and erosion are in most instances caused by meteorological conditions associated with the seasonal weather regimes occurring within an area. In San Diego County, it is the distribution of winter precipitation associated with mid-latitude cyclonic circulations, and occasional late summer tropical cyclones that are principally responsible for these hazards.

San Diego County lies on the southern edge of dry summer, subtropical North America. From west to east, a number of climatic zones ranging from steppe to humid to arid are found within a relatively short linear distance (Figure 1).

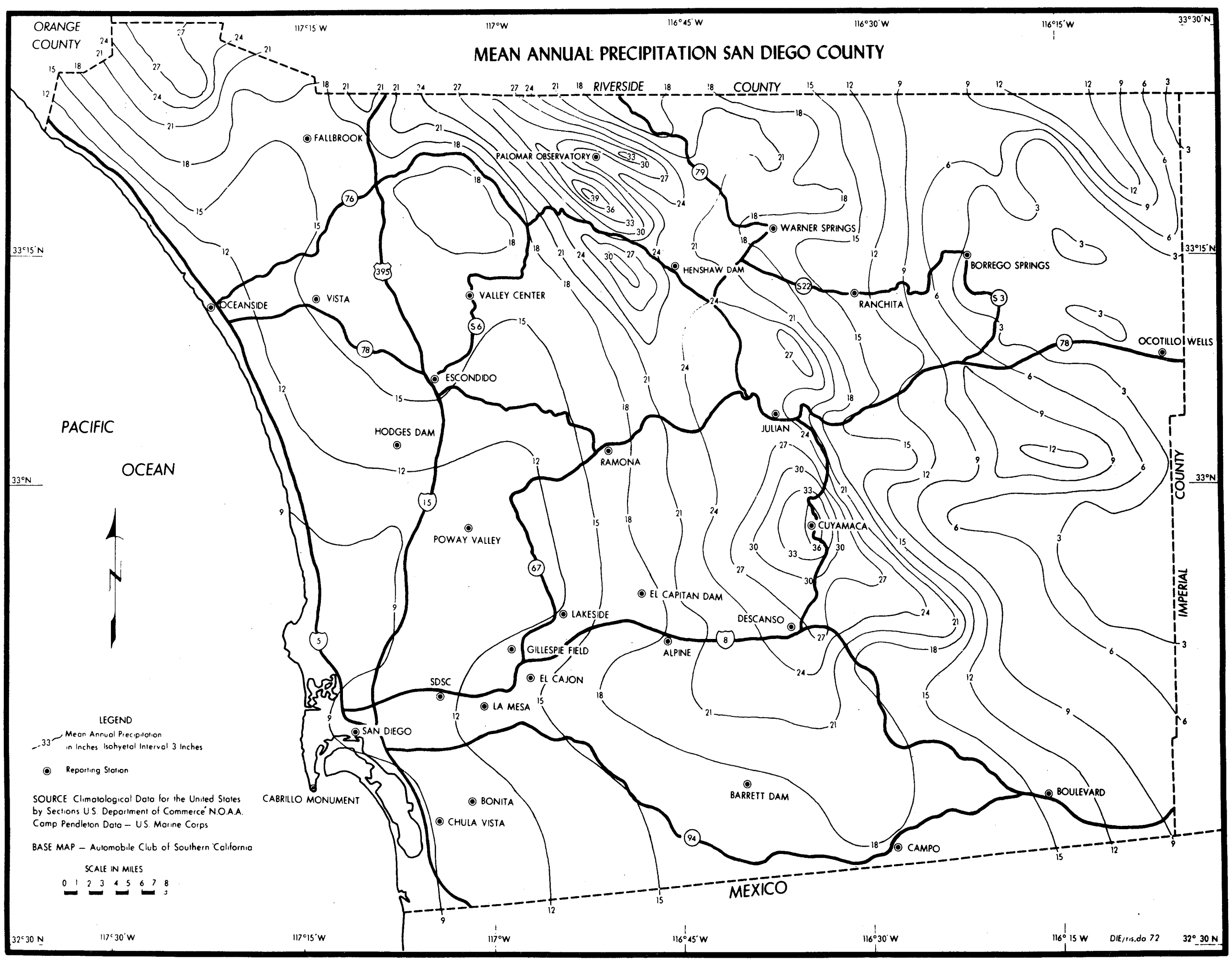

Figure 1. Mean annual precipitation, San Diego County.

The coastal terraces have a mild climate and one of the lowest seasonal temperature ranges within the continental United States (averages of 13°C in January and 22°C in August). Semiarid (steppe) conditions prevail with annual precipitation varying from 9 to 10 inches (229-254 mm), most of it falling in winter. Moving east, interior valleys and foothills are more typically Mediterranean, as they have a wider seasonal temperature range and annual rainfall measuring from 11 to 24 inches (279-610 mm). The annual picture is one of low humidity and relative mildness. On the highest summits of the Peninsular Ranges precipitation is more abundant. Crests of the Laguna and Palomar Mountains average nearly 40 inches (1016 mm) a year. Winters are relatively cold and total snowfall averages 2 to 3 feet (60-100 cm). Summers are warm. On the eastward side of the mountains aridity becomes the key word in expressing the climate. Hot summers and mild winters are characteristic of this mid-latitude desert (Figure 1).

Seasonal Summaries

Summer. During the summer months mid-latitude cyclones track too far north to influence the San Diego County area. The eastern Pacific subtropical high pressure cell becomes nearly stationary approximately 1000 to 1500 nautical miles (1800-2700 km) northwest of the southern California coast. The anticyclonic (clockwise) flow of air around this high results in persistent northwest winds over the San Diego County area lying west of the Peninsular Ranges. This flow is enhanced by the presence of a heat-induced surface "thermal trough" of low pressure lying over the desert regions of interior California and Arizona. Low clouds and fog become prevalent over coastal southern California on almost a daily basis as a result of this onshore flow of marine air. Due to the above-mentioned meteorological conditions, the areas of San Diego County lying west of the mountains are normally free of storm activity during the season.

During summer, the desert areas east of the mountains are normally covered by continental tropical air at the surface and capped by very dry superior air aloft. This situation produces an extremely arid climate, but when this combination is occasionally disturbed by an easterly flow of moist tropical air, thunderstorm conditions are created. That is, extremely high temperatures and high humidities occur in the mountains and deserts, and high level thunderstorms appear over the eastern slopes of the Peninsular Ranges where heating and orographic lifting are at a maximum. These storms can result in flood-producing rainfall over limited areas.

An easterly flow of moist tropical air occurs under the following meteorological conditions. (1) A low pressure center over Baja California or northwestern Mexico will produce an upper level easterly flow into the San Diego area. Moisture will be advected from the Gulf of California. If the upper level flow has sufficient east to west strength, thunderstorms created under these conditions have been known to move westward toward the coast after their development over the desert and mountains. Normally, thunderstorms will not occur along the coast because of the stability of the atmosphere and the absence of sufficient coastal heating needed to produce large convective cells. (2) Tropical storms usually tend to dissipate long before reaching the latitude of San Diego County. However, impulses of moist tropical air from these storms are advected into higher latitudes at upper levels resulting in an easterly flow, and in the appearance of middle and high clouds with possible showers and thunderstorms occurring. This type of circulation can cause flooding on a limited scale.

The annual probability of a tropical storm reaching the San Diego area is between 5% and 10% (Eidemiller, 1978). The most notable example of one of these storms occurred on September 10, 1976 when tropical storm Kathleen moved across northern Baja California, Mexico, and the Imperial Valley of southeastern California. This was the strongest tropical cyclone to reach southern California so far this century. Despite Kathleen's high winds and low pressures, it will probably be remembered best for the severe flash flooding that resulted. Rains began over the desert on September 9, then spread northwest to the coast by evening. Heavy runoff and rapidly rising streams prompted flash flood watches in many areas of the southwestern United States. Nearly all mountain areas from Los Angeles to San Diego County had over 5 inches (127 mm) of rain with the highest peaks (Laguna Mountains) receiving greater than 10 inches (254 mm). The rapid flow of extremely moist tropical air up the eastern and southern slopes of the mountainous terrain created an ideal situation for very heavy rains, which resulted in heavy flooding in the normally dry desert areas of San Diego County. Precipitation was not high west of the mountains.

Two tropical storms weaker than Kathleen entered this area in 1977 and 1978, but neither created any significant problems.

No tropical cyclone of hurricane intensity has occurred within the San Diego area during the past 109 years. The closest approach was by hurricane Katrina (September 1967) which came ashore at the northern end of the Gulf of California, but was shortly thereafter downgraded to a tropical storm. With probabilities of less than 1%, hurricanes are not considered a serious threat to San Diego County, but should one ever occur, heavy flooding and related damage would be expected.

Fall. Fall can be described as a transitional period between the summer stratus regime with occasional impulses of tropical air, and the winter frontal season. During the fall stratus become less prevalent, and the occurrence of large-scale offshore flow becomes more frequent, generating some of San Diego's most severe heat periods (Santa Ana winds). Storms of sufficient intensity to produce flooding and related damage are extremely rare during the fall season.

Winter. Tracts of upper level troughs and frontal systems begin to assert their influence farther south with greater frequency and intensity during winter. Three different cyclonic (counterclockwise) patterns can influence the San Diego County area during this season.

1. The first type is characterized by an active surface cold front which passes rapidly through southern California. A relatively strong upper level cold trough accompanies the surface circulation, but the trough remains well to the north and east of San Diego (Figure 2). Precipitation produced by this type of cyclonic circulation can vary from light to moderate. No particular hazards are usually associated with this type of frontal activity.

2. The second type occurs when cyclonic circulations are created at latitudes south of 35°N in the eastern North Pacific. This may result in a flow of warm, moist, unstable air to the coast of California, causing very heavy, topographically influenced rainfall. Fronts are sometimes embedded in this southwestern flow, which then permits the San Diego County area to receive the full effect of the warm and cold front passages, as well as the effect of orographic lifting (Figure 3). Outstanding examples of this type of cyclonic circulation which caused flooding and other problems occurred between December 18-27, 1921; February 10-18, 1927; February 14-March 5, 1941; March 10-15, 1941; and January 18-27, 1969.

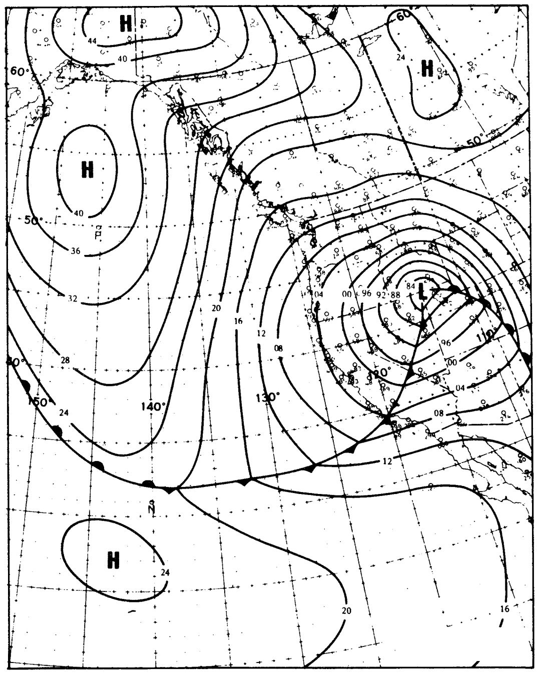

Figure 2a. Rapidly-moving surface cold front will pass through southern California producing light to moderate precipitation (Surface Chart - 1200Z, 20 January, 1962).

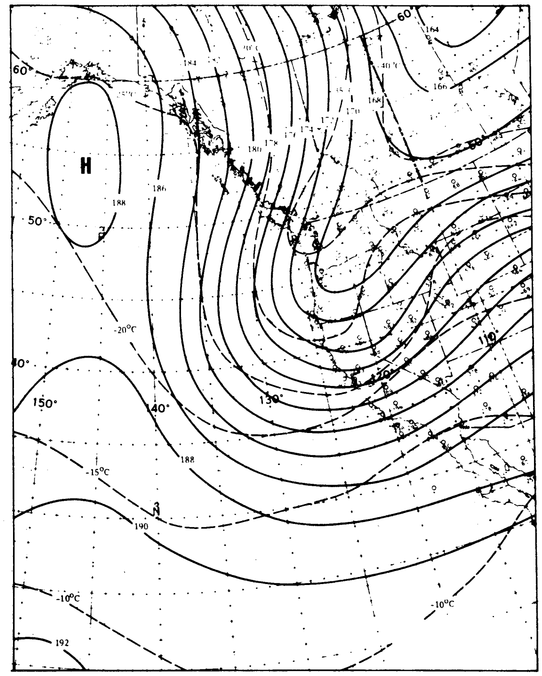

Figure 2b. Upper-level trough remaining north of San Diego County has minimal influence on precipitation in southern California (500 millibar Chart - 1200Z, 20 January, 1962).

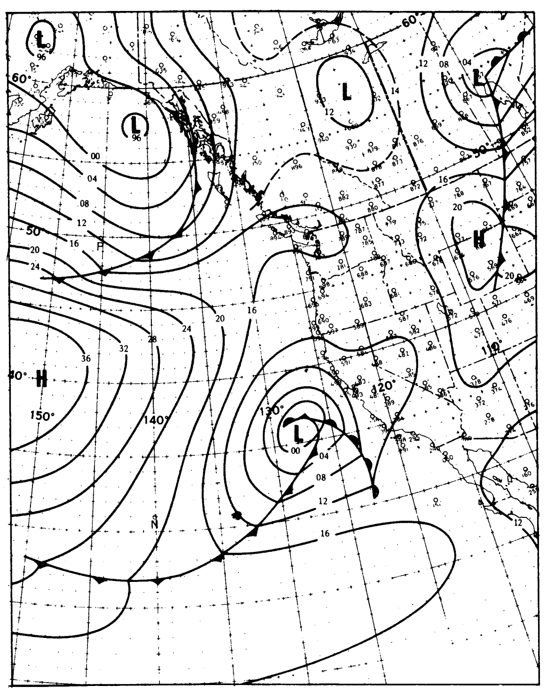

Figure 3a. Surface low of subtropical origin. San Diego County receives full effect of both warm and cold front passages. (Surface Chart - 00Z, 20 January, 1969).

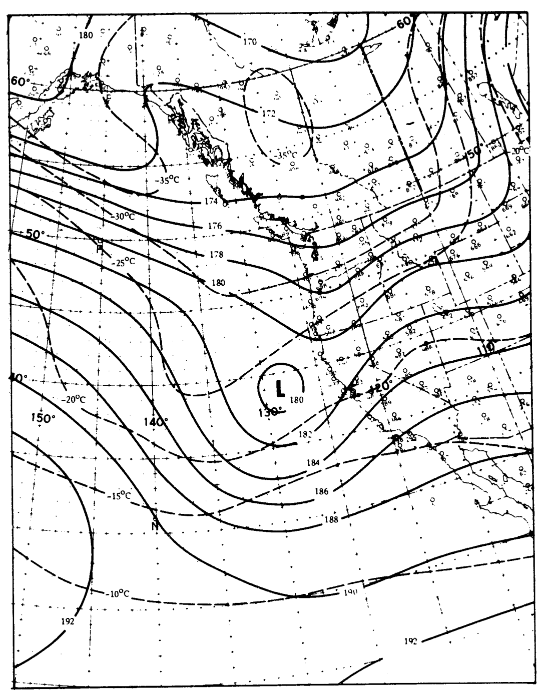

Figure 3b. Upper-level trough with closed low accompanying the surface low. (500 millibar Chart - 00Z, 20 January, 1969).

3. A prolonged period of heavy rainfall may occur in this area whenever the third type of cyclonic circulation frequents the eastern North Pacific. When a new short wave impulse of cold air enters an upper level trough in the Westerlies, it has a twofold effect. First, it causes the trough to deepen, which results in a strong southerly flow of moist air aloft along its southeastern margin. Second, it retards the eastward movement of surface lows and accompanying fronts (Figure 4). This quasi-stationary circulation extends the duration of precipitation from a period of hours to several days. Examples of these weather conditions occurred on the following dates: January 14-19 and 24-29, 1916[1]; January 16-18, 1952; March 7-17, 1952; December 31, 1976 through January 8, 1977; January 6-8 and 17-20, and February 6-14, 1978; March 1-6 and 10-12, 1978; January 15-19, 1979; January 31 - February 3 and 21-24, 1979.

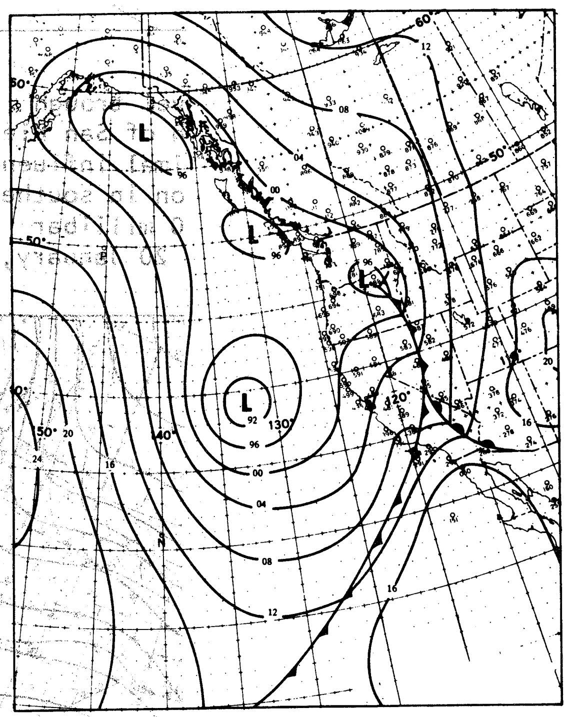

Figure 4a. Quasi-stationary surface low off the central California coast extends duration of precipitation in southern California from hours to days. (Surface Chart - 00Z, 5 March, 1978).

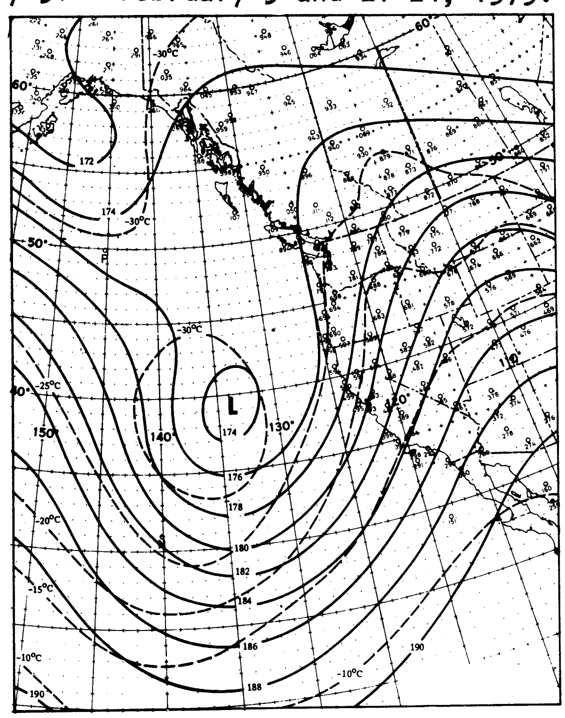

Figure 4b. Deep upper-level trough and closed low induces a southerly flow of moist air at all levels over southern California (500 millibar Chart - 00Z, 5 March, 1978).

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[1]Charles M. Hatfield, the "Rainmaker" is credited by many for the large amount of precipitation which fell during this period. However, it was merely coincidental that he was in the San Diego area at a time when the quasi-stationary type of circulation was present. This weather pattern produced record-breaking amounts of rain throughout most of the western United States in 1916.

Spring. Spring is similar to fall in that it is also a transition period. Less precipitation is expected as the tracts of upper level troughs and surface cyclonic storms begin retreating farther north. This allows the subtropical anticyclone to reintensify, establishing once again the stratus regime of late spring and summer.

SUMMARY

Flooding, landslides, erosion and related problems are most apt to occur in the San Diego County area under the following meteorological conditions: the infrequent invasion of tropical circulations during summer, and the occasional winter occurrences of (1) open wave, mid-latitude cyclones developing further south than normal, and (2) the combination of quasi-stationary surface and upper level circulations.

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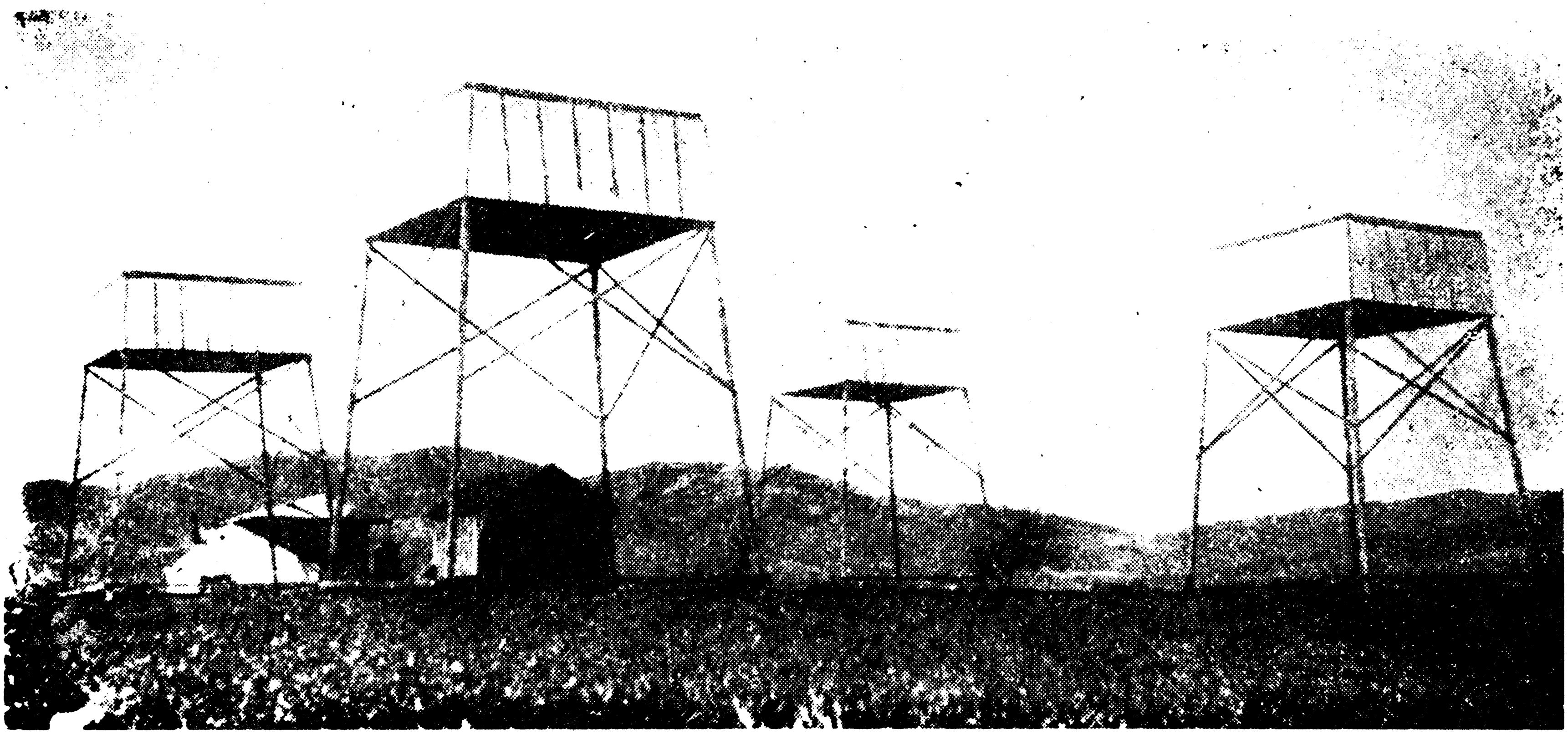

Towers erected by Charles Hatfield to mix the chemicals intended to produce the rains. Located on Otay Mesa in San Diego County, January, 1916.

FLOODS AND CHANGING STREAMS

by

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INTRODUCTION

Streams in San Diego County, like those in most of the semi-arid southwest, are ephemeral in nature. But unlike many other ephemeral streams, they are usually more disturbed by such human activities as damming, sand mining, and bridge and highway construction accompanying rapid urbanization in the river environment. Such changes distort the natural equilibrium of streams and in the process of restoring equilibrium, streams undergo changes. Streams will adjust to new conditions by changing their cross-sectional shape, slope, roughness, bed-material size, or meandering pattern. Within the existing constraints, any one or a combination of these characteristics may adjust as streams seek to maintain the balance between their ability to transport, and the load provided. In this paper, several case histories of changing streams will be described, a computer model for estimating stream erosion and sedimentation will be introduced, and finally, some social impacts of "changing streams" will be outlined.

FACTORS RESPONSIBLE FOR STREAM CHANGES AND CASE HISTORIES

For a natural stream, the slope, cross-sectional shape and plan configuration, are delicately adjusted to provide just the velocity required for the transportation of the load supplied from the drainage basin. The concept of graded stream as introduced by Mackin (Mackin, 1948) is a condition of equilibrium in streams serving as agents of transportation. With the constant changes in water discharge and other parameters, the final equilibrium is never fully attained in natural streams, although each channel is continuously readjusting its condition toward equilibrium. Environmental changes may occur naturally, as in the case of climatic variation or changes in vegetative cover due to forest fires. What is unique in San Diego County is changing streams caused by human activities. This paper will focus on this aspect of changing streams.

One major factor contributing to stream aggradation and degradation in sand mining in the stream bed. River sand deposits are formed by natural processes of hydraulic sorting wherein the clays and fine silts are washed away as suspended load during floods leaving sand in the stream bed. River sand is the most abundant mineral resource in the county. To meet the demand for rapid urban growth, sand is being mined from the stream bed at an increasing rate, leaving scattered borrow pits in nearly all major streams.

During a flood, the borrow pit usually acts as a sediment detention basin in which most of the bed load (sand) settles. As the flood water leaves the pit with its bedload depleted, it picks up new sand from the stream bed to satisfy its transport capacity and thus causes erosion downstream from the pit. Examples of stream-bed erosion due to sand mining are shown in Figures 1 and 2.

A borrow pit can also induce stream bed erosion upstream from the pit during low flow; this is because a borrow pit lowers the base level of an inflowing stream when the water level in the pit is low. In reaching this lower base level, the inflowing stream cuts into the stream bed to form a gully which extends gradually upstream in the process of erosion. This type of gully formation is shown in Figure 1 where a gully formed in the winter of 1976-77 upstream from a large borrow pit. The sand carried into the borrow pit was deposited as a delta (Figure 2).

There are numerous other case histories of stream-bed erosion caused by stream-bed mining. Examples from the San Diego River are shown in Figures 3 and 4. The photograph in Figure 3 was taken in the spring of 1978, soon after a major flood of the magnitude of a 10-year flood. Deep scour lowered the stream bed under the Highway 67 bridge north of Lakeside and thus connected sizeable borrow pits which were present on both the upstream and downstream sides. The erosion reached a depth of around 10 feet (3m) and endangered the safety of the bridge which caused its being closed to traffic until repairs were made.

The photograph in Figure 4 was taken in February, 1979, at the Magnolia Avenue bridge crossing of the San Diego River in Santee. This bridge, completed in 1977, had its pile caps buried deep in the sand bed. Erosion has since exposed the pile caps as well as the piles.

Another important factor contributing to stream bed erosion in the San Diego area is the encroachment on stream channel width by bridge embank-

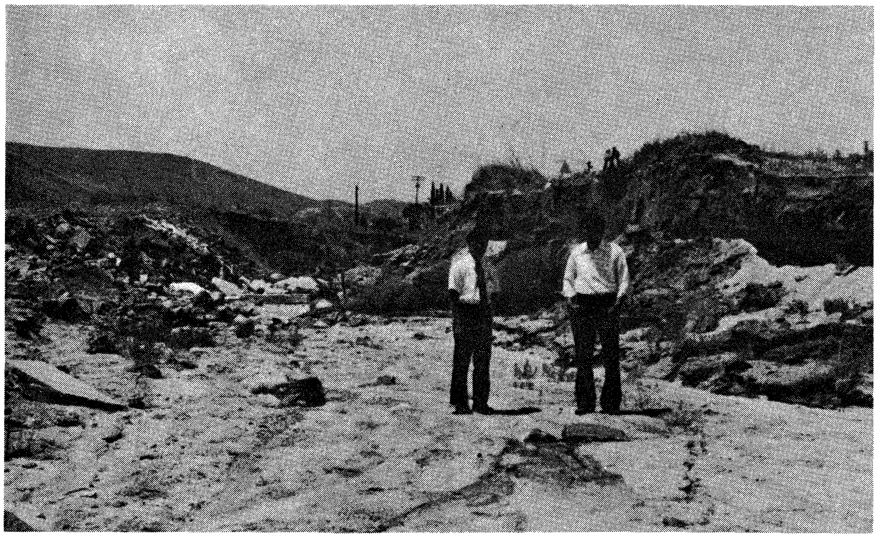


Figure 1. Stream-bed erosion upstream from a borrow pit, San Diego River near the Lakeside Sanitation Plant.

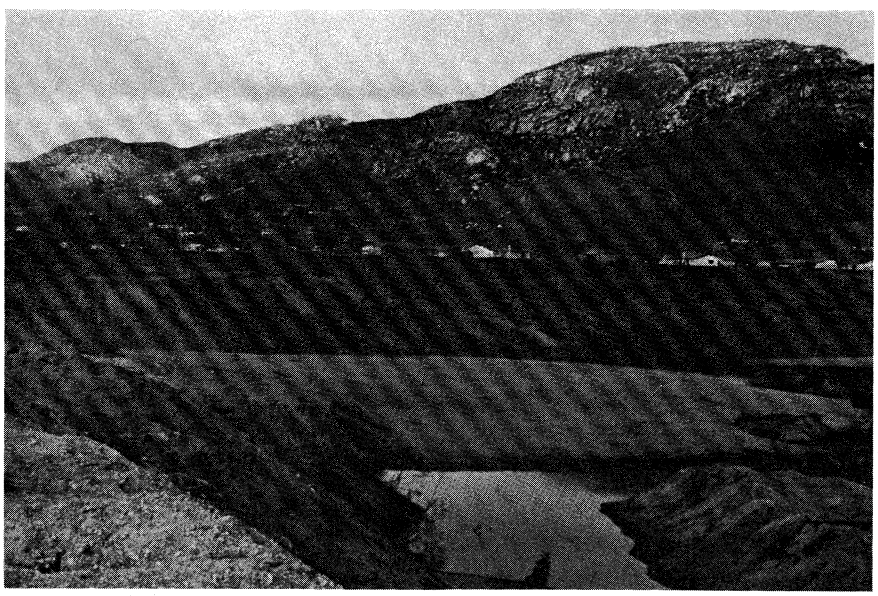


Figure 2. Sand eroded from a channel and deposited downstream as a delta in a borrow pit -- San Diego River upstream of the Highway 67 bridge.

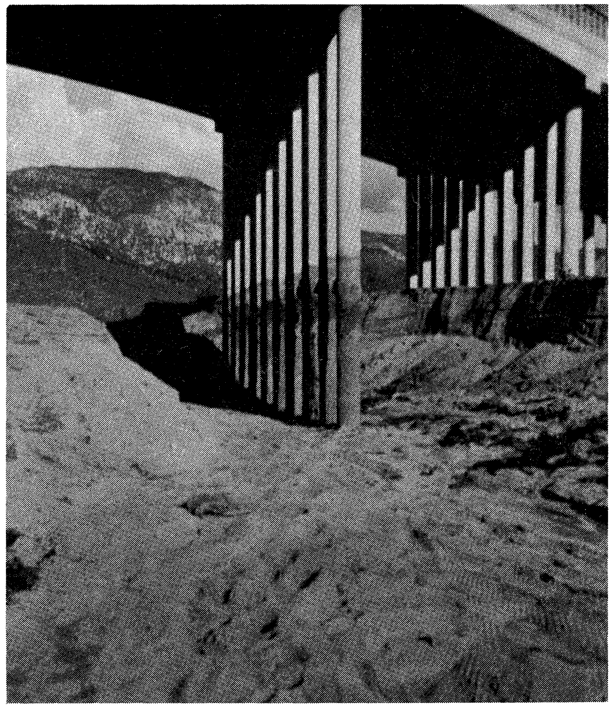


Figure 3. Stream-bed erosion in the San Diego River channel at the Highway 67 bridge over the San Diego River north of Lakeside. Approximately 10 feet (3 m) of erosion has connected deep, sand borrow pits on either side of the bridge.

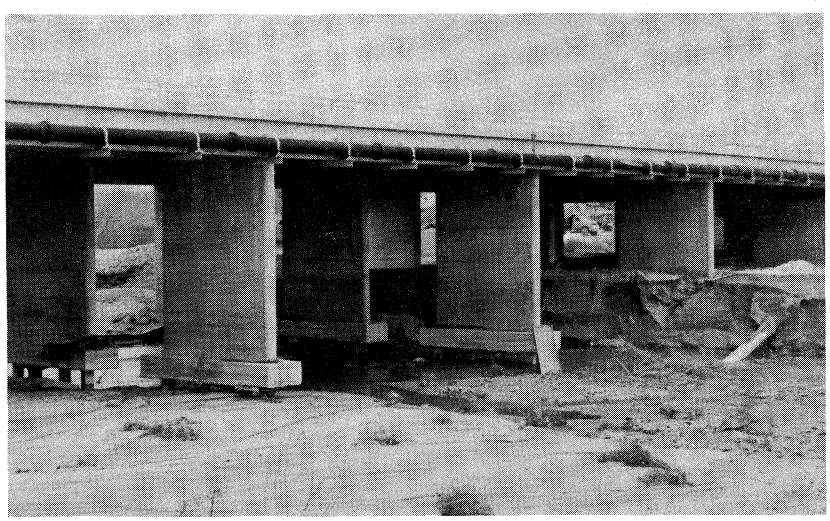


Figure 4. Stream-bed erosion in the San Diego River channel at the Magnolia Avenue bridge across the San Diego River in Santee. Erosion has exposed both pile caps and piles.

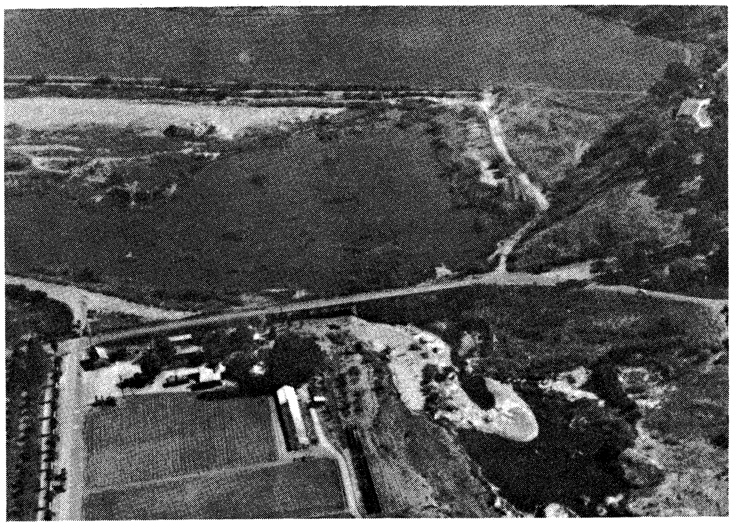
ments. As shown in Figure 5, the Via de Santa Fe bridge south of Rancho Santa Fe, on the San Dieguito River was built with long road embankments in order to reduce the bridge span. These embankments have seriously encroached upon the natural width of stream flow, resulting in accelerated flow velocity and accompanying erosion. Measurements made in the spring of 1978 showed a maximum erosion depth exceeding 15 feet (4.5m). In this particular case, erosion was not caused by encroachment alone as borrow pits also exist in the river bottom.

COMPUTER SIMULATION OF STREAM CHANGES DURING A FLOOD

A computer program has been developed to simulate stream changes during the passage of a flood (Chang and Hill, 1976). The flow diagram showing the major steps of computation is shown in Figure 6. In using this program, a river reach is defined by a series of cross-sections. The progressive variations of the stream bed and water-surface profile is first computed. Then, sediment discharges at all sections are computed using a sediment formula, such as the Engelund-Hansen formula, the modified Einstein formula, etc. The difference in sediment movement rate at adjacent sections indicates stream change: greater inflow of sediment causes deposition while greater outflow causes erosion. The amount of change for each time increment is computed and applied at each cross-section to obtain the corrected streambed profile. This iteration continues until the desired time period is covered.

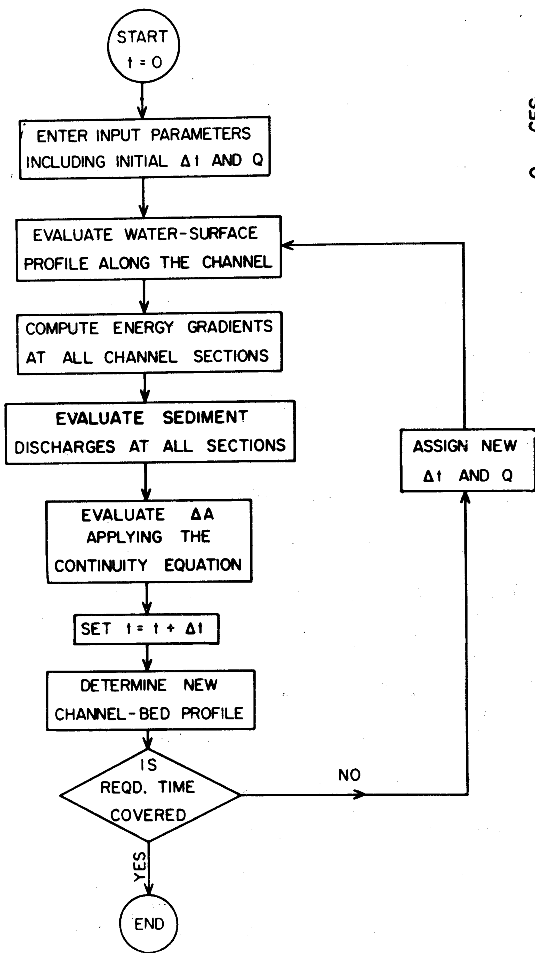
The potential stream changes in the San Dieguito River near the Via de Santa Fe bridge have been simulated using this computer program during the passage of the 100-year flood. Figures 7a and 7b show respectively, channel topography before the storm, and during the peak flood predicted to undergo erosion as deep as 25 feet (8m). Erosion of this magnitude would result in total exposure of the piles with a high probability of the bridge being washed out. During this extreme process of stream change, borrow pits in the stream slowly disappear as shown in Figures 7a and 7b.

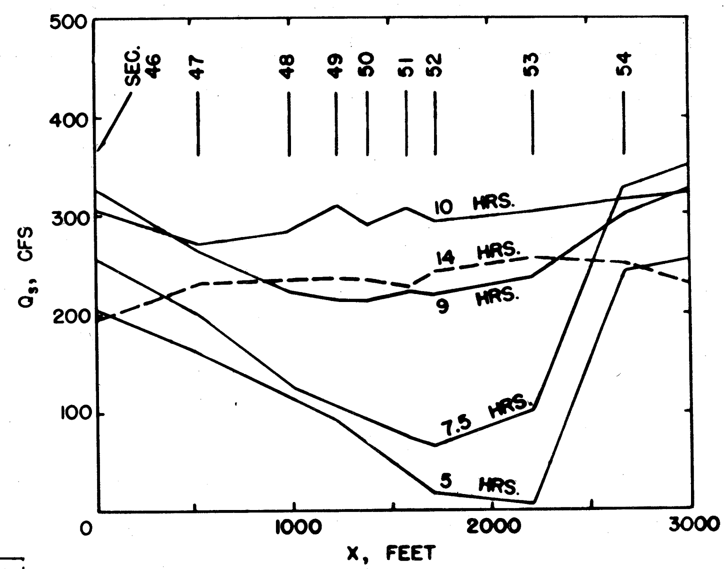
Figure 8 shows the variations of sediment discharge at different time intervals as part of the computer output. During the early intervals, the sediment discharge shows great variations along the channel because of the nonuniform channel profile due to the encroachment and borrow pits. But as time increases, the sediment discharge becomes more uniform as the channel profile undergoes adjustments. After the tenth hour, the sediment discharge



← Figure 5.

Encroachment into the San Dieguito River at the Via de Santa Fe bridge crossing, south of Rancho Santa Fe.





↑ Figure 8. Variations of sediment discharge at different time intervals during the 100-year flood on the San Dieguito River near the Via de Santa Fe bridge.

← Figure 6. Flow diagram showing major steps of the computer program for erosion simulation.

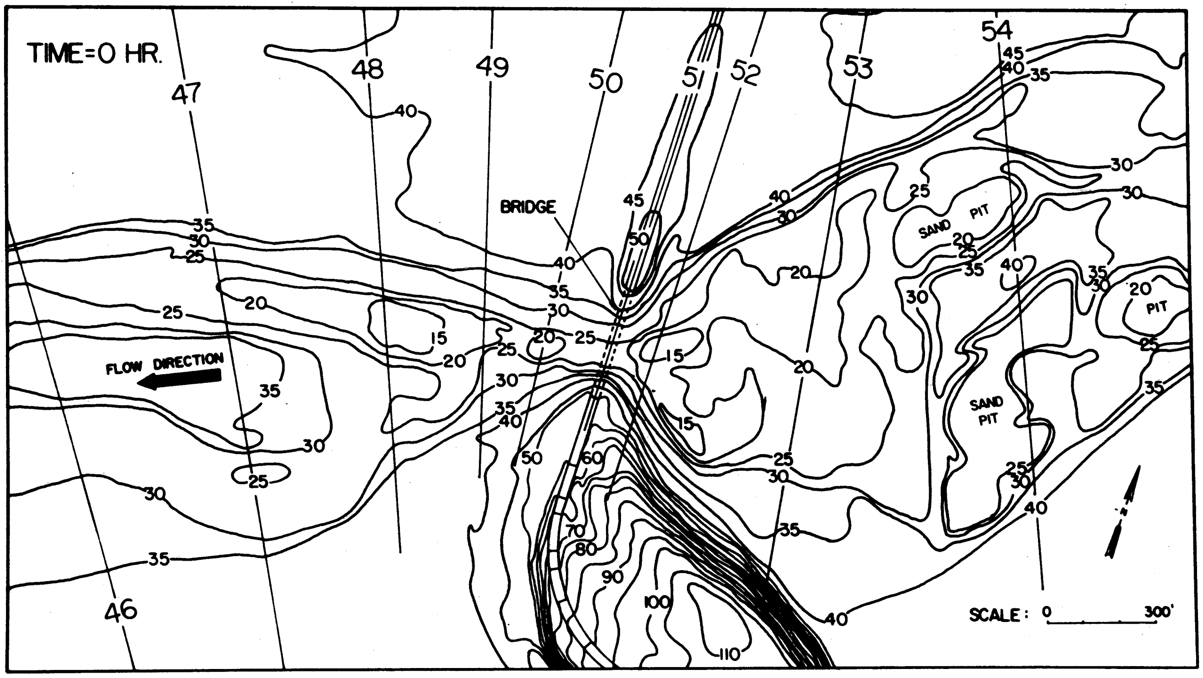


Figure 7a. Pre-flood topography of the San Dieguito River channel near Via de Santa Fe bridge south of Rancho Santa Fe.

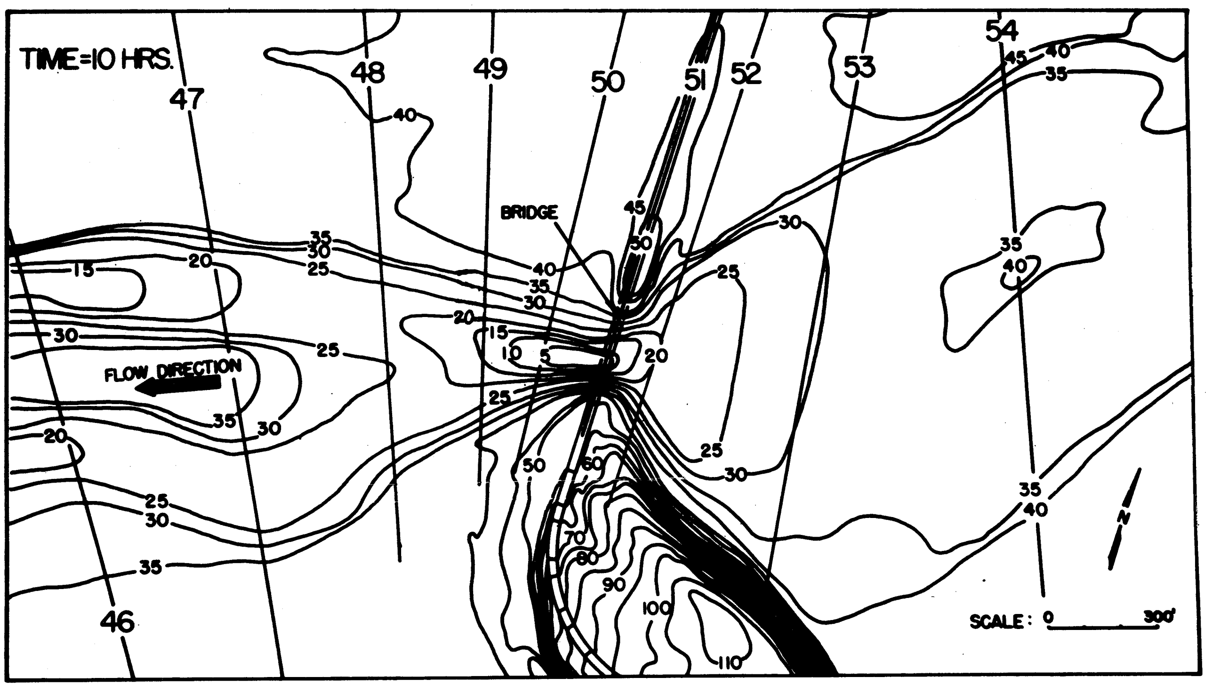


Figure 7b. Topography of the San Dieguito River channel near Via de Santa Fe bridge, south of Rancho Santa Fe, during the peak 100-year flood.

becomes quite uniform, indicating that the equilibrium channel profile has been more or less reached.

SOCIAL IMPACTS OF STREAM CHANGES

Environmental considerations require evaluation of streams in their natural or existing conditions. This usually means precisely delineating the limits of a 100-year flood. Flood hazards are reduced by restricting development within the floodway. National flood plain mapping, under a Federal Insurance Agency program has been going on for the last 10 years; one of its goals is to develop precise maps showing the limits of 100-year floods along major stream courses. Presently, flood levels are determined using computer programs which assume rigid channel boundaries during floods, therefore the effects of erosion and sedimentation in streams are not considered. While rigid boundary assumptions are quite valid for many streams, they are not accurate enough for "changing streams."

For example, as a result of stream bed erosion that occurred in the winter of 1978, the 100-year flood level in the San Diego River channel near the Magnolia Avenue bridge was lowered by about 4 feet (1.3 m) in computations using the newly eroded (post 1978) stream profile. Under the old (pre 1978) computed flood level, large overbank areas were subject to inundation, making development extremely expensive.

Using the rigid boundary assumption, the flood level near the San Dieguito River mouth in Del Mar is computed to be high enough to cause extensive flooding of several hundred homes. These homes have never been flooded in historical times, even before the completion of major dams upstream. This is because during each previous major storm the sand bar blocking the river mouth was invariably removed by the flood water, resulting in a larger opening and lower flood level. The Federal Insurance Administration has become aware of "changing streams" and its impact on flood plain mapping. Hopefully, studies will be started soon to adopt a movable bed program for use in selected stream courses.

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THE 1916 FLOODS IN SAN DIEGO

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INTRODUCTION

Noteworthy floods occur in the San Diego area on an unpredictable time scale. Until the last three years, no floods capable of generating widespread concern occurred for about four decades. However, in southern California, wetter than average years tend to follow dry years in irregular cycles averaging about 12 and 15 years duration, respectively (Ganus, 1977). Recent wetter than normal years, with accompanying flooding, have heightened local interest in floods. Since the biggest events usually attract the most attention, the intent of this article is to review the parameters of San Diego's severest historic floods, those of January, 1916.

When evaluating the local flood records, an interesting relationship appears -- that is, there is a lack of correlation between major floods and annual rainfall (rainfall years run from July 1 and June 30). For example, at the downtown San Diego rain gauge, 12.55 inches (319 mm) of precipitation was recorded for the 1915-1916 rainfall year yet had a peak flood on the San Diego River that was about 450 percent larger than the largest flood during the 1921-22 rainfall year, during which 18.65 inches (473 mm) of precipitation was recorded at the same station. The largest floods in San Diego history have occurred when heavy rains have fallen on ground already saturated by a recent storm. On the other hand, if the precipitation events were spaced far enough apart, then the typical high evaporation losses in the area dried the soil. Empty pores in the dried soil were then able to accept large quantities of water from subsequent storms, with a resultant reduction in peak flood height.

METEOROLOGICAL CONDITIONS IN JANUARY, 1916

U. S. Weather Bureau reports (1916) for San Diego describe two very wet weeks occurring from January 14 to 20, and from January 24 to 30, 1916. During the first week, a low pressure air mass crossed the coastline in central California on the 17th, slowed down over southern California and yielded heavy rains, then moved northeast on the 19th. Because light rains had fallen during the previous few days, the heavy rains of the 17th and 18th caused severe flooding. Meteorological conditions that produce extended periods of heavy rainfall are described by Eidemiller (this volume) as cyclonic circulation in the eastern North Pacific made quasi-stationary by an upper level impulse of cold air. The second major occurrence of this condition in January, 1916, caused very heavy rains on the 26th and 27th. This downpour settled on already saturated ground and nearly-full reservoirs which resulted in record setting peak discharges.

RAINFALL AND RUNOFF

During the 17 days, January 14-30, 1916, the downtown San Diego rain gauge recorded 7.08 inches (180 mm) of precipitation compared to the average annual precipitation (1912-1975) at that station of 9.79 inches (249 mm). In general, precipitation in San Diego County increases eastward, from the coast to the mountains, and thus, away from the downtown area. The unusually heavy rainfall from these two closely-spaced storms is shown for selected stations (Table 1).

Other rainfall data, helpful in understanding the 1916 floods are those of mean precipitation over some of San Diego County's major drainage basins during the January 14-30 interval (Table 2).

TABLE 2. MEAN DRAINAGE BASIN PRECIPITATION

	Drainage basin area	Mean precipitation in basin	Rainfall range East	West
San Diego River	434 Sq. miles (112,400 hectares)	19.9 inches (505 mm)	7.08 inches (30 mm) downtown	32.34 in. (821 mm) Cuyamaca Reservoir
Sweetwater River (above Sweetwater Dam)	181 sq. miles (46,880 hectares)	21.8 inches (554 mm)	8.55 inches (217 mm) Sweetwater Dam	28.68 in. (728 mm) Descanso
Otay River (above lower Otay Dam)	99 sq. miles (25,640 hectares)	19.2 inches (488 mm)	9.39 inches (239 mm) Lower Otay Dam	25.45 in. (646 mm) Dulzura

Significant flood crests occurred on the 17th and 18th due to runoff from the first major storm system (week of January 14-20). The second storm system

TABLE 1. DAILY PRECIPITATION RECORDS, JANUARY, 1916

Station		Elevation	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
San Diego River basin near mouth	- inches	87 feet	.53	.09	.95	1.55	.31	.80	--	--	--	--	tr	.21	.22	2.19	.06	.17	--
	- mm		13	2	24	39	8	20	--	--	--	--	tr	5	6	56	2	4	--
Cuyamaca Reservoir	- inches	4,677 feet	1.20	.72	3.35	5.83	5.27	1.59	--	--	--	.03	.23	1.63	1.53	8.54	1.30	1.12	--
	- mm		30	18	85	148	134	40	--	--	--	1	6	41	39	217	33	28	--
Sweetwater River basin Sweetwater Dam	- inches	300 feet	.45	.11	1.10	1.10	1.51	.46	.38	--	--	--	--	.07	.15	2.87		--	.35
	- mm		11	3	28	28	38	12	10	--	--	--	--	2	4	73		--	9
Descanso	- inches	3,500 feet	--	2.12	1.02	6.36	4.98	1.33	.67	--	--	--	.02	.38	.73	3.11	7.07	.09	.80
	- mm		--	54	26	162	126	34	17	--	--	--	1	10	19	79	180	2	20
Otay River basin Lower Otay Dam	- inches	490 feet	--	.48	.46	1.86	1.82	.53	.45	--	--	--	--	.02	.15	1.12	2.25		.25
	- mm		--	12	12	47	46	13	11	--	--	--	--	1	4	28	57		6
Dulzura	- inches	1,300 feet	1.94	.67	3.22	4.58	.88	1.01	--	--	--	--	.09	.34	2.20		9.90	.62	--
	- mm		49	17	82	116	22	26	--	--	--	--	2	9	56		251	16	--

Figure 1. Water flowing through breached abutments of Sweetwater Dam, January 30, 1916.

(week of January 24-30) dumped less total water than the first, but had the highest single-day rainfall (January 27). The rains of the second wet week fell on saturated ground and the resultant runoff set the historic records for San Diego area rivers (Figures 1 & 2). Summaries of runoff and discharge data are shown in Table 3.

TABLE 3. RUNOFF AND DISCHARGE DATA

	Peak discharge on Jan. 27 (cubic feet/second)*	Total runoff (acre-feet)*
San Diego River	75,000	213,000 (Jan. 1-31)
Sweetwater River (at Sweetwater Dam)	45,500	110,000 (Jan. 16-31)
Otay River (at Lower Otay Dam)	23,500	-- --

*1 cubic-foot/second(cfs) = 7.5 gallons = 28.4 liters
1 acre-foot = 326,000 gallons = 1,234 kiloliters

On January 27, 1916, the peak discharge of 23,500 cfs was overtopping the 40,000 acre-feet capacity Lower Otay Reservoir. A warning was sounded throughout the Otay River valley to evacuate to higher ground -- most people heeded the warning. Sapping at the base of the dam was moving boulders, and at 5:05 p.m. the stress on the dam was so great that the steel core tore from the top at its center and the dam opened outward like a pair of gates. It took 2.5 hours for the reservoir to evacuate (Figure 3). The wall of water was variously described as from 6 to 20 feet high (2 to 6m). It moved the 10 miles (16 km) to the southern end of San Diego bay in 48 minutes.

HATFIELD THE RAINMAKER

A fascinating personal story unfolded along with the floods -- the saga of Charles Hatfield. His 1916 rainmaking efforts were the basis for the 1957 film, "The Rainmaker". In 1915, San Diego was suffering from a water shortage as the main reservoir kept dwindling for lack of replenishment. Hatfield appeared before the City Council and declared that he could fill the reservoir to overflowing within a year if guaranteed $10,000 upon his success. Since there was no fee due if he failed, the City Council apparently reasoned that it was a "no-loss" situation; they okayed the deal, provided Hatfield could prove <u>he</u> caused the rains

Figure 2. Looking northwest down San Diego River
valley following passage of flood crest,
January, 1916.

Figure 3. Lower Otay River valley after failure of the dam. Note dam abutment near lower left corner and valley walls cleansed of soil and vegetation by the flood water.

should they materialize.

Shortly after his tower and vats were constructed and in operation, the January 14-20 and 24-30 storms tracked through San Diego unleashing their record runoffs. Twenty-two persons drowned in San Diego County, mostly in the Otay River valley after the Lower Otay Dam failed. Following the floods, the San Diego City Council was faced with lawsuits totalling $3,500,000. When Hatfield's lawyer pursued his client's fee the Council agreed to pay if Hatfield would acknowledge causing the rain and, hence, the floods and resultant damage. On balancing the credits and debits of this transaction, Hatfield decided to forego his $10,000 guarantee. Despite the loss of his fee, and the unfortunate floods, Hatfield considered the 1916 rains to be the never-again obtainable zenith of his rainmaking career. He then switched to another line of business and apparently "produced" no other rains throughout the remaining 42 years of his life.

FLOOD COMPARISONS AND EXPECTATIONS

It is interesting to compare the peak flow of the 1916 flood with the flood crests experienced during January, 1978 and January, 1979. These most recent runoff events have caused appreciable economic losses and shortened tempers, yet the volumes of water conveyed to the ocean pale when compared to the 1916 runoff (Table 4).

TABLE 4. PEAK DISCHARGE OF SAN DIEGO RIVER (in lower part of the valley)

January 27, 1916	75,000 cubic-feet/second
January 15, 1978	15,000 cubic-feet/second
January 31, 1979	17,000 cubic-feet/second

When contemplating the photograph of the 1979 flood in the lower San Diego River valley it is sobering to multiply that volume of water by five to estimate the effect of a 1916-size flood (Figure 4). Can it happen again? Or have conditions in the San Diego River basin changed such that it could not happen again?

It is commonly believed that the threat of flooding along the lower San Diego River has been substantially reduced since completion of the San Vicente and El Capitan reservoirs in the late 1930's. This is certainly true for any storm that occurs when water levels in the reservoirs are low. However, given a replay of the 1916 rain sequence, the first storm would likely fill, or

Figure 4. View down San Diego River valley during peak flood, January, 1979. The Town & Country Hotel and Convention Center (site of the 1979 GSA annual meeting) is just left of the center of the photograph.

nearly fill the reservoirs, leaving little or no flood-storage capacity for a second major storm arriving shortly after the first.

Another significant change in flood runoff characteristics is the effect of urbanization on peak discharge. San Diego development has entailed the usual laying of pavement for streets and erecting roofs for buildings. Thus, much of the ground in the urban areas is covered and unable to accept the fallen rain into its pores. Studies of runoff following urbanization in other areas have shown that for a given rainfall pattern, peak discharge may be more than three times as great (Leopold, 1968; Young, 1975). In the absence of quantitative studies describing the changed conditions in the San Diego area, one can only speculate on the degree of flooding given a rerun of the 1916 rainfall sequence.

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LANDSLIDES AND DEBRIS FLOWS IN SAN DIEGO COUNTY, CALIFORNIA

by

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INTRODUCTION

In the past decade, geologists in San Diego County have made significant progress in the identification and analysis of ancient landslides and mudflows. Previously, landslides in San Diego were relatively unknown. Primarily responsible for the recent advances in understanding "the secrets of mass-wastage" has been the rapid population growth during the past 10 years which forced development in marginally stable canyons and hillsides bordering and incised into the broad, flat, coastal terraces. This rapid urban expansion onto hillsides followed similar growth patterns in the Los Angeles and Orange County areas to the north. Because most of the ancient landslides lacked the classic features described in textbooks, the impending problems went essentially undetected for some developments.

The presence of large-scale landslides was suspected for several years by some geologists working in the region, but it was not until grading operations dissected some large landslides that the proof was overwhelming. Now, only 11 years after the first documented, large, ancient landslides, San Diego geologists routinely recognize the significance and extent of this hazard to development.

The western part of San Diego County is characterized by a series of broad and extensive Pleistocene marine terraces, capped with marine conglomerate and sandstone, deposited during regression of the Pleistocene sea. The terraces, are underlain by gently westerly dipping sedimentary rocks of mostly Eocene, Miocene, and Pliocene ages. Some coastal areas underlain by Cretaceous sandstones and shales occur from Point Loma, at the west end of San Diego Bay, to La Jolla (Figure 1). Most of the larger landslides occur in clay-rich Eocene and Miocene rocks. Only on Mt. Soledad, a large anticlinal feature located east of La Jolla, does the presence of steeply-dipping, bedding surfaces contribute to the landsliding process.

The sedimentary rocks described in detail by Kennedy and Moore (1971), occupy a relatively narrow coastal strip extending inland to a position approximately parallel to Interstate 15 in the north, and the Santee/San Ysidro areas in the south (Figure 1). The remainder of San Diego County, with the notable exception of a portion of the Anza-Borrego Desert, is underlain by Cretaceous granitic rocks and prebatholithic metavolcanic and metasedimentary rocks. Many large, ancient landslides and mudflows also occur in this terrane, but they have not been as thoroughly studied, nor are they believed to be as common as in the sedimentary rock terrane in the western part of the County.

LANDSLIDES IN WESTERN SAN DIEGO COUNTY

Ancient landslides that occur in Eocene and Miocene rocks of San Diego County, most notably the Santiago, Friars, and Otay formations, are typically of the bedding-plane glide (block-glide), or composite slump and bedding-plane glide variety. These landslides are usually up to three or four thousand feet in width and of equal, or slightly lesser length (Figure 2). Most of the landslides investigated have a well-defined basal slip-surface that is typically planar with a dip between horizontal to about 10 degrees in the direction of sliding. Several well-documented cases of landslides that moved up the basal slip surface are known in the San Carlos area of San Diego. One large blockslide, or composite landslide, that was studied in detail during grading for a subdivision, was observed to have occurred on a reverse dip of approximately two degrees for most of its 120 m (400 feet) length (Figure 3).

Most of the large ancient landslides in San Diego County, which the author has investigated over the last 10 years, have been interpreted as composite slump/block-glide movements. That is, the head of the slide rotated backward on an axis parallel to the slope, but the remainder of the slide followed stratification planes and tended to remain intact as a more or less single unit. Landslides of the block-glide variety do occur, but they are difficult to distinguish from the composite type of slides because the head of the slide sometimes resembles the graben-like features formed by slumping. The typical block-glide slide resembles Hough's (1957) idealized translatory slide (Figure 4). A detailed investigation of a landslide in the Poway

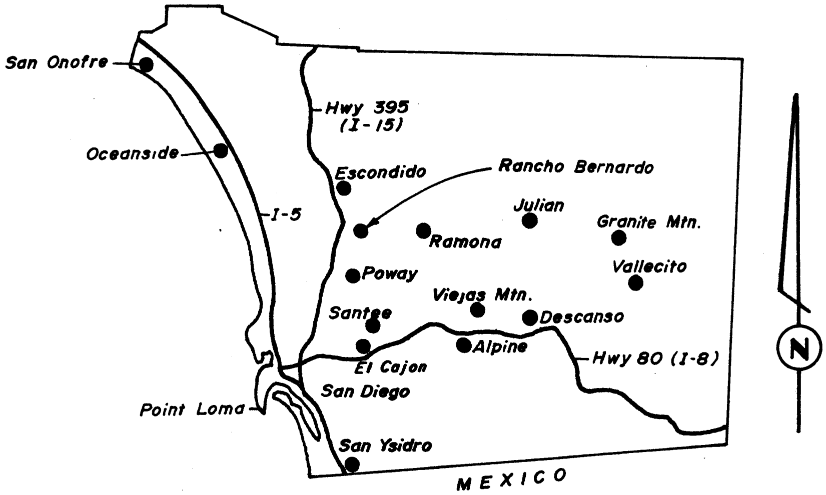

Figure 1. Location map, San Diego County, California.

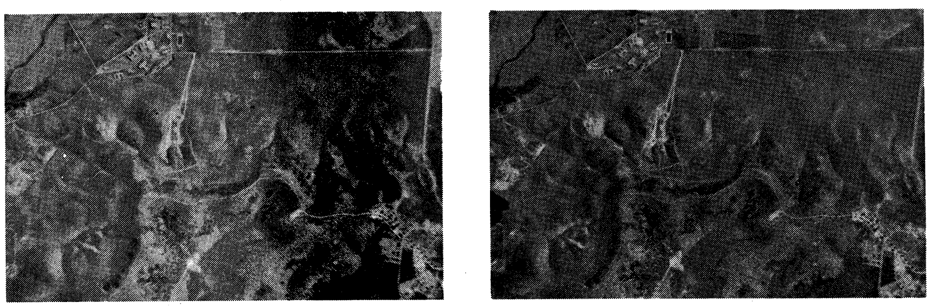

Figure 2. Typical ancient landslide in Eocene sedimentary rocks, Fletcher Hills area, El Cajon, California.

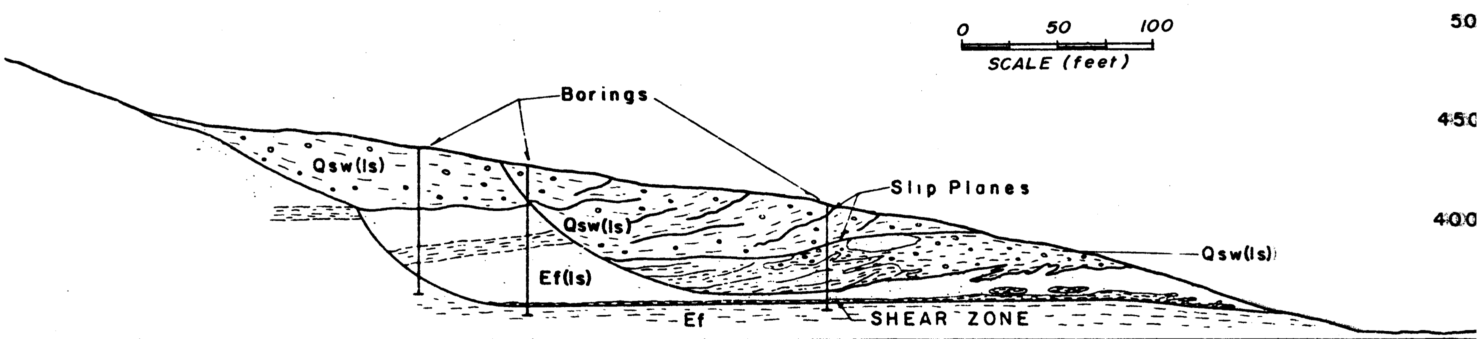

Figure 3. San Carlos landslide, section through central portion of slide showing reverse dip of two degrees on slip surface.

area revealed a section similar to the idealized translatory slide except that the direction of movement of Wedge A in Figure 4 is different from the movement that occurred in the equivalent wedge in the landslide (Figure 5). It is through this mechanism of backsliding that the graben at the head of a block-glide landslide is usually formed.

AGE OF SLIDING

It is becoming apparent as more landslide studies are completed, that the ages of large, ancient landslides in the San Diego area vary greatly. There are well-documented cases (Hart, 1972 a,b) of landslides with erosional inversion of relief in the eastern part of San Diego City and in the Poway area. There are also very young and very large landslides such as those occurring near the Mexican border (Figures 6, 7, 8).

Only a few landslides have been dated by the C^{14} method, and most of these have been dated by obtaining carbon from buried topsoils. Although it was thought that this procedure gave a fairly accurate age of sliding, recent work by specialists in Quaternary geomorphology indicates that topsoils exposed at the ground surface may be much older than previously believed. Certain soils on the west slope of the Sierra Nevada Mountains of California, for instance, have reported ages of up to 100,000 years or older. It is obvious then, that ages determined by dating topsoils are subject to some rather serious errors.

There have been probably less than 10 landslides dated in the San Diego area. Ages obtained range from approximately 6,000 to 24,000 years (Pinckney, et al, 1979, in press; Hart, 1977). These dates obtained from soils are in good agreement with dates calculated by Stout (1969) for landslides in Orange County, California that were determined from carbonized wood fragments buried near the toe of landslides.

One of the most interesting features about landslides is their changing morphology with age, and that there are many landslides of advanced years that have been so thoroughly obscured by erosion that they defy recognition by standard reconnaissance methods. Landslides of this type probably exceed the time range of C^{14} dating as indicated by Stout (1969). Landslides with erosional inversion of relief have been reported by Hart (1972b) in both Poway and San Diego City. Landslides such as these represent serious problems to the engineering geologist because they are difficult to detect, and thus

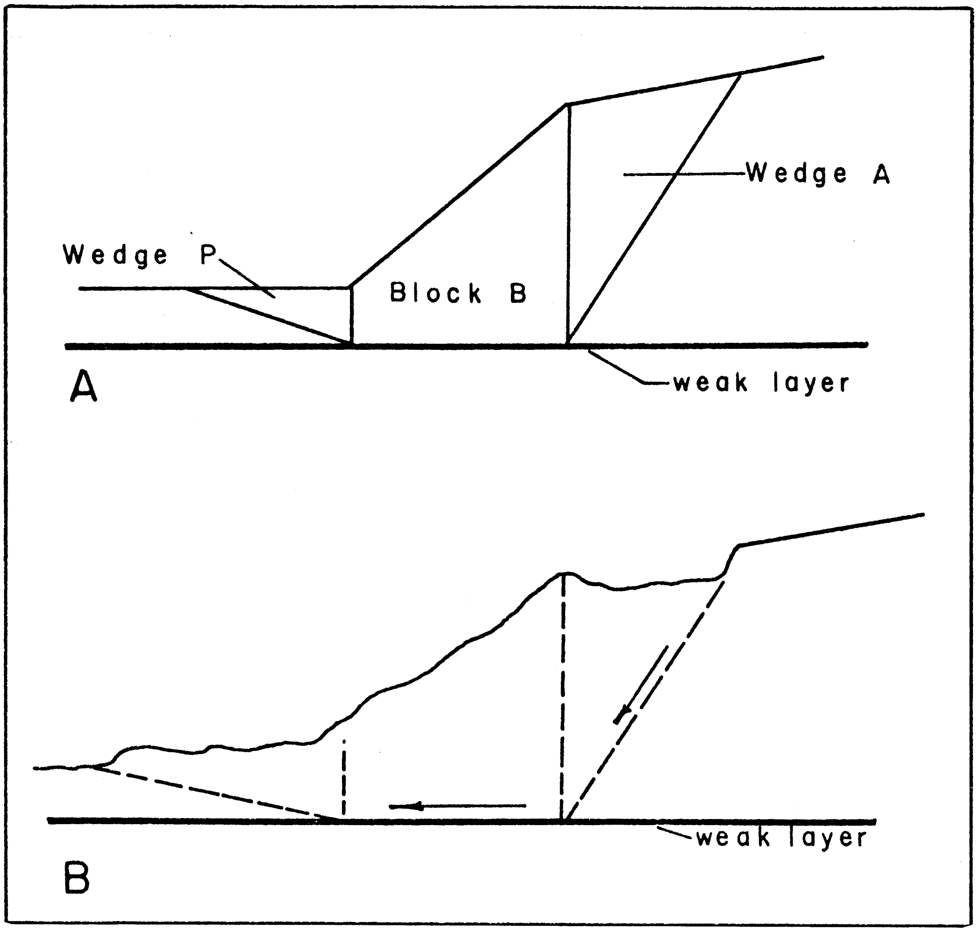

Figure 4. Characteristics of a translatory slide (modified after Hough, 1957).

Figure 6. The San Ysidro slide, view towards northeast (arrow indicates scarp).

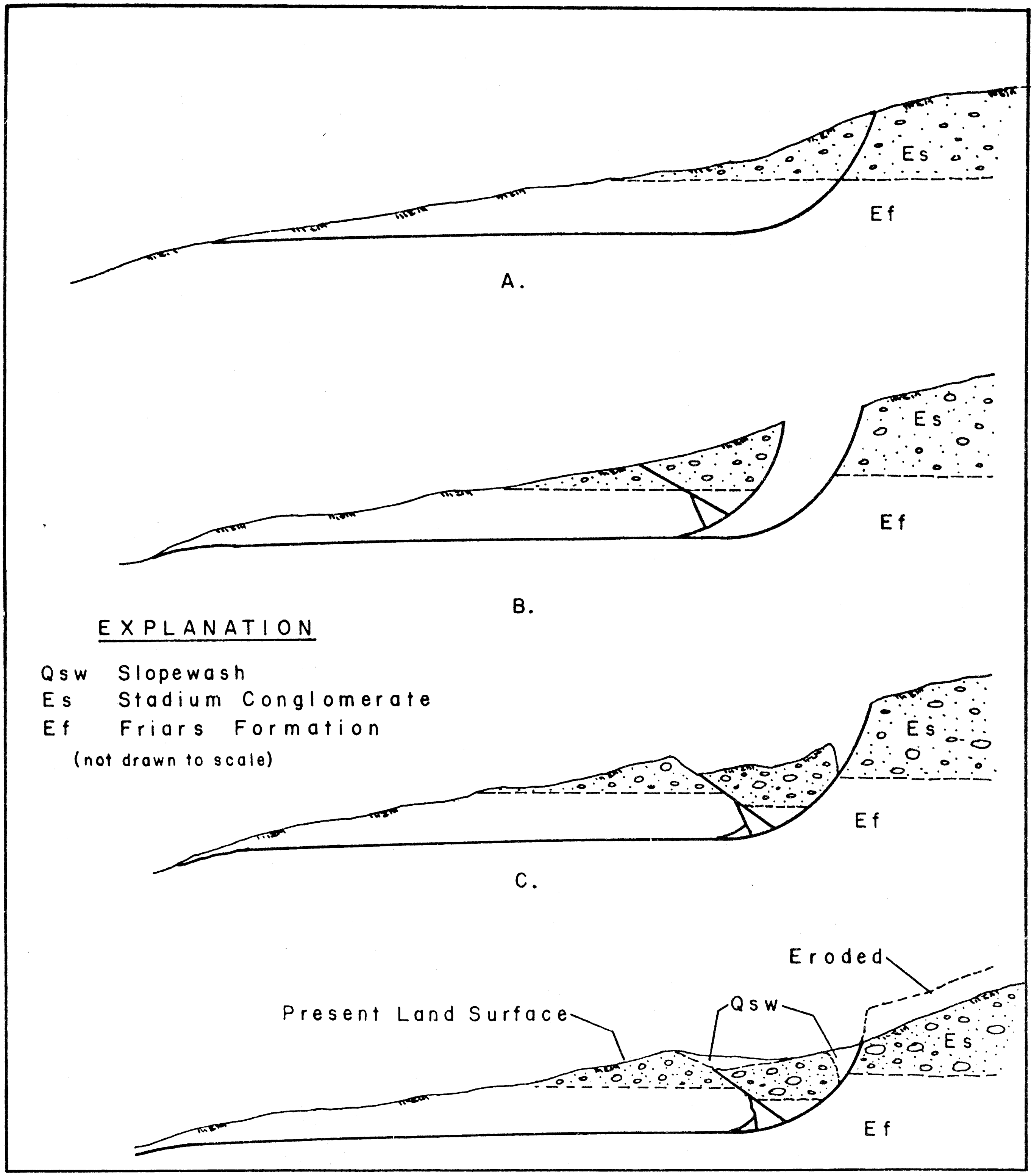

Figure 5. Sequence of sections through a landslide in the Poway area. Note similarity to Figure 4.

Figure 7. Landslide in the Otay Formation along the U. S. - Mexican border, view towards west.

Figure 8. Landslide in the Otay Formation near the Mexican border. Note the hummocky topography typical of landslide terrain. Area of Figure 7 is in upper right corner (view towards south).

they present one more reason why geologists should periodically inspect grading projects and prepare "as-graded" geologic maps.

LANDSLIDE CAUSES

Eckel (1958) summarized the causes or factors that must be present to produce a landslide. In his classic paper on landsliding, he stated that since all slides involve failure of earth material under stress, the initiation of the landslide process can be assessed according to those factors that contribute to high shear stress and those that contribute to low shear strength. Factors contributing to high shear stress include the removal of lateral support through erosion or construction, the addition of surcharge weights such as rainwater or the accumulation of slopewash, and earthquakes. The primary factors contributing to low shear strength are the presence of weak clay materials, high pore-water pressure, and viscous drag caused by seepage.

Bedding-plane Faults. In an earlier discussion on landslides in San Diego County (Hart, 1973), a comment concerning the necessity for determining the how and why of landsliding was made as follows: "One must try to answer the basic question of why did this slide occur on this hill and not on the one over there, or why not 200, 300, or 1,000 feet to the right or left?" Pinckney, et al. (1979, in press) have shed new light on the subject of the how and why of landsliding in their discussion of the influence of bedding plane faults on landslides. They report evidence of the widespread occurrence of remolded clay seams or bedding-plane faults in the Eocene sedimentary rocks of the western part of the County. Strength tests performed on typical materials encountered in the shear zones revealed residual angles of internal friction (Ø) ranging from 6 to 12 degrees and residual cohesion values (c) of less than 200 psf. These same materials, if not "pre-sheared" or remolded by movement, would yield much higher shear strengths termed "peak strengths" (typical values for Ø of approximately 20 degrees and "c" values in excess of 1,000 psf).

If the lower, or residual strengths, are assumed when analyzing the susceptibility of a natural slope to landsliding, it then becomes easier to understand why such massive landslides occur. For instance, a bedding-plane glide landslide in the San Carlos area occurred on a basal slip-surface with a reverse dip of two degrees (Figure 3). If a pre-existing shear surface (bedding-plane fault) was present prior to sliding, then the occurrence of a landslide proceeding up-dip is not as difficult to comprehend. Even so, there appears to be a factor missing when such a landslide is analyzed. The assumption that a pre-existing shear surface with low residual shear strength was present is, in itself, usually not sufficient to allow a landslide to proceed up-dip for long horizontal distances. Apparently, the missing factor in the analysis is the occurrence of high pore-water pressures or the buoyancy effect that such high pore pressures have on materials above the slip-surface. When such effects are calculated, it results in a nearly 50 percent decrease in resistance to shearing forces. This tends to support Stout's (1969) belief that the cause of sliding in the San Juan Capistrano area was excessive precipitation in late Wisconsin time (late Pleistocene). Stout cites evidence such as fossil tree ring studies, which indicates rainfall during the Wisconsin interval of more than double the present mean.

Evidence gained to date indicates that there were probably two primary causes of ancient landslides in the San Diego area. The first was the widespread occurrence of bedding-plane faults in the Eocene and Miocene sedimentary rocks, and second, the presence of a high water table (high pore pressure) and associated seepage pressures beneath canyon slopes.

Over-irrigation. There is another significant aspect related to the role of high pore water pressures in the landslide mass which many geologists (and perhaps even soil engineers) have been ignoring in their analysis of a particular site's susceptibility to landsliding. Although San Diego has a near-desert climate with a mean annual precipitation of approximately 250 mm (10 inches), Sorben and Sherrod (1977) showed that the over-irrigation of landscaping in residential subdivisions is the equivalent of 1250 to 1500 mm (50 to 60 inches) of rainfall per year. This is contributing to a general buildup of the water table under some developed areas. This means that the present equivalent precipitation exceeds the Late Pleistocene precipitation when most of the large landslides occurred. Are conditions again becoming favorable for the formation of large landslides along bedding-plane faults or the reactivation of presently stable ancient slides? It seems that the answer may be yes, as described in several examples which follow.

Examples. In the late 1950's, a large 124 lot, residential subdivision was graded in the Skylark Drive area of Oceanside, California. In 1978, after a winter with precipitation about double that of the normal, approximately 10 lots, including eight homes and a portion of Skylark Drive, began to move after almost 20 years of stability. Knowledge of this imminent disaster was discussed among local geologists and an informal visit was made to the site. After viewing the damage and studying aerial photographs taken in 1953, prior to the grading operation (Figure 9), it was obvious that the subdivision had been constructed on an ancient landslide which had probably become reactivated by heavy rainfall and a possible rise in the water table. Today, almost two years after movement began, several homes have been vacated and are in the process of slowly breaking up. A scarp has developed at the head of the slide (Figures 10 & 11) that is approximately 3 to 4 m (10 to 12 feet) in height. Horizontal movements lower in the slide mass appear to be on the order of 1 m (three or four feet). The slide is still progressing slowly, and with each week additional damage is created. Although a subsurface investigation has not been completed, it is believed that a slow buildup of the pore water pressures within the slide mass was primarily responsible for its reactivation.

Another example of an ancient landslide probably reactivated by excessive pore pressure exists in a residential subdivision located near the northern terminus of Carlton Hills Boulevard in the Santee area. In a situation similar to the Skylark Drive subdivision, the Carlton Hills Boulevard subdivision was constructed over 10 years ago (approximately 1969) on an ancient landslide. A large portion of that landslide reactivated during the wet winter of 1978. Two separate investigations of this landslide were undertaken, one financed by the County of San Diego, and a later one by the affected homeowners. Results of these investigations indicated that the piezometric surface existed at, or very near, the ground surface near the head of the reactivated portion of the slide and a much lower piezometric surface existed near the center and toe. Slope stability analyses indicated that the landslide would have had a factor of safety against failure of nearly two without the loss of shear resistance caused by the effect of excessive pore pressures. At present, almost two years after reactivation began, several of the approximately 20 homes situated on the slide have been abandoned because of severe damage. In addition, water, sewer and gas mains are in constant need of repair and the danger of continued movement remains. Homeowners involved in the Carlton Hills Boulevard slide have formed an association and hired a consultant to assist them in determining ways to halt the slide's movement. Consideration has been given to both dewatering and unloading the head of the slide by grading, however, each method represents severe economic hardship for the homeowners.

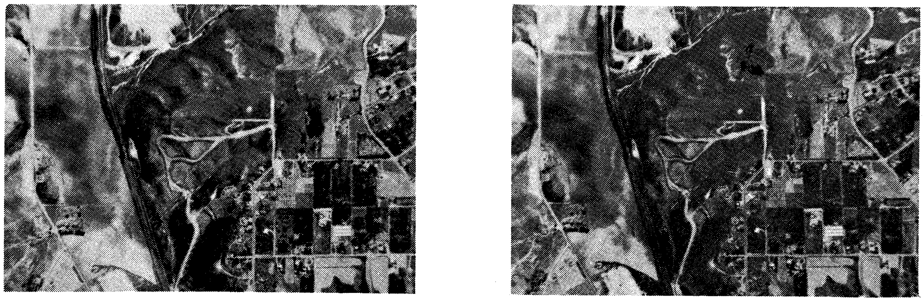

Figure 9. Landslide terrane near the Skylark Drive slide prior to development (1953). Landslide is located below newly graded road, center of photo (1" = 2,200 ft.+).

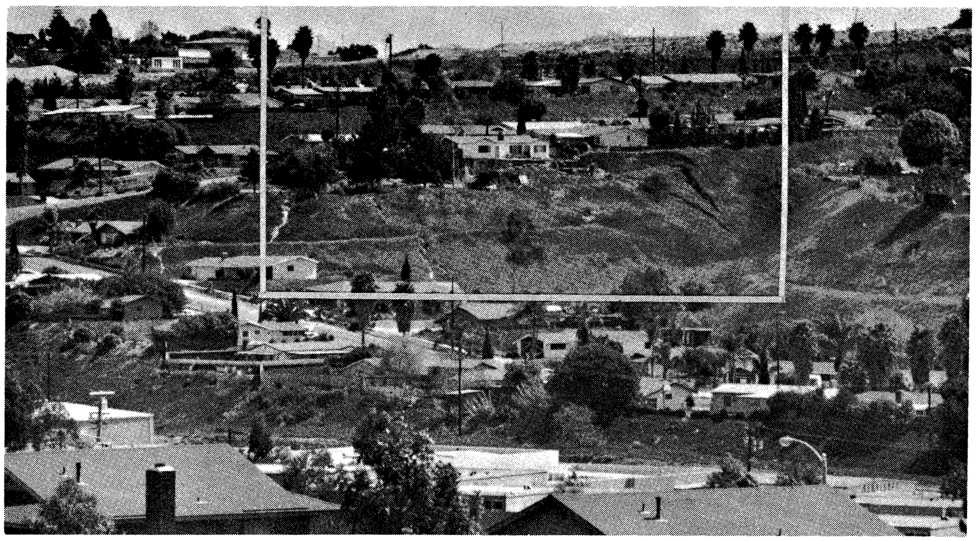

Figure 10. View of southerly portion of scarp, Skylark Drive slide, April, 1979.

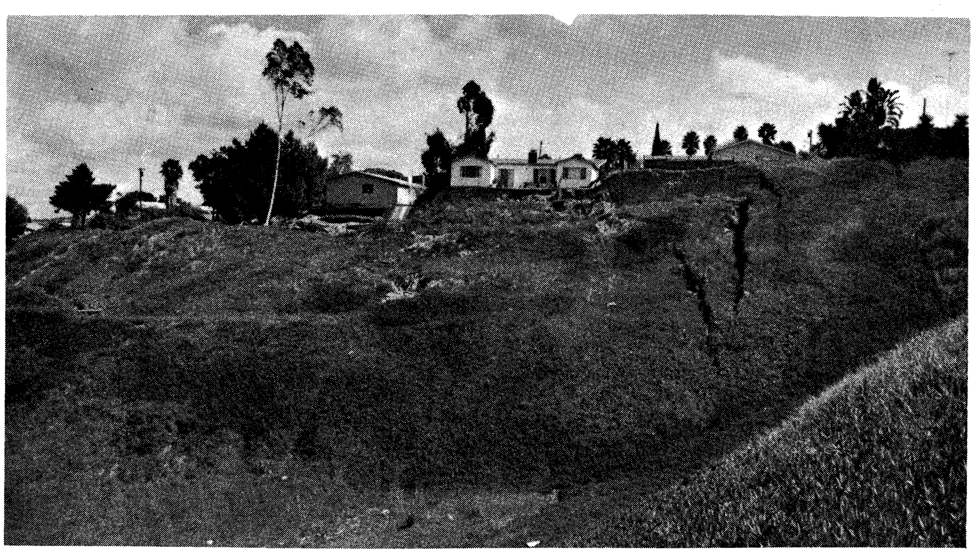

Figure 11. View of active portion of Skylark Drive slide. Area in box is area of Figure 10. Inactive portion extends beyond homes located above new scarp.

Another slow-moving landslide occurred in a densely developed area during the winter of 1978. The evidence strongly suggests that this modern slide developed solely as a result of excessive pore water pressures above a remolded clay layer or bedding-plane fault. Aerial photographs taken prior to development indicate that the presence of an ancient landslide in this locality is unlikely. The geologic consultant for the homeowners indicated that the slide, located near the intersection of Main Street and Westwind Drive in El Cajon, has severely damaged at least three of the 17 year-old residences and has caused lesser damage to approximately five others. According to the consulting soil engineer, groundwater was encountered in their exploratory borings near the head of the slide at a depth of 1 m (four feet) below grade. When pumps were installed and the water table was lowered to approximately 5 m (15 feet), the slide stopped moving.

This landslide is the most sobering for several reasons. First, according to Richard L. Threet, the geologic consultant, the failure plane occurred on a highly plastic clay seam (possibly bentonite) within the Eocene Mission Valley Formation, a unit not previously known to contain such clays or to be prone to landsliding. Second, the failure surface was planar and occurred on a reverse dip of several degrees. Third, if it is true that no ancient landslide existed previously, then this may represent the first case of a <u>modern</u> landslide developing as a result of excessive pore pressures above a plastic clay seam. Landslides such as this one may become increasingly common in the San Diego area as development continues and groundwater levels rise.

LANDSLIDES AND DEBRIS FLOWS IN BASEMENT ROCKS—EASTERN SAN DIEGO COUNTY

SETTING

Basement rocks occur in the eastern two-thirds of San Diego County and form the rugged foothills and peaks of the Peninsular Ranges. Cretaceous granitic rocks, consisting primarily of coarsely crystalline granodiorites, quartz diorites and gabbros make up the bulk of the basement rocks, however, prebatholithic metavolcanic and metasedimentary rocks are common. The metasedimentary rocks consist of well-foliated mica schists and lesser quartzites that are found as generally lenticular roof pendants on the batholithic rocks. The metavolcanic rocks, making up the Santiago Peak Volcanic unit, are composed chiefly of lightly metamorphosed andesites, breccias, and volcanically-derived sedimentary rocks. Many large, ancient landslides and mudflows have been recently discovered in these rocks.

LANDSLIDES

Probably the first large landslide discovered in the prebatholithic rocks was by two students at San Diego State University (Miller and Maulis, 1962). This landslide (Figure 12) is located on the east flank of Granite Mountain in the Anza-Borrego Desert. The Granite Mountain slide is nearly 0.8 km (0.5 mile) in width at the toe, and approximately 1.4 km (4,500 feet) in length from crown to toe. It occurs in folded and faulted Triassic schist cut by numerous pegmatite dikes. Foliation in the schist dips approximately 50 to 60 degrees northeast and is believed to have been a major cause of sliding. The total amount of lateral movement, as evidenced by displacement of dikes and stream channels, is 0.25 to 0.04 km (800 to 1,200 feet).

Several miles to the south of the Granite Mountain slide and just north of County Highway S-2, is the Vallecitos landslide (Hart, 1964). This landslide, which may be part of an even larger, more subtle appearing slide, has an almost circular shape (Figure 13). Although the Vallecitos slide has the characteristics of a classic slump at the head, there appears to be flow-banding near the lobate toe which indicates that portions of the slide may have moved as a viscous flow. The Granite Mountain slide also shows some evidence of flow. The fact that the Vallecitos landslide occurred in relatively unweathered quartz diorite is puzzling, except that it lies near the trace, and possibly directly over the Elsinore Fault. While ancient landslides are not common in granitic rocks, they are a subject of much interest since the causes are generally difficult to determine.

Not all hard-rock landslides are found in the desert areas of San Diego County. Many unnamed and little-known landslides are being discovered as engineering geologists investigate potential subdivision sites. In areas such as Jamul, Escondido, and Alpine, landslides in coarsely-crystalline granitic rocks have been discovered in outcrops where well-developed slip-surfaces are exposed. An excellent example of a slip-surface developed in granitic rock occurs east of Alpine on the north side of Interstate 8, approximately 60 m (200 feet) east of the Willows Road off-ramp. Here a roadcut has exposed the base of a large landslide and its primary zone of shearing, represented by a ±1 foot thick zone of clay gouge and slightly plastic rock flour.

DEBRIS FLOWS

Several large, ancient debris flows occur on the east flank of Viejas Mountain. The largest of these features (Figure 14), is approximately 0.5 km

Figure 12. Granite Mountain landslide, Anza-Borrego desert (1" = 1000 ft.+).

(1500 feet) in width and 2 km (6000 feet) in length. Little work has been done on these interesting landforms. Another interesting flow-like feature was discovered approximately 3 miles northeast of the debris flows on Viejas Mountain on the old Viejas Grade Road (Figure 15). Its shape resembles giant pincers about to close over a resistant outcrop of granitic rock. Note in the photograph in Figure 15, how the flow appears to have gone around this outcrop and that there is evidence that many of the smaller gullies in the vicinity post-date the flow. Little is known of the age of these debris flows. It is probable that they occurred during the same period as the large landslides of the coastal sedimentary belt previously described. They likely formed in a similar manner to recent debris flows, that is, triggered by heavy rains on deeply weathered soil mantle and possibly also as a result of ancient forest or brush fires.

CONCLUSIONS

Understanding of local landslides and related mass wastage phenomena has greatly increased during the past 10 years; beginning with the discovery of the problem in the late 1960's, to progress in understanding the causative mechanisms in the late 1970's. Most geologists now seem fully cognizant of the hazard that landslides represent to hillside development and the great significance that they have played in local erosional processes. Some of the more interesting work is still before us such as determining which areas might be subject to new sliding or reactivation of old landslides.

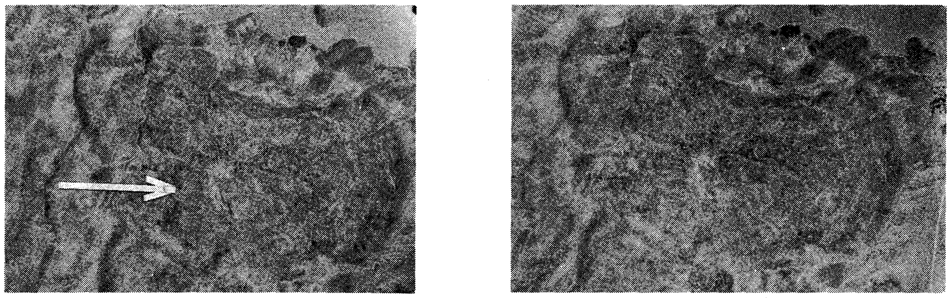

Figure 13. The Vallecitos landslide, arrow points to scarp (1" = 4,000 ft.+).

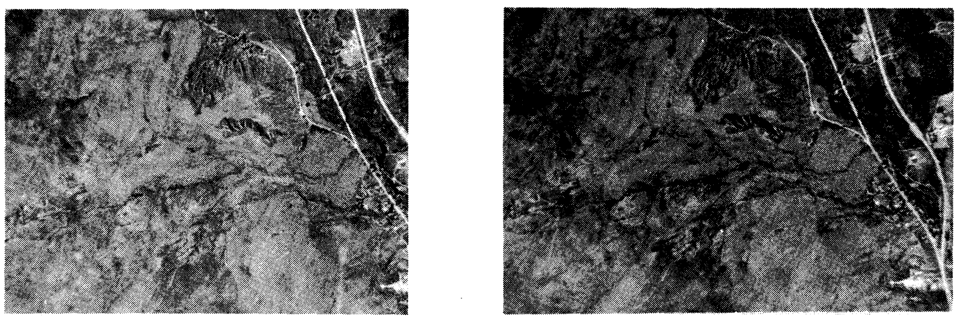

Figure 14. Viejas Mountain debris flow, right center of photo (1" = 4,000 ft.+).

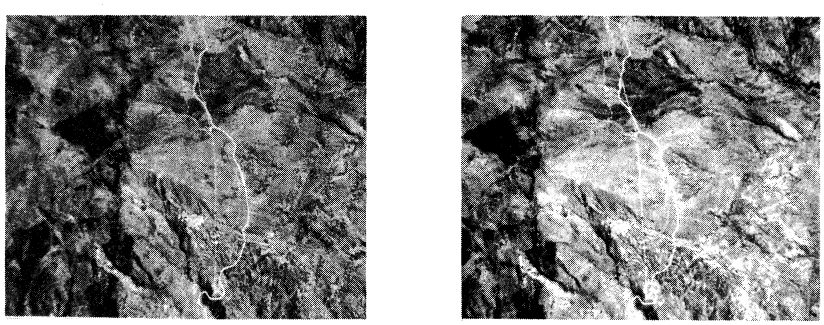

Figure 15. Viejas grade debris flow (1" = 3,000 ft.+).

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EXPANSIVE SOILS IN SAN DIEGO, CALIFORNIA

by

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INTRODUCTION

The population increase in the United States during the recent years has, to a large extent, been concentrated in the suburbs of the larger cities. Thus, there has been a significant effort to prepare master planning of these areas to best utilize the land at the lowest cost (Gizienski, 1965). In this regard, the geologist and engineer must provide input to the planning process for proposed developments on the effects of subsurface conditions, such as expansive (swelling) clay soils (Holtz, G.W. and Hurt, S.S., 1978). Expansive soils are relatively widespread in the San Diego area, and can have a significant effect on plans and development costs.

The problem of expansive soils was generally identified as being a significant problem in San Diego in the early 1960's, and has become more important as San Diego's population has increased. The major area of concern has been in residential housing. It is, therefore, important that during initial land development planning, the identification and location of expansive soils be carefully considered.

The distribution of expansive soils in San Diego can be generally related to the areal distribution of the geologic formations. Formations which contain the most highly expansive materials are the Delmar, Friars, Sweetwater, Otay, and the Quaternary coastal terraces.

The classification of expansive soils is generally based on conventional laboratory tests, and correlated with experience. This information can then be used, along with environmental factors, to evaluate potential heave and possible damage to structures.

Several design and construction methods have been used successfully in the San Diego area to reduce the risk of severe structural damage from expansive soils. Geologists and engineers cannot guarantee solutions for every swelling soil problem. However, damage can be mitigated by having a general knowledge of successful design, construction, and maintenance methods (Woodward, Clyde, Sherard and Associates, 1968).

DISTRIBUTION AND CLASSIFICATION OF EXPANSIVE SOILS IN SAN DIEGO

The distribution of expansive soils is generally a result of the geologic history, paleo climatic conditions, and the types of mineral alteration. In order to provide an indication of the location of swelling soils in San Diego, the geologic formations in San Diego which contain materials with swelling potential have been identified, and their distribution obtained from geologic maps (Weber, 1963; Kennedy, 1975; Kuper and Gastil, 1977.) This information is discussed in the following paragraphs, and is summarized in Figure 1 and Table 1.

The geologic formations in the San Diego area may be subdivided into four groups: 1) Jurassic and Cretaceous hard-rock units; 2) Cretaceous moderately indurated sedimentary formations; 3) poorly to moderately indurated Tertiary and Quaternary sedimentary rocks; and 4) largely unconsolidated Quaternary sedimentary units. The geologic column shown in Table 1 presents the various formations found in the San Diego area; a description of each soil unit is shown, as well as a classification according to expansive soil characteristics. For the purpose of this paper, the potentially expansive soil groups indicated in Table 1 are categorized as follows:

1a. Igneous and metamorphic rock with localized expansive surface soils,

1b. Sedimentary rocks with localized expansive surface soils,
2. Low to medium expansive soils,
3. Low to medium expansive soils with localized distribution of highly expansive soils, and
4. Medium to highly expansive soils.

Omitted from categories 2, 3 and 4 is the soil mantle which is generally relatively thin (less than 5 feet), and occurs over most of the San Diego area. These surficial materials exhibit a wide range of expansive characteristics, from low to very high, and should be considered in any development as a potential problem.

The general extent of the five expansive soil categories in San Diego is shown on the attached map (Figure 1) to illustrate their approximate distribution. As the boundaries shown are highly generalized, the map is intended only to provide a relative distribution of the types of expansive soils in the San Diego area.

Hard-rock units (Category 1a) with a low expansion potential are found generally east of a rough northwest-southeast diagonal line extending across the center of the study area. A few outlying knobs are present adjacent and just west of this imaginary line. These rocks are crystalline granitic, fine-crystalline meta-volcanic, and meta-sedimentary materials. While exhibiting a thin localized clayey overburden, they typically do not present significant expansive clay problems.

Sedimentary formations of low expansion characteristics (Category 1b) and with localized surface expansive soils are found throughout the geologic column (Table 1). All except one of the Cretaceous sedimentary units, present in the Point Loma and La Jolla coastal areas, fall into this group. In the Tertiary formations, granular rocks composed of nonexpansive sandstone and conglomerate extend over a relatively large area south of Poway, between Poway Valley and the El Cajon Valley. In addition, nonexpansive Tertiary formations seem to be found in irregularly-shaped areas north of Mission Valley, east of Rose Canyon, and west of the hard-rock boundary. An exception to this is the nonexpansive San Diego Formation, which extends

TABLE 1

GEOLOGIC COLUMN

Geologic Formation	General Description	Expansive Soil Classification
Alluvial Soils-Inland Valleys	Interbedded Sands and Clays	2
Alluvial Soils-Coastal Areas and Coastal Canyons	Sands, Silts, and Gravels	1b
Bay Point Formation	Sands and Gravels	1b
Low Coastal Terrace Deposits of South San Diego	Clays and Silts	4
Lindavista Formation	Sands, Cemented Gravels, and Clays with Gravels	2
San Diego Formation	Fine Sands	1b
Otay-Rosarito Beach Formation	Clays, Bentonitic Clays, and Silts with Sands	4
Sweetwater Formation	Clays, Sandy Clays, and Clayey Sands	4
Pomerado Conglomerate-Poway Group	Gravels with Sands	1b
Mission Valley Formation-Poway Group	Sands with Lean Clay Lenses	3
Stadium Conglomerate-Poway Group	Gravels with Cobbles and Sand	1b
Friars Formation-La Jolla Group	Clays with Sands	4
Scripps Formation-LaJolla Group	Sands	1b
Ardath Shale-La Jolla Group	Silts and Sands with Lean Clays	3
Torrey Sandstone-La Jolla Group	Sands	1b
Del Mar Formation-La Jolla Group	Clays with Sands	4
Mount Soledad Formation-La Jolla Group	Sands and Gravels	1b
Cabrillo Formation Sandstone-Rosario Group	Sands and Gravels	1b
Cabrillo Formation Conglomerate-Rosario Group	Sands and Gravels	1b
Point Loma Formation-Rosario Group	Sands with Silts	2
Lusardi Formation-Rosario Group	Sands with Gravel	1b
California Batholith-Hard Rocks	Granitic Rocks	1a

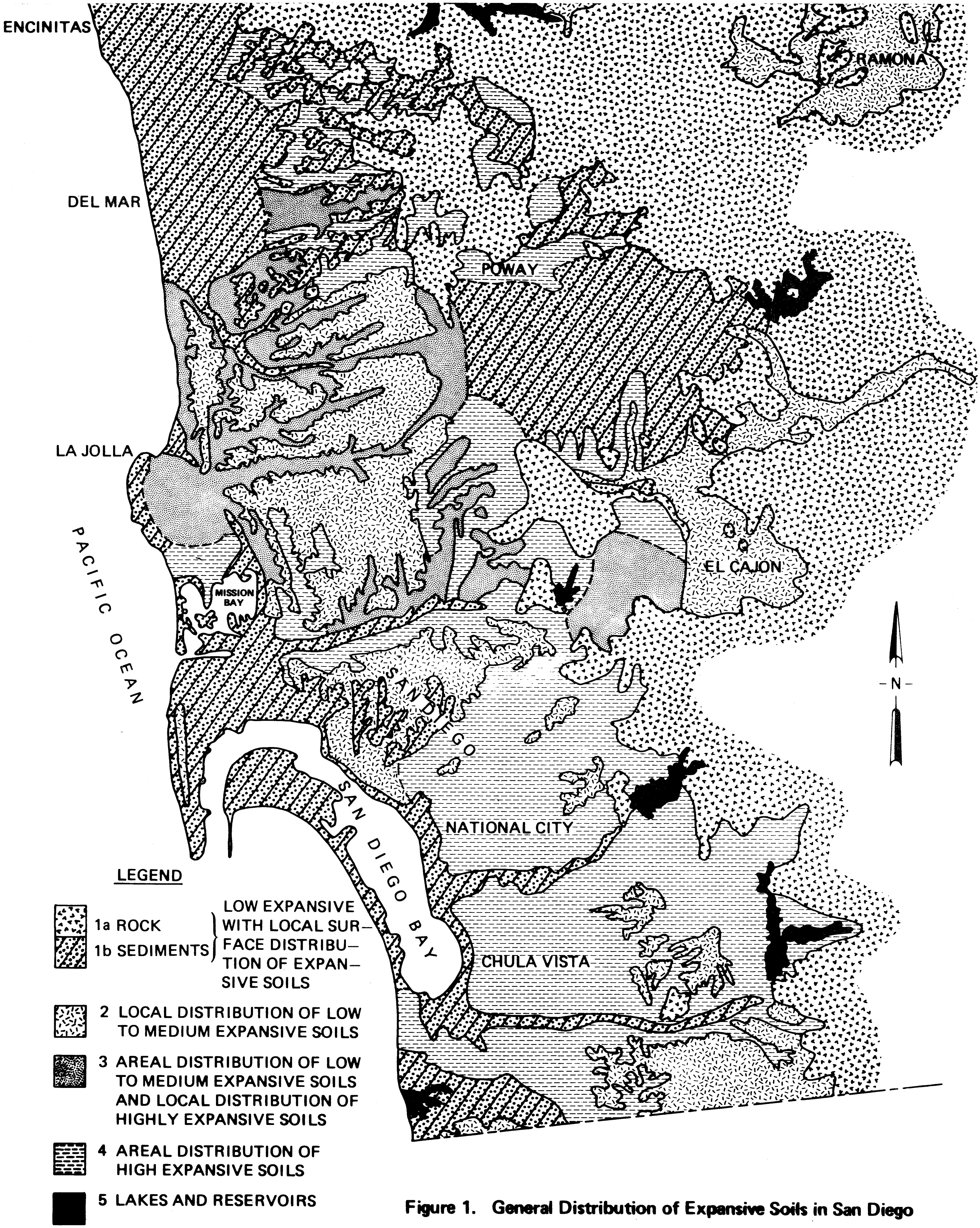

Figure 1. General Distribution of Expansive Soils in San Diego

south from Mission Valley and constitutes a major portion of the rocks underlying the higher elevations of the San Diego mesa. Alluvial soils in the lower valley areas and in the narrow canyons are primarily composed of nonexpansive sands and gravels. Other areas of low expansive materials are found around the northern end of San Diego Bay, Mission Bay, and the low coastal areas of La Jolla, Coronado, and the Silver Strand.

Three formations contain localized distributions of low and medium expansive materials (Category 2). These are: 1) the Point Loma Formation, which contains some shale beds; 2) the widespread Lindavista Formation; and 3) the recent alluvial soils of the inland valleys, such as El Cajon, Poway, Ramona, and San Pasqual. The Lindavista Formation, capping the mesas, is primarily composed of sands and cemented gravels, and is interbedded, particularly near the eastern boundary, with clay and clayey gravel.

Formations having areal distributions of low to medium expansive soils (Category 3) are the Ardath Shale and Mission Valley Formation. The Ardath Shale is found in Rose Canyon, the steep slopes of Mission Valley, and the steep sides of other inland valleys, such as Penasquitos, Carmel, and Carroll canyons. The Mission Valley Formation is found on the steep northern and southern slopes of Mission Valley, in the San Carlos and higher areas northwest of Mission Gorge, and, to a lesser degree, in areas south of Mission Valley.

In the northern portion of the study area, formations of high potential swell (Category 4) include the Delmar Formation, found in valleys to the east of Del Mar, Encinitas, and in the Rancho Santa Fe area. The Friars Formation, a unit with bad expansive soil problems, is found in the valley areas further to the east of Del Mar; in the Penasquitos and Rancho Bernardo areas; the western slopes of El Cajon Valley; Fletcher Hills; valley areas of western Kearny Mesa; eastern tributaries to Tecolote Canyon and Murphy Canyon; and in tributary valleys to the Mission Gorge area. The Sweetwater Formation and the Otay Formation now considered to be part of the Rosarita Beach Formation (Kuper and Gastil, 1977), are found south of

Mission Valley, and in the higher elevations east of Chula Vista and National City. Low coastal terrace deposits of highly expansive clays are found underlying National City and Chula Vista, and lower coastal terraces south of San Diego.

IDENTIFICATION OF EXPANSIVE SOILS

The potential for swell is dependent primarily on the properties of the soil, such as gradation, plasticity, type of minerals, mineral structure, density, and moisture content. The actual amount of swell or shrinkage beneath structures or pavements is dependent not only on the properties of the soil, but also on the environmental conditions producing moisture change, and the depth and thickness of the clayey layers.

Numerous procedures for identifying the soils that possess expansion characteristics have been developed, and have been combined with experience to provide a basis for evaluating whether or not damage to a particular type of structure may occur. Several tests have been used by soils engineering consultants in southern California (Table 2). Classification systems have been developed from these tests which generally categorize expansive soils into four broad classifications. Table 2 gives an approximate comparison of the currently used methods (Portland Cement Association, 1971).

EVALUATION OF POTENTIAL HEAVE

The "effective depth" or normal depth of water penetration in the San Diego area depends primarily upon the amount and duration of the annual rainfall, the type of vegetation, and the amount and frequency of irrigation. San Diego is in a relatively warm, arid climate where surface evaporation exceeds annual rainfall. Thus, a moisture deficiency exists in the ground which may extend to depths of 10 to 15 feet. Because the water table is generally well below the construction grades, and because the natural water content of the clays is relatively low, the soil moisture profile in San Diego is governed primarily by natural seasonal fluctuations, and by fluctuations due to intermittent irrigation. In much of the San

TABLE 2

CLASSIFICATION OF EXPANSIVE SOILS (after Portland Cement Association, 1971)

SOIL TEST	APPROXIMATE RANGES			
PLASTICITY INDEX and CLAY CONTENT (less than .002 mm)	5-15 5-15%	10-25 10-25%	20-45+ 20-30%	35+ 30-45%
LOADED SWELL TEST Swell 60 lb. Surcharge Swell 144 lb. Surcharge Swell 650 lb. Surcharge	 0-4% 0-3% 0-1%	 4-9% 3-6% 1-3%	 9-12% 6-10% 3-5%	 12%+ 10%+ 5%+
WEIGHTED EXPANSION INDEX SAN DIEGO COUNTY TEST (Ordinance 2895)	0-20	20-60	60-100	100+
FHA - PVC METER	0-2	2-4	4-6	6+
EXPANSION CLASSIFICATION	LOW	MODERATE	HIGH	VERY HIGH

Diego area, soil water variations due to these phenomena probably do not extend beneath depths of approximately 4 to 6 feet below the ground surface under normal conditions. Thus, for most design considerations, expansive clay layers below a depth of 6 feet (measured from finish grade) do not have a significant influence on foundation or concrete slab-on-grade design.

The maximum total heave which may be expected under a structure can be computed from the area under the percent swell versus depth curve (Gizienski and Lee, 1965). It is the authors' experience that in San Diego a reasonably conservative estimate of total heave under normal conditions is obtained by using the maximum percent swell for air-dried soils under a 1 psi load, and an "effective depth" of approximately 4 feet. Experience has indicated that differential movement will generally not be more than 50% of the total or maximum heave; however, this can be influenced by localized moisture changes.

Typical estimates of total and maximum differential heave under normal conditions for the various soil classification in the San Diego area are:

Expansion Classification	Total Heave	Differential Heave
Low	0 to 3/4"	1/2"
Moderate	3/4 to 1-1/2"	3/4"
High	1-1/2 to 2-1/2"	1-1/4"
Very High	over 2-1/2"	over 1-1/4"

Care should be taken to properly evaluate those conditions which may not be considered typical, and which may require detailed analysis. Such conditions include:

a) Water table within 10 feet of lot grade,
b) Drainage conditions which could lead to ponding and/or the accumulation of excessive water and/or significant penetration of water below a depth of 4 feet,
c) Clay strata with relatively high water contents which could shrink, causing settlement, as well as heave,

d) A relatively thick (greater than 4 feet) layer of highly expansive clay located at or near finish grade,

e) Areas which may be exposed to conditions of excessive water, such as near a swimming pool.

TOLERABLE HEAVE FOR RESIDENTIAL STRUCTURES

No generalization can be made regarding a mode of distress to structures due to expansive soils in San Diego. Where these soils are present near finish grade the type of damage most commonly observed to houses constructed on conventional slabs-on-grade consists of slab heave and breakage with the greatest amount of heave occurring in the center of large rooms. Interior partitions and walls may inhibit slab heave, but do not prevent it, and cracks in interior wall finish are common. In general, damage to exterior walls is less severe.

Except where a structure is connected to a supported utility or adjacent structure, differential heave within the structure, rather than total heave, generally causes damage. The tolerable differential movement of structures depends primarily upon the type of construction. Approximate values of differential heave for various structures that can occur without serious damage to frame or finish are listed below:

a) One or two-story houses with plane brick bearing walls and light structural frame can generally tolerate approximately 1/2" differential heave in a 20 feet distance.

b) Wood-frame houses can generally tolerate differential movements of up to 3/4" if properly braced in the ceilings and walls.

c) If the structures have sensitive interior or exterior finish such as plaster, ornamental stone, or tile facing, the differential movement should generally be limited to 1/4" to 1/2" maximum in a 20 feet distance.

d) If the structure is provided with a relatively rigid raft or mat foundation which will tend to redistribute the loads, total heaves of up to 2 inches or more may be tolerated.

QUALITY STANDARDS FOR EVALUATING DAMAGE

The tolerable heave of a structure is generally reflected in the acceptable extent of observable damage. The Home Owners Warranty Program (HOW) has developed some quality standards that are expressed in terms of performance standards. The format is designed for easy comprehension by both layman and builder (Home Owners Warranty Program, HOW, 1974). Items which pertain to possible damage due to heaving are presented in Table 3.

TREATMENT OF EXPANSIVE SOILS

Potential heaving of structures may be minimized by 1) excavating the expansive material and replacing it with properly compacted, nonexpansive granular fill, 2) presaturation of in-place soils, or 3) using belled piers founded below the depth of swelling (and supporting the floors between these piers). In the latter case, provisions for an opening or compressible filler beneath the floors is necessary. Damage due to swelling under light structures may also be minimized by the use of 1) slab or raft foundations, 2) dry wall construction, 3) steel or reinforced concrete framing, or 4) making provisions for jacking.

TABLE 3

QUALITY STANDARDS FOR EVALUATING DAMAGE TO RESIDENTIAL STRUCTURES

Possible Deficiency	Performance Standard
Improper drainage of the Site.	The necessary grades and swales should be established to insure proper drainage away from the house. No standing water should remain in the yard 24 hours after a rain, except swales which may drain as long as 48 hours after a rain, or sump pump discharge.
Basement or foundation wall cracks.	Non-structural cracks are not unusual in concrete foundation walls. Such cracks greater than 1/8 inch in width are considered excessive.
Cracking of basement floor.	Minor cracks in concrete basement floors are common. Cracks exceeding 3/16 inch width or 1/8 inch in vertical displacement are considered excessive.
Cracking of attached garage slab.	Cracks in garage slabs in excess of 1/4 inch in width or 1/4 inch in vertical displacement are considered excessive.
Cracking, settling, or heaving of stoops or steps.	Stoops or steps should not settle or heave in excess of 1 inch in relation to the house structure. No cracks except hairline cracks (less than 1/16 inch) are acceptable in concrete stoops.
Cracks in attached patios.	Cracks in excess of 1/4 inch width or in vertical displacement are considered excessive.
Cracks in concrete slab-on-grade floors.	Cracks which significantly impair the appearance or performance of the finish flooring material shall not be acceptable.
Cracks in masonry walls or veneer.	Small cracks are common in mortar joints of masonry construction. Cracks greater than 1/8 inch in width are considered excessive.

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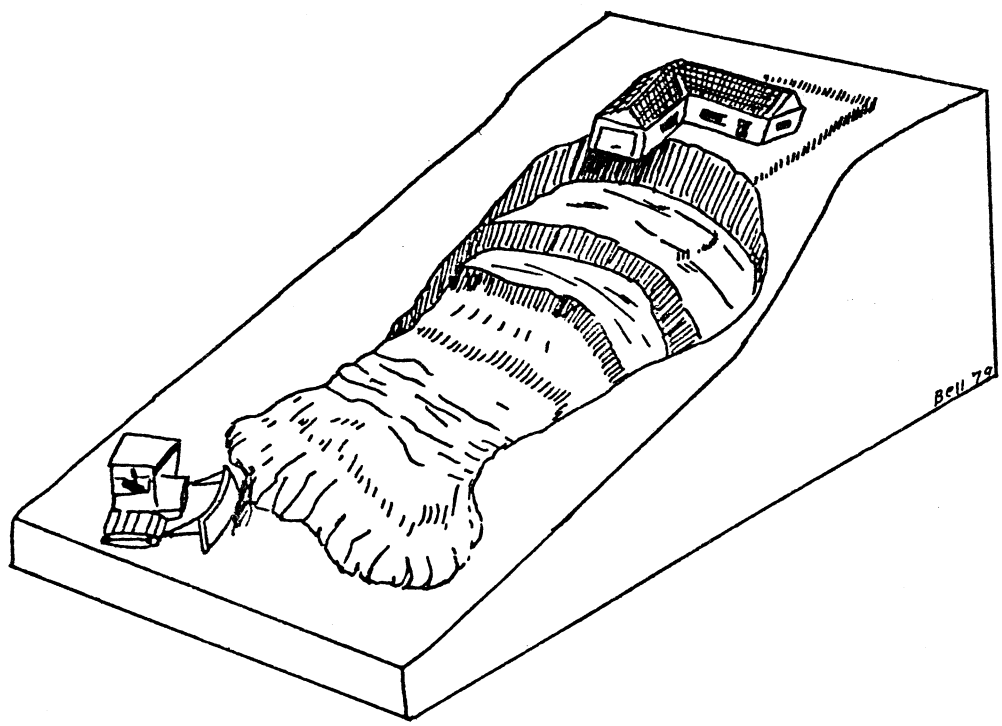
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SEA-CLIFF EROSION AT SUNSET CLIFFS, SAN DIEGO*

by

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Sea-cliff erosion at Sunset Cliffs is the result of ocean-wave action along prominent joints that are oriented obliquely to the cliff face. This in turn has led to the development of surge channels and sea caves in the cliffs. Sea-cliff retreat has averaged about 3 feet (1 m) in the past 75 years, and is associated with channel and cave development. However, where collapse of a cave roof occurs, local sea-cliff retreat can be as much as several feet in a moment. This dramatic and sudden local effect may give a false impression of rapid, regional cliff retreat.

Sunset Cliffs is a scenic, residential area in the City of San Diego, forming the northernmost part of the Pacific sea cliffs on the Point Loma Peninsula. During the past 20 years, portions of the cliff have been rapidly eroded. This cliff retreat is primarily the result of roof collapse of individual sea caves.

Sea caves are formed by wave action. The energy of the waves is concentrated and funneled along prominent joint sets in the cliff rock, gradually widening these joints to form surge channels and sea caves. Wave erosion progresses headward, laterally, and upward in the formation of sea caves, leading to uniform hollowing and eventual roof collapse. Some sea caves extend landward as much as 60 feet (19 m) from the sea-cliff face.

Since the early 1950's, roof collapse has been accelerated slightly as a result of the loss of beach sand at the base of the cliffs. In the past, the sand buffered much of the now continuously exposed sea cliffs from direct wave attack during several seasons of the year. A number of single-family dwellings, public utilities, and streets lie dangerously close to several mature sea caves.

As part of a detailed geologic study of the City of San Diego, the California Division of Mines and Geology in cooperation with the City of San Diego, investigated the nature of marine erosion at Sunset Cliffs. Detailed geologic maps (scale 1:2400) were prepared to show the geologic features controlling the erosion of the sea cliffs (Kennedy, 1966). The present report, based upon that study (and later work by the U. S. Army Corps of Engineers), suggests a possible

* Reprinted from California Geology, v. 26, February 1973, p. 27-31.

geologic basis for sea-cliff retreat at Sunset Cliffs. Numerous photographs were used to document the average annual rate of this retreat.

GEOLOGIC SETTING

Sunset Cliffs is underlain by marine Upper Cretaceous and Pleistocene sedimentary rocks. These rocks form a portion of the western limb of the Pacific Beach syncline (Kennedy and Moore, 1971), the southern extension of which is submerged beneath Mission Bay.

The Upper Cretaceous rocks, part of the Point Loma Formation (Kennedy and Moore, 1971), strike N 5° to 15° W and dip 3° to 10° E in the area studied (Figure 1). These rocks crop out continuously along the west-facing sea cliffs of Point Loma and are predominantly olive-gray, thin-bedded, well-indurated, marine sandstone and siltstone. They contain calcareous nannoplankton of Late Cretaceous (Campanian to Maestrichtian) age (Bukry and Kennedy, 1969).

The flat-lying Pleistocene deposits of the Sunset Cliffs area belong to the Bay Point Formation of Hertlein and Grant (1939, 1944). These rocks, where preserved, rest unconformably on the Point Loma Formation (Figure 3). Here the Bay Point Formation is a well-indurated sandstone which is light brown, medium to coarse grained, poorly sorted, poorly bedded, and locally well cemented. Fossil-bearing rocks at the base of the Pleistocene section (exposed at many locations on the west side of Point Loma Peninsula), correlate with fossiliferous strata 13 miles (21 km) to the north. These fossiliferous strata are reported to be late Pleistocene (Sangamon) in age (Kern, 1971).

The contact between the Pleistocene deposits and underlying Upper Cretaceous rocks is approximately 30 feet (9 m) above sea level at the southernmost part of Sunset Cliffs, sloping to near sea level at the northernmost exposures in Ocean Beach. This suggests a slight tectonic warping toward the Pacific Beach syncline during late Pleistocene time. The lowest rocks exposed in the cliffs belong to the Point Loma Formation. Two prominent vertical joint sets cut the Point Loma Formation at intersecting angles that strike N 30° to 40° E and N 40° to 50° W. Large rectangular blocks have been formed by the intersection of these joint sets with erosion by wave action taking place readily along these joints.

EROSIONAL PROCESSES

The processes of sea-cave formation in Upper Cretaceous rocks at La Jolla were described by Moore (1954). The rocks at Sunset Cliffs and La Jolla are

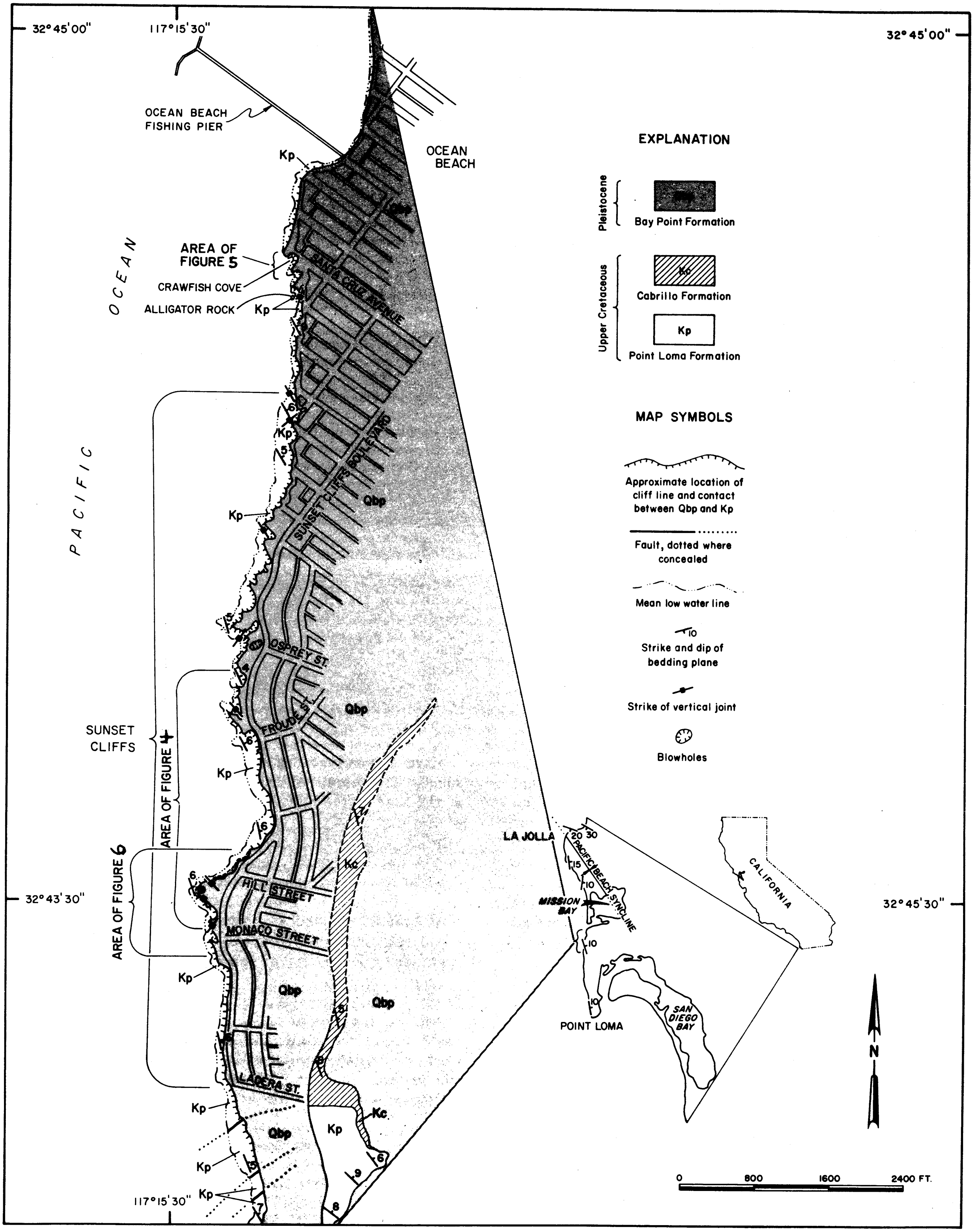


Figure 1. Geologic sketch map of Sunset Cliffs, San Diego County.

lithologically the same and lie at similar stratigraphic positions within the Point Loma Formation. The rocks at La Jolla form the northeast limb of the Pacific Beach syncline, with those at Sunset Cliffs forming the southwest limb.

The beginning stage of sea-cave development is the formation of surge channels. These channels are numerous at Sunset Cliffs (Figure 2). The channels, which follow the intersecting joint planes, gradually evolve into caves by progressive basal undercutting. The cave excavation is aided by the concentration and agitation of abrasive sand particles along these joints. Headward erosion begins along individual joint planes accompanied by gradual lateral and vertical widening. Erosion continues along a joint plane until an intersection with a cross-cutting joint plane is reached. Wave erosion then begins excavation along the intersecting plane as well as continuing headward, resulting in a broadened inner part of the cave. The caves marked C1 and C3 (Figure 2) have formed at such intersecting joint planes, as shown by their shape.

Internal cave erosion progresses until either all, or part of the roof collapses. Commonly, only part of the roof collapses so that a blowhole and natural bridge are formed such as those marked T1 and T2 (Figure 2). Upon later erosional removal of the natural bridge, or in the case of complete initial roof failure, embayments develop such as those shown to the right and left of T2 (Figure 2).

The photographs in Figures 4, 5, and 6 show that sea-cave development at Sunset Cliffs has taken many years. For example, there are only slight erosional changes for the 66-year interval between the photographs in Figure 5; this is evidence that time far in excess of 66 years is needed to carve even small surge channels here.

Periodic roof-collapse accompanied development of the sea cave shown in Figure 6 prior to the covering of its mouth by the City of San Diego in about 1960. The foreground rock that supported the wooden bridge in the 1920 photograph collapsed in the late 1940s. This alerted the City to possible future hazards related to similar failures. The grass-covered slope in the foreground of the 1971 photograph is underlain by about 10 feet (3 m) of artificial fill which was bulldozed over the rockfall area of the early 1950s. The 1971 photograph also shows that the stone bridge-support at the contact between fill and bedrock on the far side of the channel has not yet been completely eroded away.

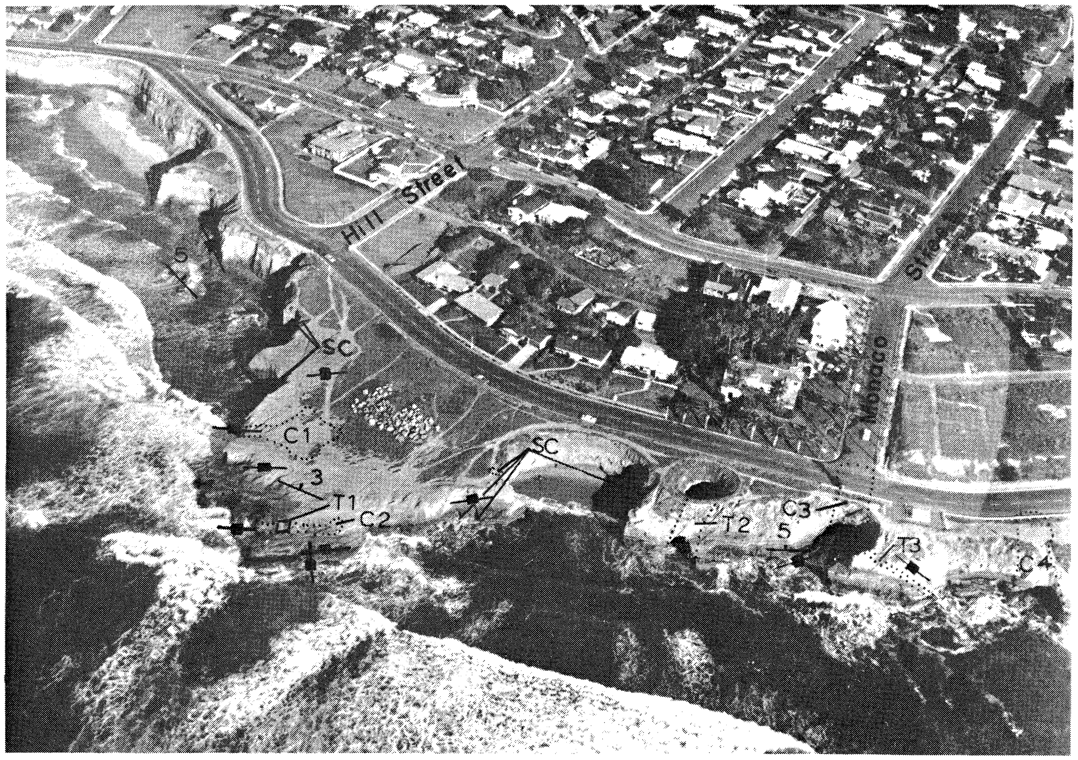
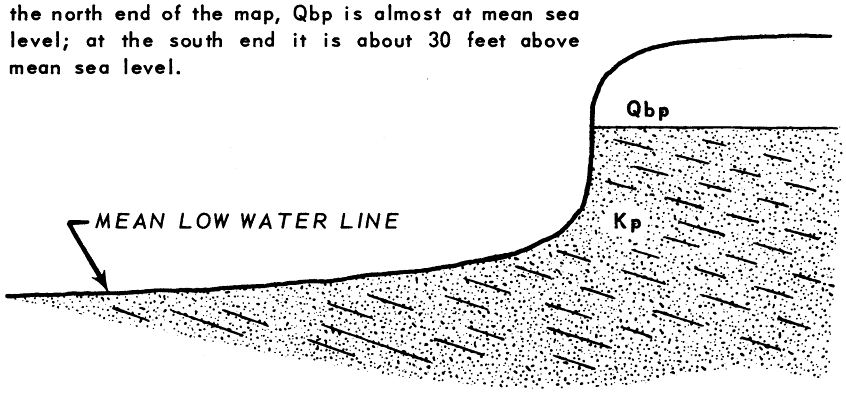


Figure 2. Photograph taken at Sunset Cliffs in 1968 during an afternoon positive 2- to 4-foot tide showing erosional features carved by ocean waves. The small headland between C1 and C2 is exposed to wave attack continuously throughout the tidal range whereas T2, T3, C3, and C4 are actively eroded only above the positive 1- to 2-foot tidal range. Dotted lines outline sea caves and tunnels; SC, surge channel; C1, C2, C3 and C4, sea caves; T1, T2, and T3, tunnels; 15, strike of vertical joint; ■, strike and dip of bedding.

Figure 3.
The schematic cross-section shows the relationship between Qbp and Kp in the face of the cliff. At the north end of the map, Qbp is almost at mean sea level; at the south end it is about 30 feet above mean sea level.



RATES OF EROSION

The rates of marine erosion at Sunset Cliffs were determined largely by studying old photographs and comparing them with newer ones. The rates have been small on a regional scale but large locally (Shepard and Grant, 1947; Shepard and Wanless, 1970).

The rapid local rate of sea-cliff retreat is controlled primarily by differential erosion of the softer rock. Shepard and Wanless (1970), in a statement regarding Sunset Cliffs, said, "Most of the stacks and natural bridges adjacent to the shale cliffs have shown conspicuous changes in recent years. However, at the north end of Sunset Cliffs, we have an example where sandstone cliffs had only very minor changes since photographed in 1887."

Within the area of the map, the average annual rate of erosional retreat of sea cliffs was appraised for a 75-year period. This was accomplished by averaging rates of those areas that have had essentially no retreat, those that locally have had large amounts of retreat for this period of time.

Approximately 75 percent of the sea-cliff area studied during this investigation has undergone no appreciable erosion during the past 75 years. Photographs of the area between Froude and Hill Streets taken in 1950 and in 1968 (Figure 4) show very little erosion for that 18-year period. Photographs taken in 1905 and 1971 of the area adjacent to Crawfish Cove at the foot of Santa Cruz Avenue (Figure 5) show that this area has undergone very minor erosional alteration in 66 years.

More than 20 percent of the cliff area has undergone erosion at a rate that is small, but measurable, for that period of time. According to Shepard and Grant (1947), a natural arch at Sunset Cliffs collapsed in the late 1930s with only a small remnant of the buttress standing in 1947. They also reported that a sea stack 10 feet (3 m) high and 3 feet (1 m) square, at the mouth of a prominent joint-controlled surge channel at Ocean Beach, was completely eroded away between 1887 and 1946. The sea-caves and tunnels at the foot of Monaco Street (Figure 2) have been eroded locally as much as 5 inches (13 cm) between 1965-1972.

Less than 5 percent of the sea-cliff area has undergone very rapid retreat (as much as 10 feet (3 m) in the past 75 years), and in each place where this much retreat has been documented, it is the result of sea-cave collapse. The partially collapsed sea cave that lies at the foot of Osprey Street (Figure 6) and extends more than 20 feet (6 m) landward from the sea-cliff face beneath Sunset Cliffs Boulevard, retreated nearly 5 feet (1.5 m) during one year in the

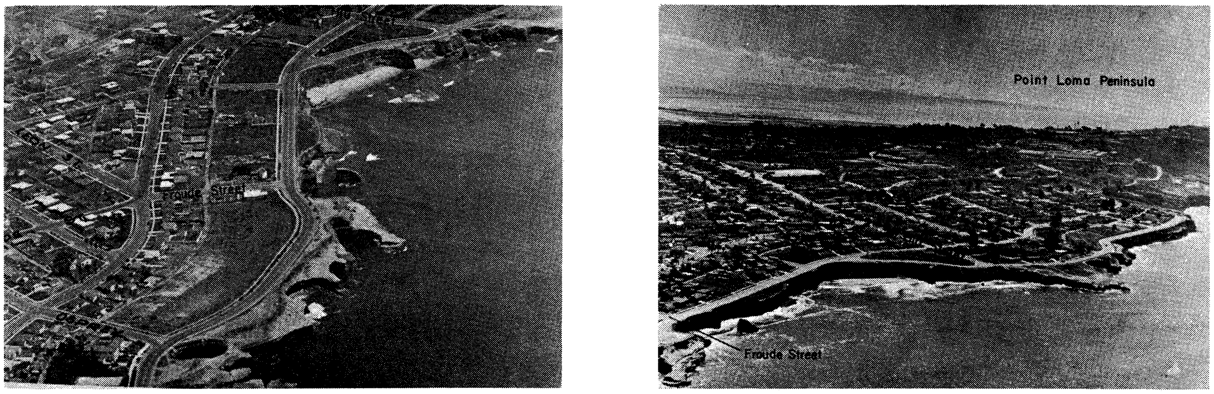


Figure 4. Photographs taken at Sunset Cliffs in 1950 (left) and 1968 (right). View southeast of the area between Froude Street and Hill Street. The buttress at the foot of Froude Street, the rocky headland south of Hill Street, and the southeast-striking tunnels inland and adjacent to the dog-leg promontory north of Froude Street have been little changed during the 18 year period between these photographs. (Older photograph courtesy of San Diego Title Insurance and Trust Company).

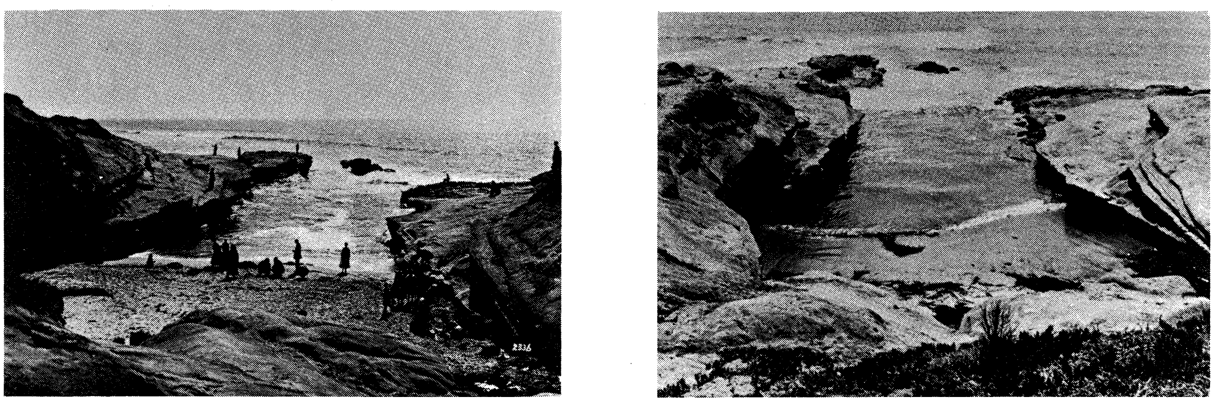


Figure 5. Photographs taken at Sunset Cliffs in 1905 (left) and 1971 (right). View southeast of Crawfish Cove at the foot of Santa Cruz Avenue. This cove has developed along several prominent, northeast-striking joint planes. Notice that the rocks at the mouth of the cove, which remain under wave attack at all tidal ranges, still exist in the 1971 photographs. Very slight erosional effects have occurred during the 66-year interval between these photographs. (Older photograph courtesy of San Diego Title Insurance and Trust Company; newer photograph by W. P. Reetz, Scripps Institution of Oceanography, La Jolla).

late 1940s. The wooden bridge and a portion of Sunset Cliffs Boulevard shown in the early photograph (Figure 6) were destroyed during that year.

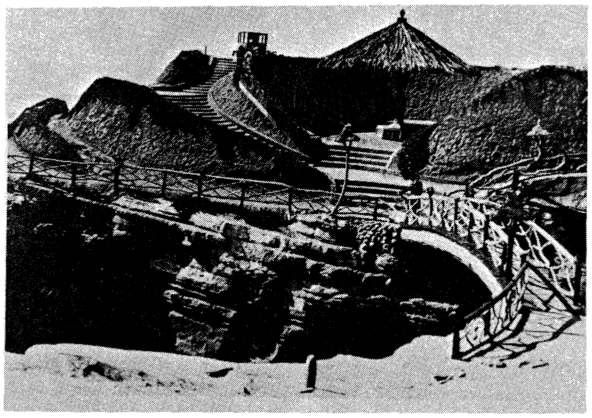
The average rate of sea-cliff erosion along Sunset Cliffs has probably accelerated slightly during the past 20 years, due to a very gradual, slight loss of beach-sand deposits that once protected the cliffs from wave action. Peacock (1965) concluded that beach deposits have dissipated at Sunset Cliffs as a result of the Mission Bay jetty development in 1951. His report suggested that the jetty has deflected seaward much of the southward-moving longshore current which transports sediment vital to the permanence of a sand beach along the shores of Point Loma. Recommendations were made to build concrete cliff-revetments, seal the sea-cave openings, and construct an artificial beach so that further cliff failures could be minimized. Revetment construction and sea-cave closures were completed in late 1971 following Corps of Engineers; Design Memorandum for Sunset Cliffs--Segment B, April 1970. Artificial beaches were not emplaced because of opposition by local property owners. In their desire to keep Sunset Cliffs esthetically pleasing, they fought against the development of what they were afraid would become a busy public recreation area and won their case as the result of public hearings held by the City.

The combined average rate of sea-cliff retreat at Sunset Cliffs is estimated to have been almost one half inch (1.25 cm) per year, or slightly more than 3 feet (1 m) for the 75-year period immediately preceding the development of the revetments and the closure of the sea caves.

CONCLUSIONS

Erosion and retreat of the sea cliffs at Sunset Cliffs is controlled largely by joint planes in the cliff rock along which ocean waves and abrasive sand are funneled. Surge channels, tunnels, and sea caves have been formed by the scouring of sedimentary rock adjacent to the joints.

By comparing old photographs belonging to the San Diego Title Insurance and Trust Company with later photographs and observations, the average amount of sea-cliff retreat during the past 75 years is estimated to be more than 3 feet (1 m). This average rate is high because of the rapid rates associated with local sea-cave collapse. The actual rates of sea-cliff retreat, which are regionally negligible and locally high, are in general agreement with estimates suggested by most earlier workers who have considered sea-cliff retreat rates associated with similar kinds of bedrock elsewhere along the coast of southern California (Emery, 1941; Moore, 1954; Shepard and Grant, 1947;



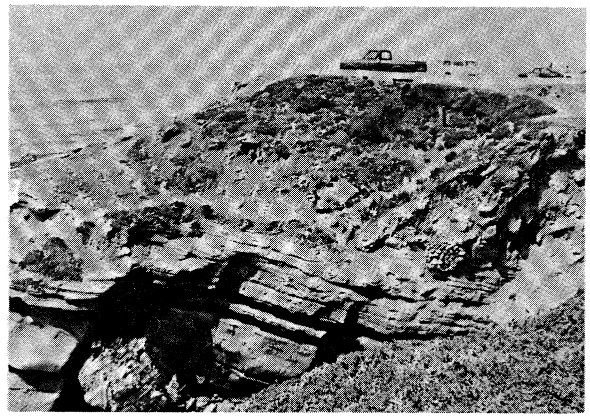


Figure 6. Photographs taken ay Sunset Cliffs in 1920 (left) and 1971 (right). View north of a collapsed sea cave at the foot of Osprey Street. The gently dipping, thin-bedded strata belong to the Upper Cretaceous Point Loma Formation. A small sliver of Pleistocene Bay Point Formation crops out on the extreme left hand side of the 1971 photograph, directly above the Point Loma Formation. Artificial fill covers most of the Pleistocene rocks and comprises the grass-covered slope in the foreground as well as slopes of the parking area in the background Notice that the stone bridge-support has not yet been completely destroyed. (Older photograph courtesy of San Diego Title Insurance and Trust Company; newer photograph by W. R. Reetz, Scripps Institution of Oceanography, La Jolla).

Shepard and Wanless, 1970). Whether the sea-cliff stabilization program begun by the Corps of Engineers (as modified by local citizens) will prove to be effective in stopping sea-cliff erosion at Sunset Cliffs, has yet to be determined.

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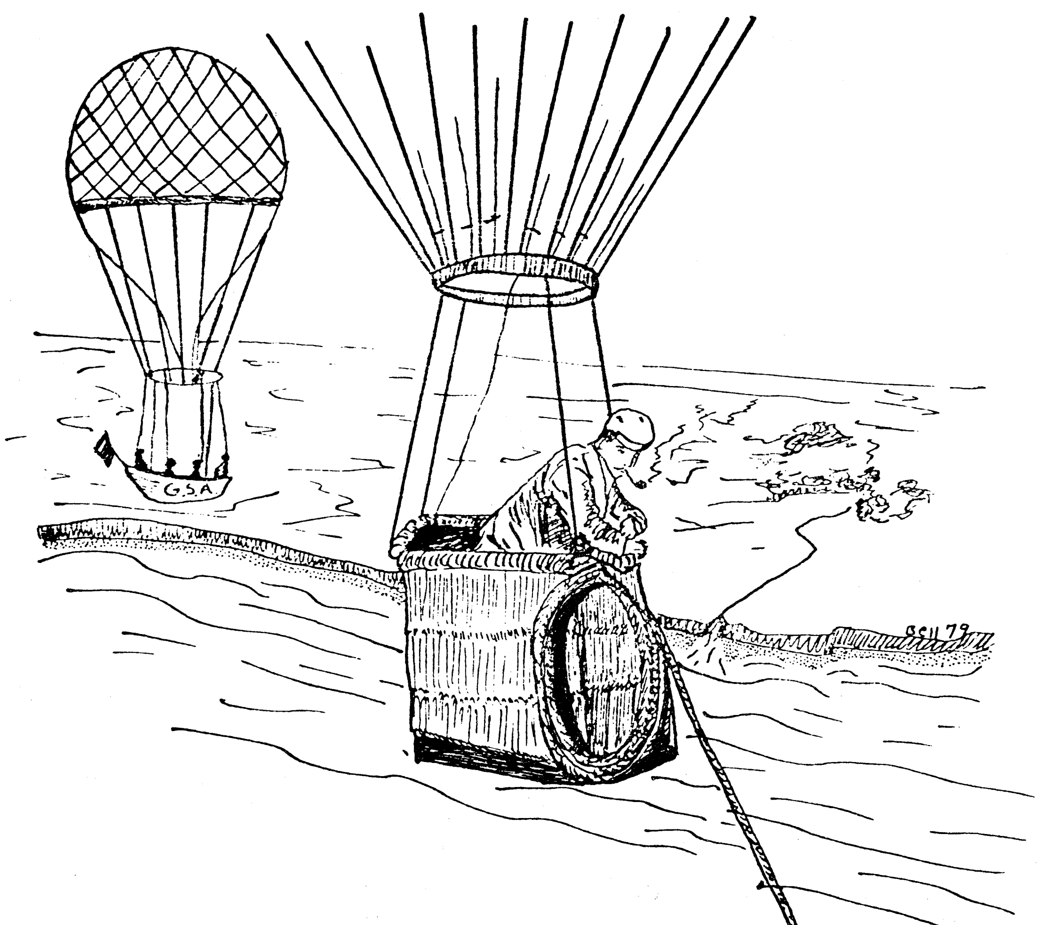

COASTAL EROSION IN SAN DIEGO COUNTY, CALIFORNIA

by

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INTRODUCTION

During the past two decades, extensive land development has occurred along the sea cliffs, particularly north of La Jolla. Until enactment of the California Zone Conservation initiative in 1972, local agencies permitted construction within a few feet of the cliffs. Developers justified this practice with the argument that the cliffs were not retreating at an appreciable rate. The reported retreat rates were usually based on experience during the past 25 to 30 years; this was a period of unusually slow erosion, characterized by low rainfall and few storms capable of producing heavy surf. Earlier coastal erosion studies showed a far less optimistic picture of sea cliff stability. For example, Vaughn (1932) reported that poorly indurated bluffs (Quaternary terrace deposits) near Scripps Institution of Oceanography at La Jolla retreated 3 to 6 m (10 to 20 feet) between 1923 and 1930. Shepard and Grant (1947) found the same area eroding at a rate of about one foot/year during storm periods just prior to 1947.

Cliffs of Eocene and Cretaceous sedimentary rock have retreated episodically due to large rock falls (Shepard and Wanless, 1971). In many places, however, these cliffs show no indications of appreciable retreat since photographic records began, approximately 50 years ago. High rainfall which occurred during 1977-78 and 1978-79 has brought on renewed interest in sea-cliff erosion rates, especially between Del Mar and Oceanside (Figure 1), where there has been a large amount of construction in recent years. Alluvial cliffs near Scripps, which appeared stable since 1947, have once again begun to show higher rates of erosion.

In 1973, extensive studies of coastal erosion began between Del Mar and Oceanside (Kuhn, 1977). Repeated measurements, with photographic coverage, was made at critical points. History of erosion was investigated by studying old maps, newspapers, weather bureau reports, ships logs, records of land ownership, and through discussions with long-time residents.

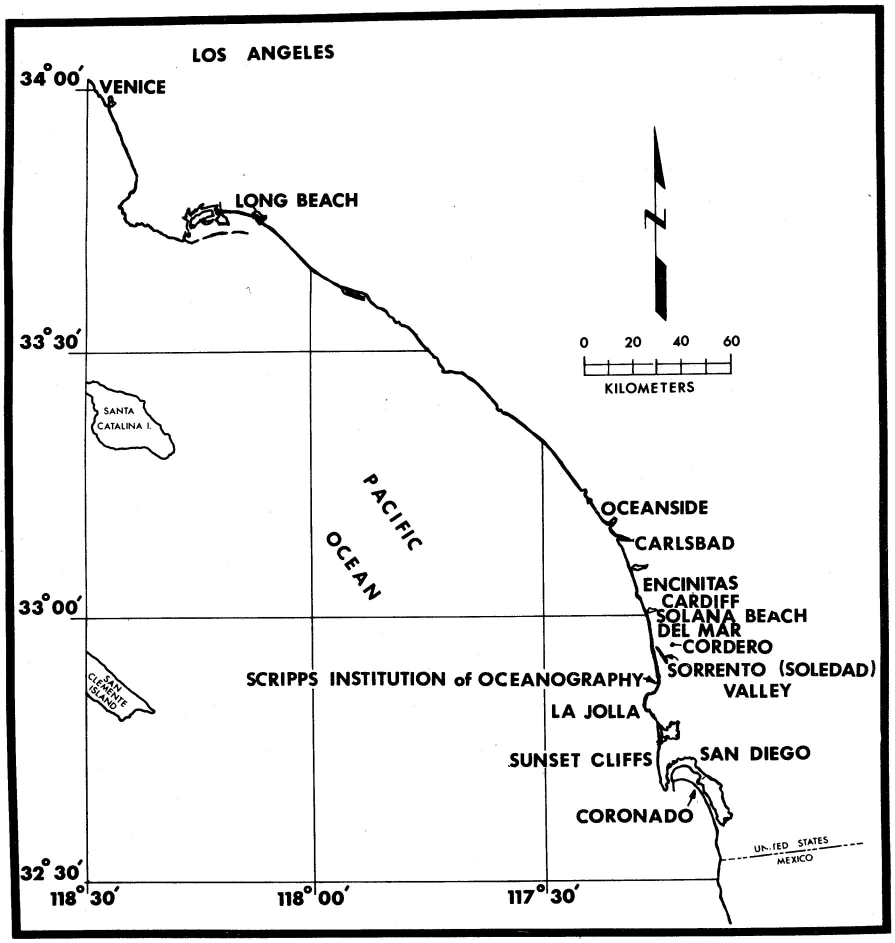

Figure 1. Location map

Coastal erosion is related to bedrock structure. Faults in north San Diego County have been mapped by Ziony, et al. (1974). Additional faults have been identified and mapped in the sea cliffs, and on the sea floor from aerial photographs. Faulting has brought soft, easily-eroded formations into contact with the coastline, accounting for important areas of erosion. Accelerated erosion occurs particularly where weaker bedding dips seaward.

Research was funded by NOAA, Office of Sea Grant (No. 04-8-M01-189), the California State Resources Agency (R/CZ-43), and the San Diego County Integrated Planning Organization (No. 11596-0800E). Cooperation and suggestions by Jeffrey D. Frautschy are appreciated.

SEA-CLIFF EROSION-HISTORICAL ASPECTS

Evidence of erosion during the past century should not be overlooked in evaluating potential hazards of building near bluff tops. Accordingly, land, road, railroad, and topographic surveys, dating back to 1876, have been located. Some of these maps and tax assessor records suggest that entire city blocks have disappeared in Encinitas since the town plat was filed in 1883 (Figure 2). Beginning in 1884, seaward property values decreased, while landward values increased. Some seaward parcels were finally removed from the tax rolls. This apparent loss of real estate coincides with an 11-year wet cycle which began in 1884 and ended in 1894.

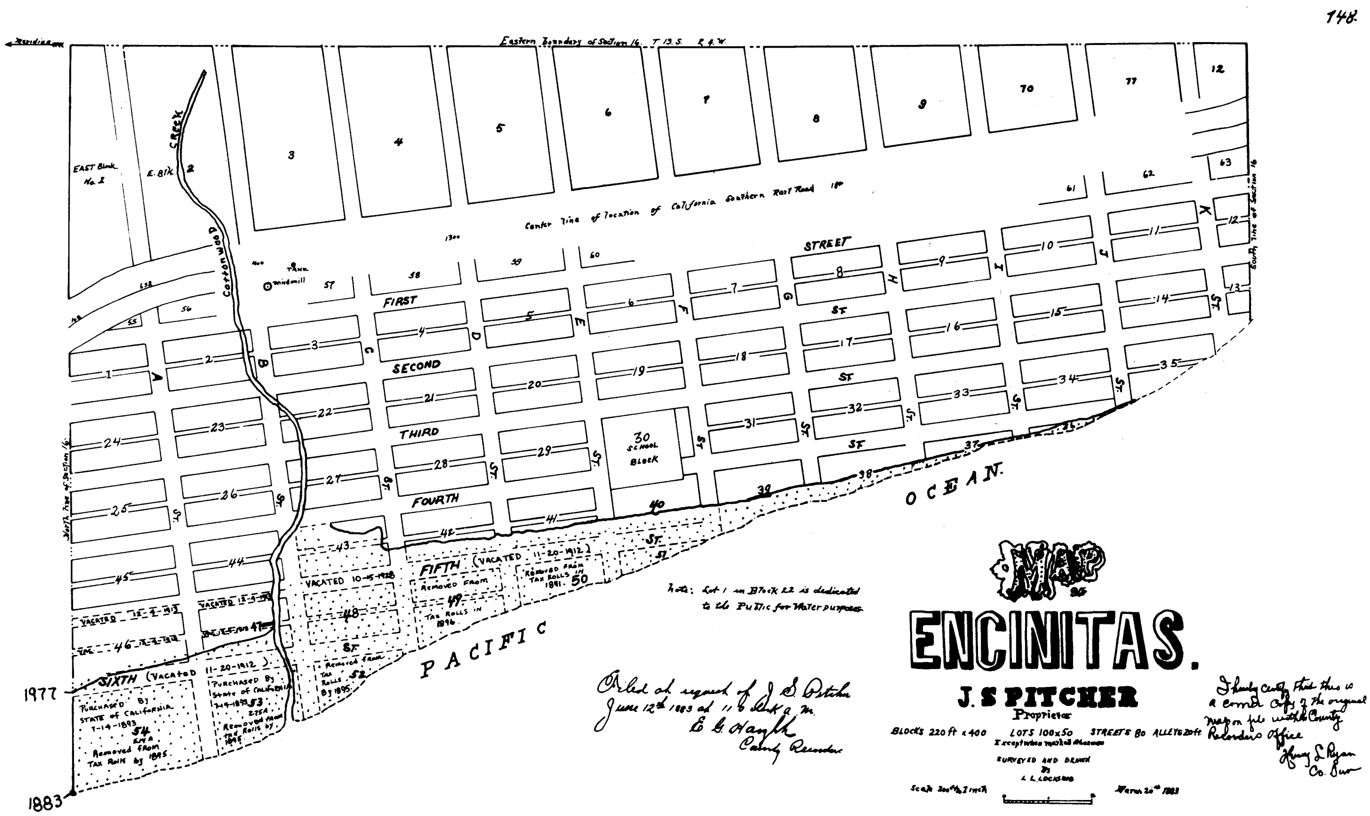

Figure 2. Town plat map of Encinitas, 1883. Apparent land loss is stippled. Solid line is the approximate present-day bluff top; dashed line (1883) may be either the former bluff top or shoreline. Several blocks of real estate were removed from county tax rolls before 1900. Map is an enhanced copy of San Diego County Recorders Subdivision Map #148, filed on June 12, 1883.

Santa Fe railroad maps and records show that tracks along the coastline have been repaired and/or relocated on numerous occasions due to bluff collapse, and flooding in adjacent river valleys.

For example, Sorrento Valley, (Soledad Valley) south of Del Mar, was particularly hard-hit during February and March, 1884. The San Diego Union reported on March 2, 1884, that telegraph lines were down, railroad tracks through the area were impassable, and that two trains were:

> "hemmed in on one side by landslides in the big Soledad cut, and on the other by the unsafe condition of the track, which is mostly underwater through the whole of Soledad flats."

Presently, the Sorrento Valley flood plain contains the same railroad tracks, major freeway rights-of-way, and an extensive industrial development.

In the southern portion of Del Mar, trains have been derailed, and even fallen over the sea cliffs. For example, a freight train went over the cliff on New Year's Eve, 1940, after the tracks were undermined by a series of heavy rains and large waves during unusually high tides.

In addition to direct damage during storms, delayed damage also occurs. For example, the Self-Realization Fellowship Temple was built in 1938, at least 30 feet back from the top of the sea cliffs. Following the 1941 storms, the bluff, weakened by rain-saturated soil and erosion by wave action, collapsed, and the temple building was destroyed. Also, sections of the old coast Highway (101), immediately south of the Self-Realization Temple, have been moved landward, and the bluff face regraded and dewatered because of cliff retreat.

ARTIFICIAL COASTAL PROTECTION

Artificial coastal protection, such as groins, jetties, bulkheads, sea walls, riprap, and rock debris are present along many sections of San Diego's retreating shoreline. The erosive side effects of these artificial devices are not fully understood, especially for periods of large storms and high tides. It has been observed that where such protective measures extend seaward beyond adjacent unprotected property, accelerated erosion occurs on immediately adjacent unprotected areas. This phenomenon was observed this past winter at La Jolla Shores, Carlsbad, and Oceanside. During these January through April, 1978 storms, beach-sand levels dropped to a near record low. Storm waves (accompanied by high tides) undercut the toe of cliff; unprotected areas (located adjacent to artificial protections) were eroded headward in a short time.

SEA-CLIFF EROSION IN URBANIZED AREAS DURING THE MAY 1973 - DECEMBER 1977 DRY PERIOD

In areas where undocumented casual work suggested little or no coastal erosion, careful work, particularly north of Del Mar, has shown that many sea cliff sections collapsed during the 1973-1977 dry period. Failures have been typically of the "landslide" and "block-fall" variety. For the most part, cliff collapse has been instantaneous, with separation occurring along fractures and bedding planes. At least 25 block-falls have been reported along the Encinitas cliffs. Blocks vary in dimensions from 0.3 to 3.5 m (1 to 12 feet) long, 1.5 to 33.5 m (5 to 110 feet) wide, and up to 10 m (32 feet) high.

A particularly large block-fall occurred on November 30, 1977, at the foot of F Street in Encinitas. The cliff face, undercut by wave erosion, was probably also weakened by ground water in fractures. The collapse crushed the beach-access stairway. Immediately following the collapse, water flowed from the cliff face at the Quaternary-Eocene unconformity, and within the Eocene formation below. Forty-eight hours after the collapse, water ceased to flow, and then started again a few days later.

RECENT BEACH AND CLIFF EROSION - JANUARY THROUGH APRIL, 1978

During the early 1978 storms, poorly-cemented, clastic sedimentary rock that fell at the foot of F Street, Encinitas, on November 30, 1978, was broken up and dispersed during a single storm period by a combination of wave action during high tides, heavy rainfall, and beach cobble abrasion. Older block-fall debris, in the same area was similarly dispersed between January and April.

Beach cobble abrasion may be locally severe following rapid beach-sand depletion. Sea-caves, shear zones, and poorly-cemented sedimentary strata were observed to be eroded by beach-cobble abrasion during periods of heavy surf and high tides.

Low Quaternary cliffs, south of Scripps Institution of Oceanography, which appeared to have stabilized during the dry period from 1947 to 1977, were subjected to considerable erosion during the January and February 1978 storms. Houses built at the cliff edge, mostly without benefit of sea-walls or other protection, were vulnerable to wave attack and cliff erosion. Protective beach-sand was removed by a combination of high waves and tides, and erosion from rain gullying. Residents, threatened with land and structural losses, took desperate measures to protect their belongings; old car bodies were placed at the toe of the slope, riprap was cemented in place, and temporary sea-walls were installed (Figure 3).

Figure 3. Storm waves battering homes along alluvial cliffs south of Scripps Institution of Oceanography, looking south. A section of the concrete seawall in the foreground collapsed later. M. Clark photo, S.I.O., February 7, 1978.

As these measures were only partially successful, some houses had to be reinforced to prevent collapse. Unprotected lots were the most severely damaged.

At the Self-Realization Temple in Encinitas, a section of cliff separated along parallel fractures and collapsed on April 26, 1978 (Figures 4A and 4B). The collapse measured 3.6 to 4.9 m (12 to 16 feet) long, 34 m (112 feet) wide, and a maximum of 19 m (40 feet) high. Ground water flowed from the newly-exposed cliff face.

Rapid cliff degradation was observed wherever storm-drain pipes, fences, stairways, and lifeguard towers were present along former natural drainages. Water, collected in man-made structures, causes accelerated erosion wherever it is allowed to run directly over the cliffs. Beach-access stairways, located in or near these drainages, commonly collapse both at the top (Figure 5A), and the base of the cliffs (Figure 5B). Storm drain pipe collapse often initiates severe gullying of the bluff face.

BLUFF-TOP GRADING

Slope failures often occur following bluff-top grading. Also, drainage ways are often created along which surface runoff can produce accelerated erosion of the bluff-top face. Where Quaternary terrace deposits and natural soils (including protective vegetation and case-hardened surface materials) are undisturbed, and drainage directed away from the cliffs, erosion appears to have been slow (Figure 6A).

In 1971-72, along south Solana Beach, the bluff-top was excavated down 4.6 to 5.5 m (15 to 18 feet), and surface water was allowed to run over the bluff face. Upper cliff slopes have eroded, and in some cases collapsed, during periods of heavy rainfall (Figure 6B). Part of the base of the cliff has eroded headward 2.4 to 3.0 m (8 to 10 feet) between 1972-1978 (Figure 6C).

Cliff collapse also occurred following extensive bluff-top grading in front of the Marine Biology Building at Scripps. Hannan (1975) reported that these cliffs, carved into Quaternary sedimentary deposits, retreated 16.5 m (54 feet) between 1912 and 1975. In 1975, these cliffs retreated 1.5 to 2.4 m (5 to 8 feet) in places.

EFFECTS OF GROUND WATER

Irrigation of landscaped areas along the coastline has had at least three important effects: 1) it has caused the water table to rise, even during dry periods (adding to the weight of the soil, which favors landslide development), 2) it has increased porewater pressure in potential slide areas, and 3) in some cases, it has produced solution cavities, favoring the formation of sea-caves some

Figure 4A. (Before) View southeast at the base of the cliffs at the Self-Realization Temple, Encinitas, looking south, February 3, 1978.

Figure 4B. Same view after cliff collapse on April 26, 1978. Photographed on May 2, 1978.

Figure 5A. View northeast shows stairway at D Street, Encinitas. It collapsed, starting at the top, during the rains of January, 1978.

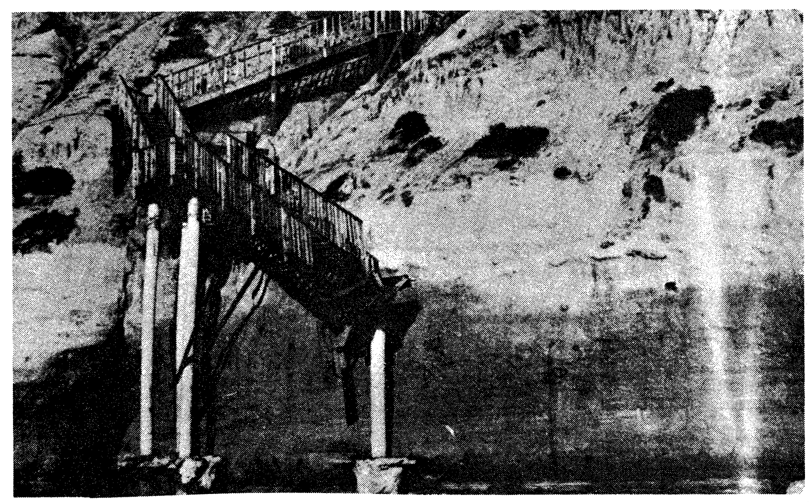

Figure 5B. Stairway damaged at the base during heavy storm surf and high tides in November, 1972. Photo from Solana Beach Publication "Broken Promise", 1972.

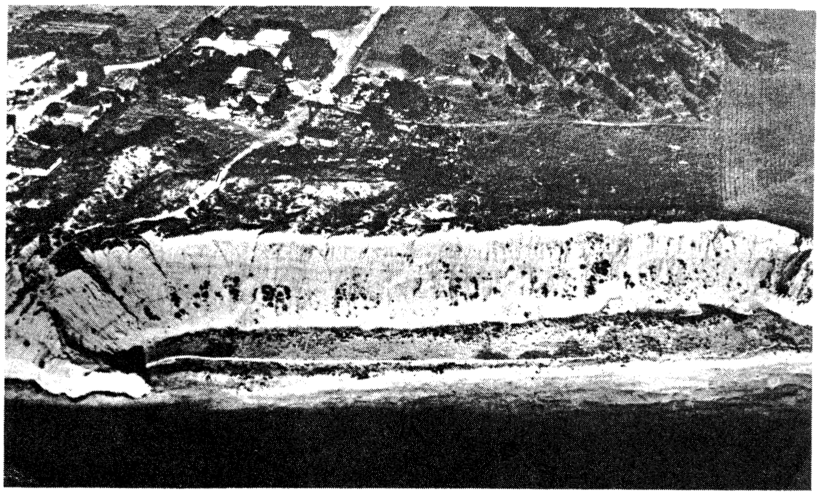

Figure 6A. Oblique view east of a portion of south Solana Beach prior to bluff-top development. Shore Processes Lab.,S.I.O. photo, 1954.

Figure 6B. Oblique view after development. B & A Engineering photo, June, 1974.

Figure 6C. Cliff base eroded 0.9 to 1.5 m, January to April, 1978. Arrow shows cliff base collapse of 2.4 to 3.0 m between 1972 and 1978. L. Ford, S.I.O., April 11, 1978.

distance back from the cliff faces.

CONCLUSIONS

The concept of an average, long-term, regional, coastal sea-cliff retreat rate is likely valid over thousands of years. Short-term provincial cliff retreat however, is episodic, and appears to be related to meteorological conditions, composition, induration and structure of cliff-forming formations, and to a combination of natural and man-made erosive agents.

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ROAD LOG TO SELECTED GEOLOGIC HAZARDS, SAN DIEGO METROPOLITAN AREA

Gregory T. Farrand and William J. Elliott

Cumulative Mileage	
0.0	Start trip from the Town and Country Hotel at the San Diego River crossing with Fashion Valley road and proceed north. As a result of heavy rainfall in the winters of 1977 and 1978, the San Diego River flooded portions of Mission Valley (see Chang, this volume). In the immediate area, the river rose to the base of the wooden pedestrian walkway located several hundred feet to the east and flooded portions of the Town and Country Hotel property, Fashion Valley Road, and the adjacent golf course (see Abbott, this volume).
0.3	Turn left (west) on Friars Road. Turn right on Napa Street (1.7). Turn right (north) on Morena Boulevard (2.0), then northwest on West Morena Boulevard at fork in road (2.1). West Morena Boulevard runs subparallel and adjacent to the northwesterly-trending Rose Canyon fault zone (see articles by Gastil, <u>et al</u>., Greene, <u>et al</u>., Simons, and Threet, this volume). In this <u>area</u>, the reddish-brown sandstones and cobbly sandstones are Late Pleistocene deposits of the Bay Point Formation.
5.2	Turn west on Garnet Avenue. Turn right on Mission Bay Drive (5.7), left (west) on Bluffside Avenue (5.7), and right on Pacifica Drive (6.0).
6.1 <u>STOP 1</u>	Park next to the drive-in theater and walk to the cut slope located behind the theater. The uppermost cobble conglomerate bed has been mapped as the Pleistocene Bay Point Formation. The yellowish sandstone and conglomerate strata immediately below the Bay Point Formation are deposits of the Pliocene San Diego Formation which are broken by the Country Club fault, a strand in the Rose Canyon fault zone.
6.1	Continue north on Pacifica Drive. Turn left on Loring Street (6.4), then right (north) on Soledad Mountain Road (6.9).
7.9	Turn right on Desert View Drive.
8.1	Eight homes on the west side of Desert View Drive were destroyed by landsliding in December, 1961 (Figure 1). The slide occurred during construction as a result of oversteepened cuts in faulted and jointed siltstones and claystones of the Eocene Ardath Shale. These homesites were subsequently regraded, including construction of buttress fills, and new homes have been built. Desert View Drive becomes Palomino Circle.
8.7	Turn right on Soledad Mountain Road. Turn right on La Jolla Scenic Drive (9.6) and right on Soledad Park Road (10.0).

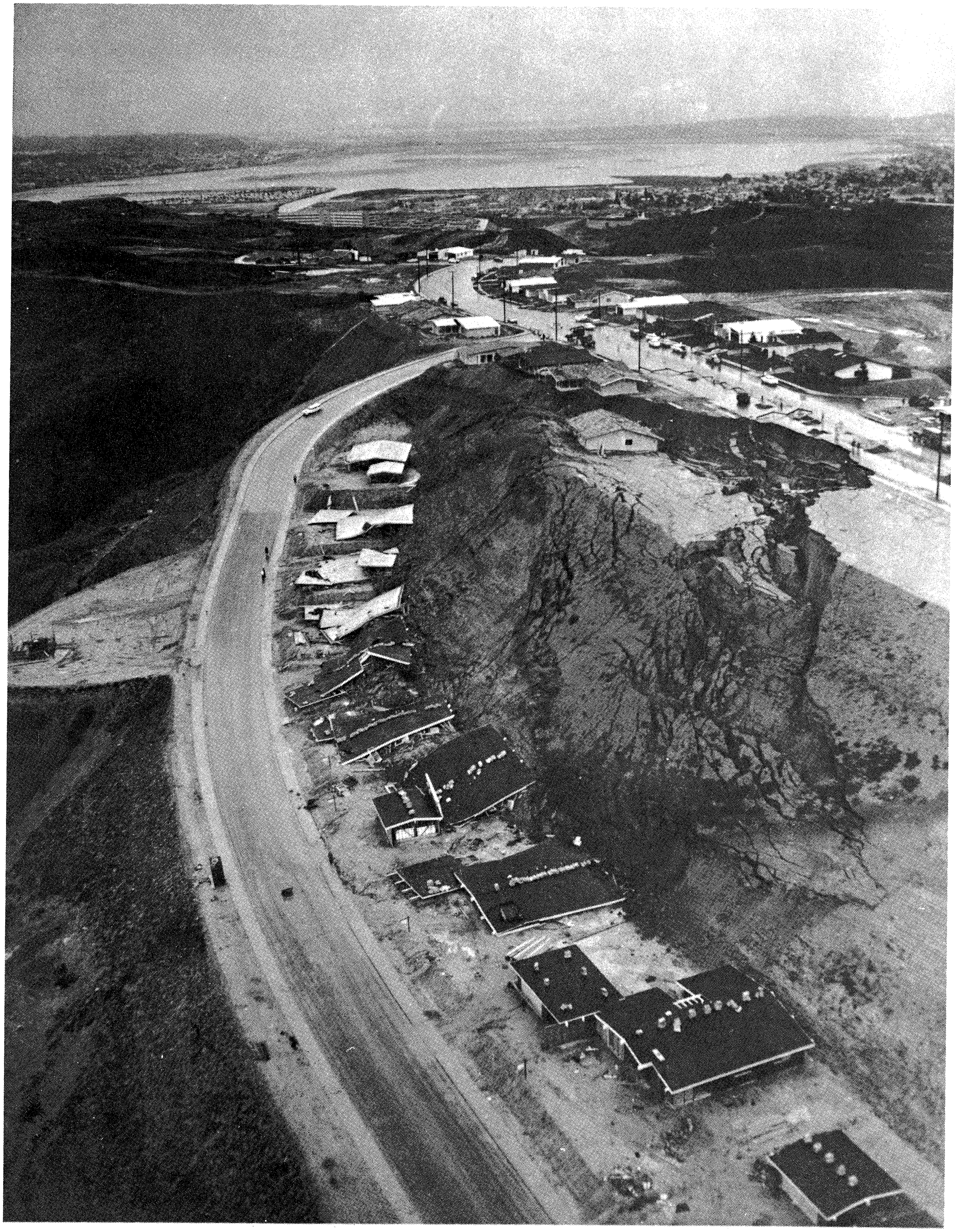

Figure 1. View of Mount Soledad landslide of December 14, 1961, looking toward the south. Landslide destroyed seven homes under construction near the intersection of Desert View Drive and Soledad Mountain Road. Failure was due principally to oversteepening of faulted and jointed, Eocene Ardath Shale inclined in the same general direction as the cut slope. Photograph from Union-Tribune Publishing Co., San Diego, CA.

10.2 STOP 2 Park by Easter Cross on Mount Soledad (elevation 811 feet) for an excellent view of metropolitan San Diego. Mount Soledad is, in part, underlain by a thin cap of red-brown cobble conglomerate and sandstone of the Pleistocene Lindavista Formation. Eocene Mount Soledad conglomerate occurs east of the cross and conglomerates of the Cretaceous Cabrillo Formation occur to the west. The northwesterly-trending Rose Canyon fault and Mount Soledad fault lie to the east and west of the cross, respectively. The large north-south trending canyon to the east is Rose Canyon, and the broad, flat surface beyond is Linda Vista Mesa. Note that the red sandstones and cobble conglomerate of the Lindavista Formation that cap Linda Vista Mesa, about 350 feet.

10.2 Return (west) to Soledad Park Road. Turn right (northwest) on Via Capri (10.4), left on Hidden Valley Road (11.3) and left on Ardath Road (11.7). Go straight across Torrey Pines Road (11.9) and proceed north on La Jolla Shores Drive. Turn left on El Paseo Grande (12.8). Scripps Institution of Oceanography is on the right (north). Continue west to parking lot at Scripps (12.9).

12.9 STOP 3 Walk about 100 yards south along the beach to observe seawalls and structural damage which occurred during recent winter storms (see Kuhn and Shepard, this volume).

12.9 Return to parking lot and continue south on El Paseo Grande. Bear right on Camino del Oro (13.2), then turn left on Avenida de la Playa (13.5).

13.8 Turn right on La Jolla Shores Drive. Turn right (west) on Torrey Pines Road (14.0).

14.3 Tilted beds of the Cretaceous Point Loma Formation are exposed in cut slopes on the left. The Rose Canyon and Mount Soledad faults also occur in this area (not visible from road).

14.8 Turn right on Prospect Place.

15.0 Bear right and down ramp on Cave Street. Access to the Sunny Jim Cave (15.1) on the right (enter through La Jolla Cave and Shell Shop) was created by tunneling through Point Loma Formation sandstones and shales down to an existing sea cave. Photographs taken in 1906 and recently of the cave opening indicate that only minor erosion of the sea cave has occurred. Continue west on Cave Street.

15.1 Cave Street becomes Coast Boulevard. Continue south on Coast Boulevard and/or Coast Boulevard South for a view of the shoreline. The coastal terrace is underlain by Late Pleistocene Bay Point Formation and Cretaceous Point Loma Formation.

15.9 Continue along shore on Coast Boulevard.

16.3 Coast Boulevard becomes Ravina Street. Turn right (south) on La Jolla Boulevard (16.4) and then right (south) on Mission Boulevard (19.2). South on Pacific Beach Drive, Mission Boulevard is built on a sand spit. Mission Bay, on the left, was, until development began in the 1950's, a slough with tidal flats called False Bay (Figure 2).

21.5 Turn left on West Mission Bay Drive. Turn right on Sunset Cliffs Boulevard (22.6). The San Diego River Channel (23.1) was constructed by the U. S. Army Corps of Engineers in conjunction with dredging and development of Mission Bay.

23.4 Bear right on Sunset Cliffs Boulevard. Turn right (west) on Del Mar Avenue (24.8) and proceed to the dead end (25.0). Park for Stop 4.

25.0 <u>STOP 4</u> Prior to April, 1979, an abandoned two-story apartment building existed on the now vacant lot on the south side of Del Mar Avenue. When the westerly one-third of the building foundation was undermined by sea-cliff erosion, the building was condemned and demolished. The underlying materials consist of weakly-cemented sandstones of the Bay Point Formation which are in turn underlain by indurated sandstones and shales of the Point Loma Formation.

25.2 Return to Sunset Cliffs Boulevard and turn right (south).

25.7 <u>STOP 5</u> Stop near the sea cliff at second parking lot on right. Differential wave erosion along northwesterly- and northeasterly-trending joints within the Point Loma Formation can be observed here (Kennedy, this volume).

25.7 Turn around and go north on Sunset Cliffs Boulevard. Turn right (east) on Point Loma Avenue (25.9), left on Catalina Boulevard (26.7), right on Chatsworth Boulevard (26.8). Bear right on Lytton Street (28.9), turn left (north) on Rosecrans Street (29.0). Keep right on Rosecrans at the Interstate Highway 5 South sign (29.7). Rosecrans becomes Taylor Street (30.0). Turn right (southeast) on San Diego Avenue (30.1) which then becomes Congress Street. This is the Old Town area of San Diego.

30.7 Go straight across (southeast) San Diego Avenue on Congress Street. Stop at Congress Street cul-de-sac (30.9).

30.9 <u>STOP 6</u> In the cut slope behind the apartment building is an exposure of steeply tilted and faulted beds of the San Diego Formation and Pleistocene Lindavista Formation. The Old Town Fault, a strand of the Rose Canyon fault zone, has been mapped about 1000 feet to the north of this stop by Kennedy, <u>et al.</u>, (1975). Backtrack along Congress Street. Turn left (south) on Old Town Avenue (31.0) and south on Interstate Highway 5 (31.2).

Figure 2. Topography of Mission Bay-Mount Soledad area. 1903 edition, La Jolla 15 minute quadrangle, surveyed 1901-02.

35.9 Take Coronado Island offramp (State Highway 75), pass through toll gate (38.1) and continue northwest on 4th Street.

38.1 A strip of land along the southeast side of Coronado Island is underlain by fill materials derived from channel dredging operations in San Diego Bay.

38.3 4th Street becomes 3rd Street. Turn left on B Avenue (38.5), then left on 6th Street (38.8).

38.9 A gently sloping, topographic lineament with relief of several meters can be traced south-southwest from 4th Street to the west end of Glorietta Bay. This lineament may be interpreted as a possible fault-line scarp since it is approximately aligned with an offshore fault (Coronado fault) identified by Kennedy, et al., (1977) by seismic reflection profiling. It could also simply be an erosional feature.

39.0 Turn right on Pomona Avenue and continue south. Turn left (south) on Orange Avenue (39.7). Orange Avenue becomes Silver Strand Boulevard (39.8). The Silver Strand is a tombolo that connects Coronado Island to the mainland at Imperial Beach. An estimated sand loss of 1,400,000 cu.yds./yr. from Silver Strand Beach (Nordstrom and Inman, 1973) is periodically replenished with sand from channel dredging.

47.2 Silver Strand Boulevard becomes Palm Avenue. Continue east on Palm Avenue through Imperial Beach.

50.1 Turn right (southeast) on Beyer Boulevard. Turn right (south) on East Beyer Boulevard (52.8), then left (southeast) on San Ysidro Boulevard (53.9) which is also referred to as Border Village Road. Bear left (northeast) up the paved alley (54.1) and go right (southeast) alongside railroad tracks past steel railroad depot building (54.2). Just before reaching the USA/Mexico International Border fence, turn left (east) across railroad tracks onto a dirt road (54.3). Follow this dirt road up the hill parallel to the Border fence.

54.4 STOP 7 Stop adjacent to fenced, abandoned transformer station on the left. The cut slope located at the back of the station exposes a steeply inclined shear zone which has been cited by Kennedy, et al., (1975, Figure 43) as evidence for extending the San Ysidro fault to the USA/Mexico border. An alternative interpretation of this exposure (Hart, 1977) is that the shear zone is instead due to landsliding. Turn around and return to San Ysidro Boulevard.

54.7 Turn right on San Ysidro Boulevard. Turn right on East Beyer Boulevard (54.8). East Beyer Boulevard becomes Otay Mesa Road (55.9). Continue north-northeast.

56.5 Light grey sandstones of the Miocene Otay Member (Kuper and Gastil, 1977, and Scheidemann, 1977) of the Rosarito Beach Formation (Minch, 1967) are exposed in cut slopes on right.

57.0 Contact between yellowish cobble conglomerate and fine sandstones of the Pliocene San Diego Formation and the Miocene Otay Member.

57.3 Coarse, angular cobble to boulder conglomerate is exposed in cut on left. The majority of the top of Otay Mesa is capped by these locally-derived sediments which are probably Pleistocene terrace deposits.

57.7 Turn right (south) on Dillon Trail, a dirt road located about 100 feet before the stop sign at intersection of Otay Mesa Road and road leading to Interstate Highway 805. Row of eucalyptus trees are on the left side of road (58.2). Turn right (west) at fork in road (58.6), heading toward wire fence and shed on right side of road (58.7). Turn left (south) at the City of San Diego Survey monument sign (58.9) and bear left (southeast) at fork in road (59.0). Follow road southeast along rim of Otay Mesa.

59.1 The hummocky terrain south of Otay Mesa is the San Ysidro land-
<u>STOP 8</u> slide (see Hart, this volume). Recent landslide features such as blocked drainage and well-developed topographic benches and head scarps can be observed (Figure 3).

59.1 Continue southeast along mesa rim.

59.3 San Ysidro slide/Tijuana River flood plain overlook. Ponds in a
<u>STOP 9</u> graben of the landslide can be observed during periods of high precipitation. The lineaments described by Kennedy, <u>et al</u>., (1975) as faults and interpreted by Hart (1977) as landslide scarps can be seen here.

59.3 Proceed southeast along mesa rim.

59.6 In bottom of swale, turn left (northwest) on dirt road and proceed back toward eucalyptus trees and Dillon trail.

60.9 Turn right (north) on Otay Mesa Road from Dillon trail. Turn left (west) at stop sign (61.0), proceed toward Interstate Highway 805. Turn right (north) on Interstate Highway 805 (61.7). Take California Highway 94 east (73.0).

76.2 Eocene Stadium conglomerate is exposed in cut slope on the right.

78.2 Jurassic Santiago Peak Volcanics are exposed on the left.

79.4 Take California Highway 125 north. Turn right on Severin Drive/Fuerte Drive offramp (81.5), left on Severin Drive (81.9) and left (northwest) on Amaya Drive (82.4).

82.7 Turn right on Fletcher Parkway. At this intersection the Eocene Stadium Conglomerate is exposed.

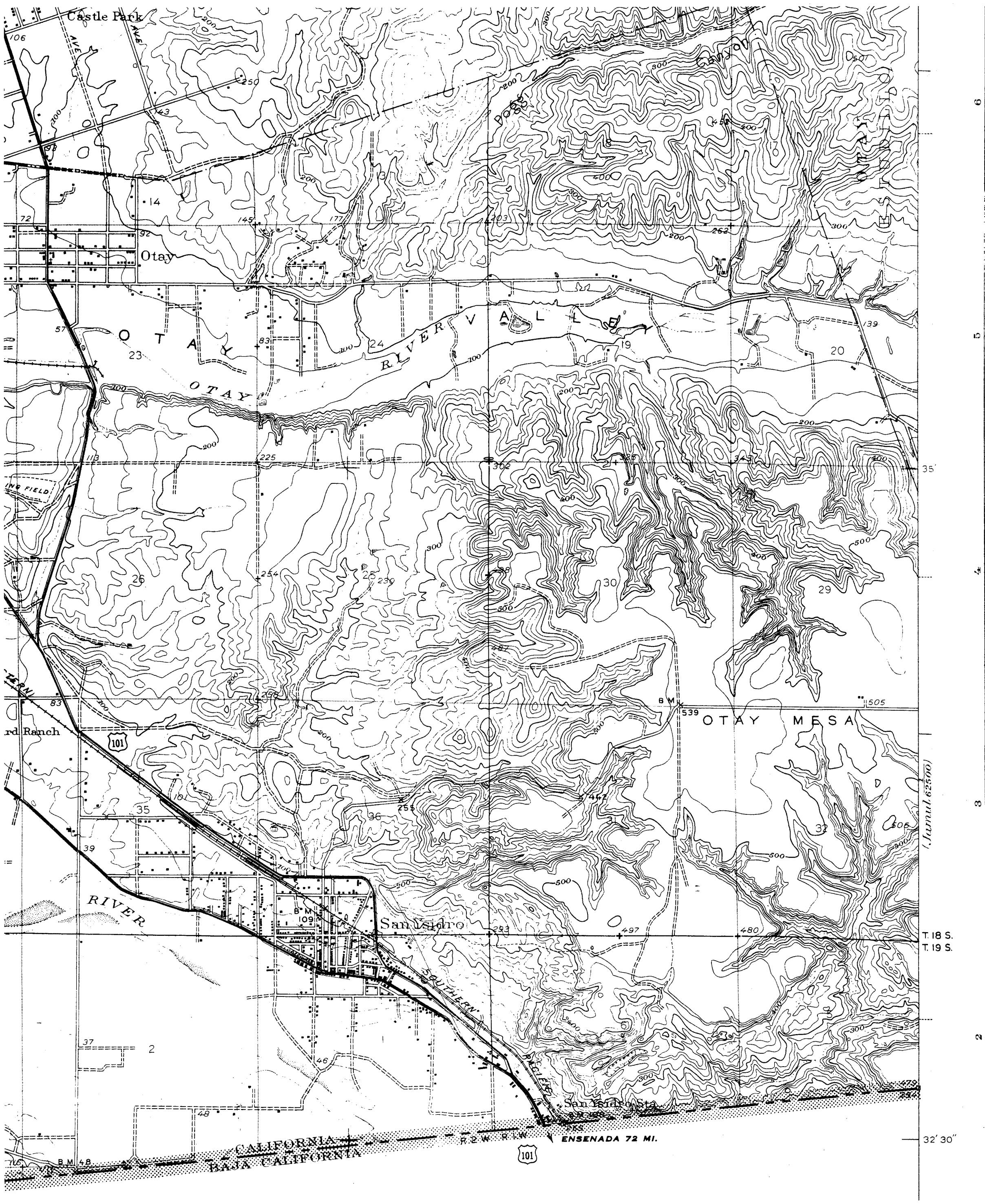

Figure 3. Topography of Otay Mesa area. Note landslide features, e.g. arcuate head scarps, hummocky topography and ponds. 1943 edition, San Ysidro 15 minute quadrangle, surveyed 1941.

83.7 Turn left on Navajo Road. Then right on Fanita Drive (84.0).

84.5 Red-brown cobble conglomerate and sandstone of the Eocene Pomerado Conglomerate and the underlying light grey to tan sandstone and mudstone of the Eocene Mission Valley Formation are exposed on right at top of hill.

84.8 Eocene Stadium Conglomerate is exposed on the right. The cobbles of the Stadium and Pomerado Conglomerates consist predominantly of distinctive, slightly metamorphosed rhyolite and rhyodacite "Poway" clasts. The conglomerate being mined for aggregate on the north wall of Mission Valley (northeast of Town & Country Hotel) is primarily Stadium Conglomerate.

85.0 Light grey to brown sandstones of the Eocene Friars Formation are exposed on the right.

85.8 Turn right (east) on Fanita Rancho Road. Bear left on Todos Santos Drive (85.8).

86.0 On the right side of Todos Santos Drive is the site of the
STOP 10 Fanita Corona Subdivision landslide described by Hannon (1970) in which eight houses were destroyed and several others distressed by landsliding in 1965-66. The active portion of this slide occurs within a larger ancient landslide mapped by Hart (1972). The larger ancient landslide extends up the hill toward the water tank. Sedimentary rocks in this region consist of shallow-dipping, pale green to light grey claystones, mudstones and sandstones of the Eocene Friars Formation. Many of the ancient landslides and reactivated landslides in the San Diego region occur in the Friars Formation.

86.1 Turn right on Fanita Rancho Road. Turn right on Fanita Drive (86.3), right on Mission Gorge Road (87.2) and left (north) on Carlton Hills Boulevard (87.4). Proceed to north end of Carlton Hills Boulevard to Stop 11.

89.0 Following heavy rains in the winter of 1977-78, an ancient
STOP 11 landslide was reactivated that affected about 25 homes, some of which were damaged and subsequently abandoned. In an effort to stabilize the slide, remedial grading was done to remove some of the driving forces from the head area (see Hart, this volume). Surface drainage structures were constructed to reduce water infiltration. Disrupted streets, sidewalks, and utilities were also repaired and most of the homes are still occupied.

89.1 The two homes on the west side of Carlton Hills Boulevard at Swanton Drive are located at the westerly boundary of the active portion of the slide. These homes underwent severe distortion. The head scarp of the reactivated portion of this landslide can be observed about 200 feet north of Carlton Hills Boulevard cul-de-sac. Retrace route along Carlton Hills Boulevard.

90.3 **San Diego River.**

90.7 Turn right on Mission Gorge Road. Turn right on Father Junipero Serra Trail (92.6) and follow through Mission Gorge along the San Diego River.

93.3 Old Mission Dam on the right was constructed of terra cota brick between 1803-1816 by the Franciscan fathers to provide water to the Mission San Diego de Alcala in Mission Valley.

95.3 Turn left (east) on Mission Gorge Road. View soil slips in cut slopes on right. The geologic materials consist of Eocene Friars Formation claystones and sandstones. Turn right on Golfcrest Drive (95.8) and right (west) on Monteverde Drive (96.3). Park near 6855 Monteverde (96.6).

96.6 STOP 12 Rowena landslide. In early 1978, an ancient landslide was re-activated, damaging six homes at the top of a cut slope along the west side of Rowena Avenue (uphill to the east). Six other homes, situated at the toe of slope (along the east side of Monteverde Drive), were also threatened by movement at the toe of the slide. Plastic sheeting was placed over the slope to reduce water infiltration during the 1978-79 rainy season. Movement continues and the slide is now encraoching within a few feet of several homes at the toe. Proposed remedial measures include removing some of the homes at the top, regrading the slope to a 3 1/2 (horizontal): 1 (vertical) slope and construction of a shear key and buttress fill.

96.6 Turn around and return to Golfcrest Drive.

97.0 Turn right on Golfcrest Drive. Turn right on Navajo Road (97.6), left on College Avenue (99.6), right (west) on Interstate Highway 8, exit at Hotel Circle (107.0) and go east. Turn left on Fashion Valley Road (107.3).

107.3 End of trip at Town & Country Hotel.

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