UNITED STATES OF AMERICA
NUCLEAR REGULATORY COMMISSION

BEFORE THE ATOMIC SAFETY AND LICENSING BOARD

In the Matter of)
)
PACIFIC GAS AND ELECTRIC COMPANY) Docket No. 50-275
Diablo Canyon Nuclear Power Plant) Docket No. 50-323
Units Nos. 1 and 2)

DIRECT TESTIMONY OF APPLICANT PACIFIC GAS AND ELECTRIC COMPANY FOR HEARINGS COMMENCING DECEMBER 4, 1978

VOLUME I

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INDEX
OF
TESTIMONY

Title Of Testimony	Authors
Establishment Of Seismic Events For Which Plant Is Designed	R. V. Bettinger
Characteristics Of Faults	R. Jahns D. Hamilton
Characteristics Of Earthquakes	S. Smith
Characteristics Of Ground Motion At Site	J. A. Blume
Seismic Instrumentaion Systems	O. W. Steinhardt
Establishment Of The Ability Of The Plant To Withstand The Design Seismic Events	J. B. Hoch
Evaluation Of Plant Structures	V. J. Ghio
Hosgri Analysis And The Evaluation Of The Containment Structure	V. J. Ghio L. Malik
Hosgri Analysis And The Evaluation Of The Auxiliary Building	V. J. Ghio L. Malik
Hosgri Analysis And Evaluation Of The Turbine Building	V. J. Ghio D. Lang
Hosgri Analysis And Evaluation Of The Intake Structure	V. J. Ghio D. Lang
Hosgri Analysis And The Evaluation Of The Outdoor Water Tanks	V. J. Ghio D. Jhaveri
Hosgri Analysis And The Evaluation Of The Buried Tanks & Piping Systems	J. A. McLaughlin R. T. Lawson
Introduction & Evaluation Of Plant System	H. J. Gormly
Systems & Functions	W. C. Gangloff

Title Of Testimony	Authors
Reactor & Reactor Coolant System	T. Esselman
Auxiliary Mechanical Equipment	T. Esselman P. G. Antiochos
Other Piping Systems	T. Esselman R. E. Bacher
Electrical Equipment & Instrumentation	T. Esselman R. A. Young

TESTIMONY OF
RICHARD V. BETTINGER
ON BEHALF OF
PACIFIC GAS AND ELECTRIC COMPANY
DECEMBER 4, 1978
DOCKET NOS. 50-275, 50-323

My testimony deals with the investigation, studies and analyses conducted by the Company and our consultants concerning the geological and seismological aspects of Diablo Canyon.

The initial phase of the investigation of the geology and seismology of the Diablo Canyon area commenced in late 1965. Our first step was to retain the best consulting expertise available to us to advise as to the suitability of the site, define the investigation required, and to provide criteria to assure a safe design. The principal consultants initially retained were:

Geology

E. C. Marliave (deceased) - Consulting geologist. Formerly held the position of Chief Engineering Geologist for the State of California.

Dr. Richard H. Jahns - Dean of the School of Earth Sciences, Stanford University.

Seismology

Dr. Hugo Benioff (deceased) - Consulting seismologist. Formerly Professor of Seismology at California Institute of Technology.

Dr. Stewart M. Smith - Chairman, Department of Geophysics, University of Washington.

Engineering

Dr. John A. Blume - Consulting structural engineer and head of J. A. Blume & Associates.

Edward Keith - At that time Associate of J. A. Blume - Now with EDS Nuclear

These consultants have been assisted by others: Dr. Jahns by Mr. Douglas Hamilton and his staff at Earth Sciences Associates; Dr. Smith by university colleagues through TERA corporation; and Dr. Blume by the substantial staff of his own consulting engineering firm. In addition, during the Hosgri reanalysis, the following consultants were called upon:

ANCO Engineers
Earthquake Engineering Services
EDS Nuclear
Harding : Lawson Associates
Wyle Laboratories
Dr. Jack D. Benjamin
Dr. Bruce Bolt
Dr. C. Allin Cornell
Dr. John Lysmer
Dr. H. Bolton Seed

Initially, our consultants were requested to define the scope of the investigations required to enable the Company to construct a nuclear power plant at Diablo Canyon that would be safe in earthquakes. It was decided that it would be necessary to:

1. Determine the maximum earthquake shaking motions that can be expected at the site.
2. Establish structural design criteria for buildings and equipment such that they will accommodate these motions with a margin of safety, and
3. Whether the probability of surface fault rupture through the site was sufficiently remote that it could be disregarded in the design.

At the time the purposes and scope of the investigations were established, no AEC criteria had been published for such investigations. For Diablo Canyon, our consultants determined the extent of work required, with Company engineers assisting and coordinating. The work was of course subject to subsequent review by the AEC and its consultants. In 1967, the AEC commenced preparation of geologic and seismic criteria for nuclear power plants. We and our consultants have followed development of these criteria in connection with the Diablo Canyon work. The criteria were published on November 13, 1973.

The 1966 investigations established that the site is in an area of relatively low seismicity, a conclusion which remains valid today. The regional geology, as evidenced on shore, was used to identify which faults could generate major earthquakes. Because the absence of seismic activity that would indicate a nearby significant offshore fault and the conservative assumption of a large earthquake anywhere in the region (including one directly under the site), offshore exploration did not seem necessary.

The major faults identified at that time by Dr. Smith as governing the seismicity of the region were the San Andreas Fault 48 miles northeast, the Nacimiento Fault 20 miles northeast, and the Santa Ynez Fault 50 miles to the south. This permitted definition of the most severe earthquakes that could occur in the region.

For each of the controlling faults, Dr. Smith postulated the most severe earthquake which he believed could occur and that the event would start at the points on the faults nearest to the site. The events were described in terms of the length of fault rupturing during the earthquake, the amount of fault displacement, the duration of shaking, and magnitude. In addition to the postulation of very large earthquakes on these three faults, allowance was made for the possible occurrence of a large earthquake shock not associated with any fault (6.75M) directly under the site. This element of conservatism was necessary because the state-of-the-art in seismology did not permit a conclusion that the absence of surface faulting would preclude the occurrence of a large earthquake, or aftershock anywhere in the local site area. Dr. Smith will discuss this in greater detail in his testimony.

Evaluation of the information on the controlling earthquakes, together with the distance of the site from the faults, the characteristics of the rock at the site, and other factors, enabled Dr. Blume to specify the corresponding complex pattern of vibrations which comprise the ground motion at the site. The specification is in terms of maximum displacement, velocity, acceleration, frequency, and duration.

The various events and corresponding maximum ground accelerations at the site as recommended by our consultants are summarized below:

Fault	Closest Point to Site (miles)	Length of Fault Rupture (miles)	Maximum Displacement on Fault (feet)	Richter Mag.	Max. Ground Acceleration at (g)
San Andreas	48	200	20 Horiz. 3 Vert.	8.5	.10
Nacimiento	20	60	6 Horiz.	7.25	.15
Santa Ynez	50	80	10 Horiz.	7.5	.05
Under site (not a fault breaking the surface, and perhaps not caused by an event on a fault.)	--	--	--	6.75	.20

Dr. Blume's recommended design criteria took into account the fact that earthquakes starting from remote sources can cause ground shaking with different characteristics than those starting from nearby sources. The ground motion specified is an "envelope" of the most severe characteristics from the various earthquakes studies.

Thus, a great earthquake similar to the San Francisco 1906 event on the San Andreas Fault, which had a magnitude estimated to be on the order of 8.25 together with the major aftershock under the site, was considered in determining the most severe shaking at the site. Although the postulated San Andreas event would be a significant earthquake, its distance from the site was great enough to result in the Nacimiento event and the aftershock under the site becoming the events which controlled the design.

Dr. Blume specified that normal working stresses (without the customary increase in allowable stress ordinarily permitted for earthquake design) should be used to design the structures and equipment at Diablo Canyon. To assure adequate energy absorbing capability, he further specified that the design be checked using ground motions twice as severe as those calculated from the postulated maximum earthquakes. (The resulting maximum ground acceleration, 0.4g, termed the double design earthquake, corresponds to the concept of "Safe Shutdown Earthquake" subsequently used by the AEC in its criteria released on November 13, 1973.)

The detailed investigations at the site itself were complete and without precedent in their extent and detail. They involved detailed geologic mapping of existing features and aerial photography. Almost 2 miles of interconnecting exploration trenches, up to 40 feet deep, were excavated through the area proposed for the reactor and related plant structures. The trenches permitted detailed examination of the bedrock structure, ancient wave-cut coastal terraces and overlying sedimentary deposits. This work demonstrated that the site had not been affected by significant fault movements. The geologic relationships present there showed that the probability of the site being affected by surface fault displacement was so infinitely remote that it could be disregarded in the design of the plant. Representatives of both the Atomic Energy Commission and of the U.S. Geological Survey inspected the site and the exploration trenches. They agreed that the exploration work confirmed the absence of any significant faulting at or near the site.

The U.S. Geological Survey transmitted a supplemental geologic report on Diablo Canyon Unit #2 to the Atomic Energy Commission on June 5, 1970. Part of the conclusions in that report were:

"It is concluded that some new data are available now that were not available at the time the initial reviews were made of the geology and seismology of the Diablo Canyon site. These data include some recent, but largely unpublished, geologic mapping of the Edna fault zone, and some data on recent seismicity on the continental shelf offshore from the reactor site. However, none of these new data appear to affect the earthquake potential of the site area, and hence do not constitute any threat to the safe construction of a nuclear facility at the Diablo Canyon plant site."

The geologic and seismologic studies were reviewed by AEC, by USGS, and by the Coast and Geodetic Survey. In 1970, government scientists made use of their offshore geophysical surveys in evaluating the Company's submittals.

The seismic design criteria which we proposed to use were approved with only minor modifications, and were incorporated into the construction permits for the two nuclear units.

In 1972, Mr. Hamilton learned of an article in Memoir #15 of the American Association of Petroleum Geologists, published in 1971, which indicated the presence of a fault (since named the Hosgri Fault) some 4-5 miles offshore from Diablo Canyon. The article was authored by Ernest G. Hoskins and John R. Griffiths, Shell Oil Company geologists. They reported on offshore surveys done in connection with oil exploration performed by Shell during the mid-1960's along the central and northern California coast. The work was a survey of conditions at considerable depth beneath the ocean floor to study large offshore basins. Mr. Hamilton called our attention to the paper and its map.

Given the information developed in our earlier geologic and seismologic investigations, these features did not appear significant in terms of the design criteria for the plant. Nevertheless, investigation continued.

Mr. Hamilton was able to contact Mr. Hoskins and discuss the Shell surveys. Mr. Hamilton then visited the Shell office in Los Angeles and reviewed some of the data used in the paper. These data suggested that the faulting described by Hoskins and Griffiths was relatively old. Since the seismic record of the area also suggested, at most, a low level of seismic activity, the allowances made in the design for an assumed large earthquake beneath the site were judged to be fully capable of accounting for any events associated with this new feature.

However, the Hoskins and Griffiths work was additional relevant geologic information and when PGandE's FSAR was submitted to the AEC during the summer of 1973, it included a description of the offshore fault mapped by Hoskins and Griffiths, including the indications of minor seismic activity possibly associated with it.

During the AEC's review of the FSAR, they requested further information about the faults that had been mapped by Hoskins and Griffiths.

PGandE then learned that the USGS, in connection with an ongoing program of coastal research funded by the AEC, was planning on conducting survey work specifically directed to the central California coastal region, including the Diablo Canyon vicinity. This work was in fact performed by the survey ship Kelez in October-November 1973. PGandE learned in mid-November that the USGS work supposedly disclosed indications of surface faulting at the sea floor. After consultation with the USGS, we commissioned our own survey to supplement their information and to clear up possible confusion over the nature of the sea floor scarp identified in the press as a "surface fault". Our findings and those of USGS were reviewed at a meeting with the AEC staff in January 1974, specifically in relation to three local faults mapped by the USGS. In its report of that meeting, the staff concluded that one of those faults might be related to the larger structure mapped by Hoskins and Griffiths; however, they felt that any ground motions produced at the site by an earthquake on any of these faults would be well within the limits for which the plant was designed.

In December 1974, after we had responded to AEC questions about the Hosgri Fault, the AEC took the position that the Hosgri Fault could affect the seismic design basis of the plant. It requested that the plant be checked for a site ground motion somewhat greater than that specified by us in the original design.

In January 1975, the USGS evaluation of the Hosgri Fault was forwarded to the NRC. The evaluation took the position that the new, higher ground motion level specified by the NRC was still inadequate. This conclusion was apparently largely influenced by a university senior report sponsored by the USGS. This senior report, by student William Gawthrop, raised the possibility that the origin of the 1927, 7.3M Lompoc earthquake could be reassigned to the southern end of the Hosgri structure rather than to fault further offshore. The Gawthrop paper was open-filed in May 1975.

After extensive review and analysis, the Company's consultants determined that Mr. Gawthrop's contention could not be supported by either the seismological or geological data. They instead assigned the Lompoc earthquake to a fault referred to as the "offshore Lompoc fault" located southwest of the Hosgri Fault.

The NRC requested additional information about the 1927 earthquake and other matters in light of the USGS evaluation of January 1975. This information was developed using further offshore data which had subsequently been open-filed by the USGS and proprietary data which was purchased, together with additional seismological studies by Dr. Smith.

In December of 1975, Dr. Clarence Hall published a paper which suggested extensive movement along the Hosgri Fault. Our consultants reviewed this paper and did additional field work to check some of the evidence cited. They were then able to conclude that his postulation of large movement was precluded by other evidence.

In April 1976, after we had submitted to the NRC considerable additional information and had participated in numerous discussions with its staff, a further USGS evaluation was given to the NRC. In this evaluation, the USGS repeated its position as set forth in January 1975, but this time recommended a specific basis for estimating earthquake parameters. The ground motion at the site from this postulated earthquake was substantially more severe than the already higher values studied in December 1974, at the AEC's request. The NRC accepted this April 1976 assessment and asked us to provide an appropriate evaluation of the plant.

The Company, reinforced by the exhaustive studies and opinions of its consultants, believe that the earthquake parameters selected by the USGS and the resulting ground motion values are unreasonably high and therefore result in conservatisms far in excess of that which should reasonably required.

On May 11, 1976, the NRC issued Supplement 4 to the Safety Evaluation Report wherein they established the additional seismic design bases to provide for the earthquake potential of the Hosgri Fault. That report contained the following statement:

> "The ground motion values recommended by the U.S. Geological Survey are based on

> instrumental data insofar as possible and do not reflect the presence of structures. These values must be translated into quantitative measures of effective acceleration for design purposes. To develop an effective acceleration for Diablo Canyon, we have obtained the advice of our consultant in this area, Dr. N. M. Newmark of N. M. Newmark Consulting Engineering Services. He has recommended, and we have accepted, that an effective horizontal ground acceleration of 0.75g be used for the development of design response spectra. We will provide additional discussion of this matter, and a report from our consultant, Dr. Newmark, in a future supplement to the Safety Evaluation Report."

That report also established the procedures to be used in evaluating the plant's capability to withstand the postulated Hosgri earthquake. Those procedures are as follows:

1. A magnitude 7.5 earthquake on the Hosgri Fault should be assumed with horizontal ground response spectra

normalized to an effective value of 0.75g for engineering reevaluation of the plant.

2. A revision of the design response spectra will be accepted depending on the equivalent length of the foundations of individual buildings. This revision recognizes that ground motion waves are not synchronized underneath structures during earthquakes. In other words, different points in the foundation base slab will not experience the maxima in the ground motion at the same time.

3. Where such revision in response spectra is used, appropriate allowance for tilting and torsion, which may result from the non-synchonized earthquake motion considered in item 2 above, will be required.

4 In reevaluating the capability of the plant structures, systems and components, inelastic behavior may be relied upon to absorb the ground

> motion energy. Where such behavior is relied upon, a ductility ratio not exceeding 1.2 is acceptable in determining seismic loads and motions. For each particular structure where inelastic behavior is utilized, justification and bases will be required for assuring that the additional strains and deformations will not affect the safety functions of the plant systems and structures. The use of a ductility ratio is permissible only for near-field earthquakes, such as the earthquake postulated for the Hosgri Fault.

Accordingly, we developed the response spectra and associated acceptance criteria based on the Safety Evaluation Report of May 11, 1976. This material was docketed in July 1976. Based on review of this submittal and of additional information which we provided in August and September of 1976, and also based on the recommendations of Dr. Newmark, the NRC issued Supplement No. 5 to the S.E.R. on September 10, 1976. This supplement accepted the use of either Dr. Newmark's spectra or those proposed by our consultant, Dr. John A. Blume, as the basis for reevaluation. However, the NRC staff required some changes in the details of the Blume spectra and stipulated that they not fall below the Newmark spectra at any frequency.

Inelastic response was generally allowed in applying the Blume spectra to the buildings, whereas only limited instances of inelastic response was acceptable with the Newmark spectra.

On February 4, 1977, Company representatives and consultants met with the NRC staff to finalize the Specifications for Seismic Review of Major Structures for 7.5M Hosgri Earthquake which became the basis for our review. The plant and its seismic evaluation have been so reviewed in a conscientious and exhaustively detailed manner.

TESTIMONY OF
DOUGLAS H. HAMILTON
AND
RICHARD H. JAHNS
ON BEHALF OF
PACIFIC GAS AND ELECTRIC COMPANY
DECEMBER 4, 1978
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GEOLOGIC AND SEISMOLOGIC SETTING OF THE DIABLO CANYON POWER PLANT

I. Overview of geology and seismology
  A. Introduction to the coastal region of central California, location of the Diablo Canyon site
  B. Regional geology
    1. Regional features
      a. The San Andreas fault
        i. General features
        ii. The San Andreas fault as a plate boundary
        iii. Summary history of offset along the San Andreas fault since late Mesozoic time
      b. Structural provinces
        i. Regional Tectonic pattern
        ii. Distribution of late Quaternary deformation and seismicity
        iii. Tectonic provinces and boundary regions

        - (1) The Southern Coast Ranges and offshore basins
        - (2) The Western Transverse Ranges
        - (3) The zone of transition and merging between the Southern Coast Ranges and the Western Transverse Ranges

2. Stratigraphy - character and distribution of rock units
    - a. Basement rocks and pre-Cenozoic rocks
        - i. General features
        - ii. The Salinian basement complex - Granitic and crystalline metamorphic rocks, and Great Valley sequence sedimentary rocks
        - iii. Franciscan assemblage and ophiolite
    - b. Cenozoic sedimentary and volcanic rocks
        - i. General features
        - ii. Widespread units
        - iii. Areally restricted units
        - iv. Comparison of the stratigraphic section in the offshore

Oceano Well with on-land stratigraphic sections east of the Hosgri fault.

3. Faults
    a. Major faults of the Southern Coast Ranges and offshore basins
    b. Major faults of the Western Transverse Ranges
    c. Cumulative Neogene and Holocene right slip along faults of the Southern Coast Ranges

C. Seismicity
    1. Historical seismicity of the Coastal Region
    2. Seismologic characteristics of the coastal region of central California

II. Site geology
    A. Geologic setting
    B. General features of the site
    C. Mapping and exploration of the site

III. The Hosgri fault
    A. Overview
    B. Exploration; geophysical expression
    C. Geology of the main reach, Point Sal to Cambria
    D. Geology of the Hosgri zone north of Cambria; relationship to the San Simeon fault

E. Geology of the Hosgri zone south of Point Sal; relationship to the Western Transverse Ranges

F. Overall structural relationships of the Hosgri fault

G. Evidence relating to late Pleistocene and Holocene displacements

IV. Conclusions

I

OVERVIEW OF GEOLOGY AND SEISMOLOGY

A. Introduction To The Coastal Region Of Central California; Location Of The Diablo Canyon Site.

The Diablo Canyon site is located along the southwest-facing coast of the mountainous peninsula that lies between San Luis Obispo Bay and Estero Bay, in south-central California (Figure 1). More specifically, it occupies part of a narrow coastal terrace that fringes the seaward margin of the San Luis Range, which forms the backbone of this peninsula. The terrace at the site is underlain by sedimentary rocks, chiefly sandstone and siltstone, of the middle Miocene Obispo Formation (approximately 16 million years old). Prior to project construction, these rocks of the terrace bench were overlain by an unfaulted sequence of sand, clayey sand, gravel, and rubble, all of Pleistocene age.

The San Luis Range lies within the Southern Coast Ranges structural province of California. This extensive province, with characteristic geologic features and a northwest-southeast structural grain, can be taken to include both the Coast Range mountains west of the San Andreas fault, and the adjacent offshore region extending southwestward to the edge of the continental slope. The Southern Coast Ranges province extends northward to Monterey Bay and southward to a zone of structural transition into the bordering western part of the Transverse Ranges structural and geomorphic province (Figures 2, 3).

Most of the major fault and fold features that define the structural grain of the Southern Coast Ranges are aligned northwest-southwest, essentially parallel with the nearest reach of the San Andreas fault. Toward the southerly end of the province, this grain bends markedly to an east-southeasterly orientation in a zone of transition with the east-west aligned Western Transverse Ranges farther south. The San Luis Range lies north of the transition zone, but is in a part of the Coast Ranges province where some faults and folds trend northwest and others trend west-northwest.

The coast line of the Southern Coast Ranges province corresponds approximately to a structural zone of flexuring, referred to here as the Coastal Boundary zone, that forms a broad border between the generally uplifted onshore region and the downwarped offshore region. The southerly part of this zone includes the Hosgri fault, which is the nearest capable fault to the Diablo Canyon site.

During the approximately 200 years of historic record, the interior of the Southern Coast Ranges province has exhibited a moderate level of seismic activity, with scattered earthquakes ranging up to a maximum of magnitude 6. In geologic terms the period of historical record is brief, but evidence that late Quaternary surface displacements along major faults in the province have been minor or nonexistent indicates that this pattern of small to moderate earthquakes has characterized most of the province during the past 100,000 years or more. This contrasts sharply with the geologic and historic evidence of recurrent major or great earthquakes along the San Andreas fault.

B. Regional Geology

1. Regional Features

a. The San Andreas Fault

i. General Features

The principal structural feature in California is the San Andreas fault. This is a great break of regional extent that forms a near-vertical boundary between the coastal margin of the State and the main continental mass of North America. As such, it is a first-order fault -- a "master feature" both in terms of regional structure and in terms of global plate tectonics.

The San Andreas fault is a continuous, through-going break that extends over a distance of about 1200 km (800 miles), from points offshore from Cape Mendocino on the north of the Gulf of California to the south (Figures 2, 3, 4). Throughout its length, the San Andreas is characterized by right-lateral strike-slip relative motion -- that is, displacement along it is predominantly horizontal, and the ground on the west side moves northward relative to that on the east side. Contemporary geodetic data show that this northward movement of the ground west of the San Andreas fault is occurring fairly steadily, thus building up strain across the fault. Along most of the length of the fault the strain accumulates over intervals of time, ranging from tens of years to several centuries, before reaching a level that exceeds the strength of the material in the fault zone. The fault-zone material then fails by shearing, and the crustal blocks on opposite sides of the fault move right-laterally relative to each other. In the northerly and south-central reaches of the San Andreas, such displacement episodes occur infrequently, at intervals of many decades to a few centuries, but with displacements of 10 to 30 feet and accompanying earthquakes of very large magnitude -- in the 7 to 8-plus range. In the reaches opposite the Monterey Bay region and south of the Transverse Ranges, episodes of slip are more frequent and the accumulating strain is released more evenly and in smaller increments. Earthquakes in these regions of the San Andreas fault occur at intervals of years to tens of years, and over a wide range of magnitudes, up to about 7.5. These relatively high rates of slip give rise to distinctive fault-line topography along the trace of the San Andreas, as shown in Figure 5.

Most of the central part of the San Andreas fault has long followed the same trace it now occupies. For more than twenty million years, the only major change involving the abandoning of one course for a new one is in the area where the fault crosses the east-west structural grain of the Transverse Ranges. There, beginning about 5 million years ago, it formed a great bend and deflected toward the east-southwest, leaving an inactive former trace known as the San Gabriel fault.

Major branches splay from the San Andreas fault in two general areas, one near the San Francisco Bay region in central California, and the other near the San Bernardino Valley in southern California. Part of the cumulative offset and part of the contemporary strain relief along the San Andreas fault system is accommodated on these faults, although the major displacements are confined to the main trace. The principal branch faults in central California are the Calaveras and Hayward faults, east of San Francisco Bay, and the San Gregorio fault along the coast west of the Bay.

Matching and restoration of distinctive rock units and other geologic features that once were continuous but are now located at widely separated points across the San Andreas fault shows that the cumulative slip along this break over the past 22 million years amounts to about 300 km (190 miles). Older rock units in northern California appear to have been displaced by even greater amounts, and the total right slip since the time of formation of one of the offset units (about 100 million years ago) is about 550 km (330 miles). Reconstruction of the environment of deposition of a sedimentary formation located along the west side of the San Andreas fault near Point Arena, in northern California, has led to the view that this formation accumulated in a fault-controlled trough along the line of the present San Andreas. An age on the order of 100 million years for this part of the San Andreas system is thus suggested.

ii. The San Andreas Fault As A Plate Boundary

Studies based on the relatively recent concepts of global plate tectonics have shown that for many millions of years the boundary between the oceanic crustal plate of the eastern Pacific Ocean and the continental crustal plate of North America was characterized by relative underthrusting of the North American plate by the Pacific plate. Relative motion at the plate boundary was therefore represented mainly by large-scale thrust faulting at depth, such as that occurring along some other plate boundaries of the world at the present time. Underthrusting of the west coast of South America by the adjacent oceanic plate is a contemporary example. About 29 million years ago in California, however, the progressively changing geometry of the plate boundaries reached a configuration such that the underthrusting boundary movement ceased and was replaced by strike-slip (horizontal sliding) movement between the plates. By approximately 22 million years ago the horizontal shearing between the Pacific and North American plates had become concentrated on the San Andreas fault (Figure 4). This is shown by the evidence of distinctive volcanic and other rock units that were originally deposited across the fault and then offset to locations that are now distant from each other but still close to the trace of the fault (Figure 6).

It is possible that the strike-slip plate-boundary shearing developed preferentially along a preexisting major fault, as there is evidence of an earlier period of large-scale offset along the San Andreas fault north of the Transverse Ranges (Figure 6). But no evidence of a corresponding earlier period of fault offset along the San Andreas south of the Transverse Ranges has yet been well identified. This has been cited in support of some arguments to the effect that offset along the other faults along the coastline in northern California may account for much of the apparent "excess" of offset on the San Andreas north of the Transverse Ranges.

Whatever the history of movement along either the San Andreas fault or some ancient precursor prior to 22 million years ago, the evidence is clear that the San Andreas has been the dominant locus of shear resulting from differential movement between the Pacific and North American crustal plates during the past 22 million years. It is the only geologic feature that can be traced without interruption from northern to southern California, the only great structure that shows consistent geologic and geodetic evidence of continuing strain accumulation throughout its length, and the only regional fault the ends of which are marked by divergent plate boundary features (the spreading ridges centers in the Gulf of California on the south; the Mendocino triple junction on the north) that can generate and accommodate the large amounts of offset recorded along its central reach (Figure 5).

Evidence that the San Andreas fault is a master break representing the boundary between the Pacific and North American crustal plates does not mean that no other deformation is associated with the right lateral shear concentrated along the San Andreas. Indeed, it is generally agreed that much of the deformation resulting from regional north-south compression in both the Coast Ranges and in the Transverse Ranges is an element of the San Andreas stress-strain system. Deformation in these regions, which includes both folding and several styles of faulting, is nonetheless subsidiary, in terms of cumulative fault slip and crustal shortening, to the deformation concentrated along the San Andreas. In the vicinity of the Transverse Ranges and the "big bend" reach of the San Andreas fault, the deformation is apparently influenced and accentuated by an interfering stress-strain system associated with east-west extension in the plate north of the Garlock fault and east of the San Andreas fault. This has given rise to the existence of a special domain of east-west oriented left-lateral shear and related elements of deformation that are unique to the boundary region between the Transverse Ranges and Coast Ranges provinces. This is discussed further in the following section on structural provinces, and is illustrated on Figure 8.

iii. Summary History Of Offset Along The San Andreas Fault Since Mesozoic Time

The major elements of geologic evidence for the history of offset along the San Andreas fault are shown on the accompanying map, Figure 6. Probably the least equivocal evidence for large offset is the correlation of the Pinnacles volcanics, on the west side of the fault in central California, with the Neenach volcanics, on its east side near the Transverse Ranges. These petrologically distinctive rocks, which have been shown by radiometric dating to be of the same age, probably were of limited original areal extent. They are now located about 300 km (190 miles) apart, thus demonstrating that that much slip has occurred along the San Andreas in the last 23.5 million years. Sedimentary rocks of about the same age in southern California are displaced across the fault by about the same distance.

In both northern and southern California, several other correlated pairs of rock units of successively younger ages have been shown to be offset by progressively smaller amounts. The rate of slip has not been uniform through geologic time, however, but rather is characterized by a long episode of little or no movement, between 24 and 60 million years ago, and then by relatively rapid movement during the last 12 million years. Most critical, for considerations of present seismicity, is the slip behavior of the San Andreas and other faults during the past 5 million years or so. This most recent period of geologic time has been characterized by rather uniform (and rapid) plate-boundary movements and rather uniform plate geometry. Most of the movement between the Pacific and North American plates has been concentrated by slip directly along the San Andreas during this time. It has, in consequence, been the main locus of strain release and earthquake generation during latest Tertiary and Quaternary time (Figure 7).

The earlier history of the San Andreas fault is less clear. Two sets of geologic features are recognized that seem to have been displaced, from south-central to northern California, over distances on the order of 500-550 km (300+ miles). One of these features is the southwest margin of the Sierra Nevada batholith of granitic rocks, which appears to be displaced from points near Bakersfield to a position somewhere north of Bodega Head, a distance of about 500 km. The other feature is a sedimentary formation, between Fort Ross and Point Arena, that contains rocks of unusual petrologic character.

Materials in these rocks are thought to have been eroded from a bedrock source now located at Eagle Rest Peak, some 550 km to the south.

The evidence for 500 to 500 km of total slip along the northerly part of the San Andreas fault since early Tertiary time, however, contrasts with evidence in southern California that distinctive Mesozoic or older crystalline basement rocks are not displaced any more than overlying sedimentary rocks of late Miocene (5 to 13 million years) age. While theories abound, no satisfactory resolution of this apparent contradiction has yet been suggested and documented.

b. Structural Provinces

i. Regional Tectonic Pattern

The regional pattern of faults in the part of California extending westward from the Death Valley trend to the continental margin between the latitudes of Monterey Bay and Los Angeles is shown in Figure 8. The dominant element of this pattern is the San Andreas fault, a continental-scale break that is a transform suture between the North American crustal plate on the northeast and the Pacific crustal plate on the southwest. Extending northeastward from the San Andreas in the "Big Bend" area is the Garlock fault, a major discontinuity between the Sierra Nevada and Basin and Range provinces on the north and the Mojave Desert province on the south. The Big Pine fault and its westward projection mark a transitional boundary in that part of the region southwest of the San Andreas, between the Coast Ranges province on the north and the Transverse Ranges province on the south.

Faults with northwesterly trend, similar to that of the San Andreas, are dominant in the Coast Ranges and Mojave Desert provinces. Most are steeply dipping features, but numerous low-angle thrust faults are known in the southern-most part of the Coast Ranges. The principal faults in the Basin and Range province trend north to north-northwest, and in general more northerly than the San Andreas fault and the faults in the Mojave Desert. The Transverse Ranges province, in contrast, is characterized by faults with east-west trend. Many of them are thrusts with low to moderate dips.

The pattern of major faults is complex, and its totally complete history of development remains to be deciphered. Nonetheless, much is now known about this history, and certainly enough to reveal the principal aspects of regional tectonic behavior through middle and late Cenozoic time. Three important generalizations can be noted here for the past 25 million years of regional history:

1. Fault behavior in the region evidently has been associated with sea floor tectonics in the adjacent East Pacific domain, but in ways not yet completely understood.

2. Transverse Ranges structure has played an important role during much of the reference period, at times

an active one and at times a more passive one, but the San Andreas fault has been a dominating influence, expecially during later parts of the period.

3. Tectonic evolution in the region has not been uniform through time.

The last generalization is of special importance in the context of evaluating present and future fault behavior. Many of the faults shown in Figure 1 have moved in different senses at different times, and most of them, including the San Andreas, have not moved at grossly uniform rates throughout their respective histories. For example, many faults in the ground away from the San Andreas, including several that formerly represented major zones of dislocation (e.g., parts of the Sur-Nacimiento, Rinconada, and San Simeon faults in the Southern Coast Ranges), are now, in effect, relic or "fossil" parts of an older structural system. Thus translation of total slip into an appraisal of present capability for any of them can be misleading or seriously in error unless the pertinent variations in time-history are factored into the analysis.

For present purposes, it is appropriate to focus upon fault behavior through the most recent 4-1/2 million years of geologic time. This is a period during which the Gulf of California has been opening under fairly uniform conditions of seafloor spreading along the East Pacific rise, the San Andreas fault has been extremely active, and present elements of regional tectonic behavior have been established. It corresponds to late Pliocene + Pleistocene + Holocene time. In later parts of this discussion, the focus is more specifically directed to tectonic behavior in the Southern Coast Ranges and Western Transverse Ranges provinces during late Quaternary time, i.e., during latest Pleistocene + Holocene time.

Some 4 or 5 million years ago, the San Andreas fault, with dominant rightslip, appears to have abandoned a straight trend that included the present San Gabriel fault (Figure 1), and to have adopted its present more easterly trend through the Transverse Ranges between the "Big Bend" area and San Bernardino. The continued movements along this master break, together with thrusting and folding along east-west trends in the Transverse Ranges, are regarded by most investigators as expressions of regional north-south or north-northwest-south-southeast crustal shortening. This strain system, represented diagrammatically by the pair of large arrows in Figure 8, simply and satisfactorily describes the know right-slip along the San Andreas fault and nearly all of the known north-south compression by thrusting and folding. It is less satisfactory in explaining the origin of the major bend in the present San Andreas trend and the known left-slip along the Garlock, White Wolf, and other faults with northeasterly trend. Considered alone, it is quite incompatible with known left-slip along west-to northwest-trending faults, most important among which are the Santa Ynez fault and the numerous major breaks extending along the Mission Hills - San Cayetano - Santa Susana - Sierra Madre - Cucamonga trend between the Santa Barbara and San Bernardino areas.

In his analysis of the White Wolf fault relative to the regional tectonic pattern, Benioff (1955) outlined the inadequacy of a simple stress system in which the San Andreas and Garlock faults are viewed as conjugate fractures reflecting north-south compression or a simple shearing couple. He pointed out that the major bend in the San Andreas fault "together with the left strike-slip displacements on the Garlock fault indicate that in addition to the regional movements parallel to the San Andreas fault there is a regional movement parallel to the Garlock fault. These two movements are eventually incompatible and it appears that the White Wolf fault is an expression of this incompatibility." More specifically, he suggested regional "movement of the mass north of the Garlock fault in a westerly direction relative to the southern mass."

To describe the known relationships more completely, it is necessary to consider the ground lying north of the Garlock fault. This ground, often neglected in analyses of the San Andreas stress-strain system, has been characterized by east-west extension during the reference period of late Pliocene + Quaternary time. Its principal faults, such as those of the Sierra Nevada, Panamint, and Death Valley zones, are inclined at moderate to moderately high angles and have behaved mainly as normal dip-slip breaks, in contrast to the near-vertical right-slip faults with northwest trend in the Mojave Desert to the south. Moreover, the indicated crustal extension may well be cumulative in a westerly direction toward the San Andreas fault, as suggested diagrammatically by the smaller arrows in Figure 8.

Whether described as a west-southwestward shove or as a very broad counter-clockwise rotation against the San Andreas fault and the Coast Ranges structure farther west, this relative movement of the crust north of the Garlock fault bespeaks the existence of stresses in addition to those that would account simply for north-south regional crustal shortening. Such stresses imposed from an easterly direction would explain development and progressive accentuation of the major bend in the San Andreas fault, as well as bends farther west between typical west-trending Transverse Ranges faults and typical northwest-trending Coast Ranges faults (Figure 8). They also would explain the widespread evidences of left-flip components along many west-to northwest-trending faults in the region.

In summary, the regional tectonic pattern for late Pliocene + Quaternary time emphasizes the importance of the San Andreas and Garlock faults, the San Andreas as a master break and plate boundary, and the Garlock as a boundary element for a domain of westward crustal impingement. Such impingement, acting in concert with the regional strain system of nearly north-south crustal shortening, also focuses attention on the narrow east-west belt along which Coast Ranges faults bend abruptly or gradually eastward into Transverse Ranges trends. This is a belt of junction or abutment of right-slip and left-slip faults, with repeated geometric relationships similar to that between the San Andreas and Garlock faults in the "Big Bend" area (Figure 8). Despite the bending, the San Andreas fault has maintained a continuous course southeastward across the Transverse Ranges province, whereas the second- and lesser-order faults of the Coast Ranges have not done so. As lesser analogues of the bent and relatively "locked" segment of the San Andreas, the bent segments of Coast Ranges faults can be regarded as small domains of special strain accumulation along the northerly border of the Transverse Ranges province.

ii. Distribution Of Late Quaternary Deformation And Seismicity

The distribution of holocene and historic tectonism in the Southern Coast Ranges, Western Transverse Ranges, and adjacent offshore area is indicated by four principal types of evidence. These are (1) observed fault rupture; (2) geodetic measurements showing active deformation; (3) geomorphic expression of faulting and deformation of late Quaternary deposits; and (4) associated seismic activity. The pattern indicated by such lines of evidence is shown on Figure 18.

Review of such evidence has shown that tectonic activity is predominantly concentrated along the San Andreas fault. In the mainsouthern part of the Coast Ranges province, no other faults show evidence of more than minor seismic activity during Holocene time. The same is generally true of the adjacent offshore region, where both the sea floor and the unconformity at the base of the post-Wisconsinan sea floor deposits provide useful datum surfaces for gauging Holocene deformation down to about 350 feet of depth. Unambiguous evidence of extensive post-Wisconsinan deformation in the offshore region has been identified only in the area along the coast line between Point Sal and Point Arguello, which lies in the belt of transition between structural trends of the Coast Ranges and those of the Western Transverse Ranges. Obvious fault scarps also are present in the Santa Lucia Bank area, but there they are below the depth of Wisconsinan low-stand subaerial erosion, and hence may well be older than late Quaternary.

In contrast to the apparently low level of late Quaternary tectonism in the Southern Coast Ranges, the

Western Transverse Ranges (and Santa Barbara channel) and the adjacent belt of transition show fairly widespread evidence of tectonism during this time. Rupture has occurred during historic time along the Big Pine and San Fernando faults. Contemporary creep is reported on the Mesa fault through Santa Barbara, and breaks of Holocene alluvium are known along several fault traces. Study of repeated leveling traverses (Willott, 1972) has suggested that vertical deformation is currently taking place, chiefly through differential movement along faults, in the Transverse Ranges and transition zone. Recent study of the marine terraces along the coastline west of Ventura by Lajoie and others has shown that the 40,000 year old terrace has been uplifted by as much as 250 meters along the Ventura Avenue anticline, and offset by faulting. The Holocene terrace in the same area has been uplifted several meters above the present sea level.

At least three damaging shocks (1925 Santa Barbara, 1971 San Fernando, 1978 Santa Barbara) have originated along Western Transverse Ranges faults during this century. Further, the 1927 Lompoc earthquake has been shown to have originated in the zone of structural merging and transition along the northerly border of the Western Transverse Ranges. As in the Southern Coast Ranges, numerous smaller earthquakes also occur throughout the Western Transverse Ranges region. Notable concentrations of seismic activity have been identified in the eastern Santa Barbara channel, the Purisima and Casmalia Hills, and the offshore area between Point Conception and Point Argeullo.

(1) The Southern Coast Ranges And Offshore Basins Tectonic Province

The Southern Coast Ranges tectonic province is characterized by faults with northwesterly trends and typically right-lateral or high-angle senses of movement. The larger faults, which may be regarded as second-order features relative to the San Andreas, are 50 to 100 miles long, and some of them form parts of even larger structural trends. Cumulative displacement along the fault typically amounts to thousands of feet of vertical slip and thousands of feet to a few miles of lateral slip, and most of these breaks have a complex history of movements. Features of fault-line morphology are common along their general traces, and late Quaternary surface movement can be inferred along some local segments. Most of the larger faults have records of historic seismicity, with a range from small shocks up to earthquakes of about 6.0 magnitude, but expressions of Holocene surface displacements are characteristically lacking. Unambiguous examples of second-order faults within the Southern Coast Ranges tectonic province include the Nacimiento, Rinconada, Santa Lucia Bank, and possibly the

San Simeon. The Hosgri fault has dimensions that equal those of some second-order faults; however, no record of its behavior during early and middle Pleistocene time remains owing to successive episodes of marine planation of the rocks within which it is developed. Consequently, it has not been possible to determine whether it should be regarded as a second-order or a large third-order fault.

Relatively large basin-margin faults, other relatively large faults that appear to be isolated within the tectonic framework of the Coast Ranges, and the principal branches of second-order faults can be regarded as third-order faults. Such faults typically are tens of miles long and some of them, like some of the second-order faults, form parts of longer structural trends. They show displacements of hundreds to a few thousands of feet, ordinarily dominated by vertical slip. Features of erosional fault-line topography are present locally, but expressions of late Quaternary surface faulting are rare or absent. Many faults of this order have records of minor historic seismicity, and several of them could have been the sources of shocks in the intermediate, locally damaging range. Clear examples of third-order faults within the Southern Coast Ranges include the Edna and West Huasna faults.

Faults of the Southern Coast Ranges typically bend toward the east as traced southeastward, and some develop into reverse or thrust faults as they enter the transition region along the northerly border of the Western Transverse Ranges province.

(2) The Western Transverse Ranges Tectonic Province

The Western Transverse Ranges tectonic province is characterized by faults with east-west trends and, typically, reverse or left-oblique senses of movement. The major faults in this province are 50 to 90 miles long, and they exhibit geologic and geomorphic evidence of movement during late Quaternary time. The historic level of geologic and seismic activity associated with the Transverse Ranges system clearly exceeds that in the Coast Ranges. Surface movements and large earthquakes have occurred on several different faults diversely located within the Transverse Ranges, whereas in the Southern Coast Ranges such effects have occurred only along the bordering San Andreas fault during historic time and perhaps even during Holocene time.

Because of the differing structural style and level of activity in the two tectonic provinces, it is not possible directly to compare orders of faults in the Coast Ranges with orders of those in the Transverse Ranges. From the historic and the late Quaternary geologic records and from consideration of the mechanics of faulting, especially the relatively higher stress across a fault plane during reverse slippage, it is evident that the seismic potential is significantly greater for active reverse faults in the Transverse Ranges and transition regions than it is for "capable," but not necessarily active, Coast Ranges strike-slip and normal faults of comparable or even substantially greater dimensions. This is graphically shown in maps recently prepared by the California Division of Mines and Geology (Greensfelder, 1972; Jennings, 1973), which show eight or nine "seismically capable" faults in the Western Transverse Ranges, but only three in the Central Coast Ranges.

(3) The Zone Of Transition And Merging Between The Southern Coast Ranges And The Western Transverse Ranges

The zone of structural transition and merging between the Southern Coast Ranges and the Western Transverse Ranges forms a 20-mile wide band across the south end of the Coast Ranges province (Figure 8). In its easterly part, the south boundary of this zone corresponds to the Big Pine fault, which clearly separates Coast Ranges structures from Transverse Range structures. The westerly part of this south boundary corresponds generally to a line through areas where most faults of east-west Transverse Ranges trend begin to bend toward the northwest. The boundary line itself gradually bends toward the southwest, intersecting the coast line just south of Point Arguello.

The north boundary of the transition zone can be taken as the line connecting areas where Coast Ranges faults begin to bend eastward. Defined in this way, the line extends 110 miles westward from the north end of the "Big Bend" of the San Andreas fault to the outer part of the Santa Lucia Bank fault system.

The tectonic style observed in this transition zone evidently results from two competing regional stress-strain systems, and it reflects the merging and intersection of northwest trends characterized by right lateral movements with east-west trends characterized by left lateral movements. These effects are especially pronounced in the westerly part of the transition zone, where there is no clear-cut boundary structure like the Big Pine fault farther east. The second and probably more fundamental tectonic effect derives from the westward shift of ground north of the Garlock and Big Pine faults, relative to the Western Transverse Ranges, as described earlier. This shift appears to have been the primary cause of the "Big Bend" distortion of the San Andreas, and probably also has sheared off the south end of major Coast Ranges faults, such as the Rinconada and South Nacimiento, along the Big Pine fault. Farther west within the transition zone, Coast Ranges and offshore basin faults bend eastward, change to compressional styles of movement, and die out within the transition zone.

A notable feature of the tectonic style within the transition zone is the existence of reverse or thrust movements along northwest to nearly north-trending faults, some of them parts of longer fault sets that extend northward beyond the transition zone. Relatively short, isolated faults also show substantial reverse movement, especially in the central part of the area of bending, merging, and intersection that lies offshore from Purisima Point. The reverse faults noted by Dibblee (1972) as associated with the southerly part of his proposed Rinconada fault system also are confined mainly to the ground included within the transition zone.

Because the transition zone is a region of "tectonic fight," where competing lateral movements within and between the Coast Ranges and Western Transverse Ranges must be accommodated through bending, vertical offsets, and other adjustments, it is characterized by local accumulations of strain in substantial amounts. This strain is relieved through folding and faulting with accompanying seismic activity. Because of the locally enhanced compressive stress regime, however, faults of all scales (including the San Andreas) tend to remain locked until high strain levels are reached, and then to generate correspondingly large earthquakes when they do yield. The Fort Tejon earthquake of 1857, the damaging Los Alamos shocks of 1902 and 1915, the large Lompoc earthquake of

1927, and the 1969 earthquake swarm in the Santa Lucia Bank system are examples of this feature of transition zone tectonics.

2. Stratigraphy - Character and Distribution Of Rock Units

a. Basement Rocks And Pre-Cenozoic Rocks

i. General Features

The pre-Tertiary bedrock sequence of the Southern Coast Ranges includes four major rock assemblages. The distribution and structural interrelationships of the units that contain these four rock assemblages provide essential clues to the early geologic history of this region.

The four assemblages are divided generally into a continental crust basement, the Salinian basement complex of granitic and crystalline metamorphic rocks; derivative sedimentary rocks known as the Great Valley assemblage; oceanic crust, represented by ophiolite assemblage rocks; and derivative sedimentary and volcanic rocks, represented by the Franciscan assemblage. The general character and distribution of these units are briefly noted below. Their regional distribution is shown on Figure 9.

ii. The Salinian Basement Complex - Granitic And Crystalline Metamorphic Rocks, And Great Valley Sequence Sedimentary Rocks

The ground between the San Andreas fault and a series of faults referred to collectively as the Sur-Nacimiento fault zone is underlain by a complex of crystalline igneous and metamorphic rocks, known as the Salinian basement complex. This complex includes two general rock types -- crystalline metamorphic rocks formed by recrystallization of sedimentary rocks, and granitic rocks formed by crystallization from melts, or magmas, that were intruded into the metamorphic rock series. This complex of rocks forms a typical continental crust. It is generally believed to represent an original southerly extension of the Sierra Nevada batholith, which was partially underthrust by oceanic rocks and then displaced to its present location by northward movement along the San Andreas fault.

A sequence of clastic sedimentary rocks known as the Great Valley sequence and apparently derived largely from erosion of the crystalline complex during late Mesozoic time, is now present overlying both the Salinian basement rocks and Franciscan and ophiolite rocks.

iii. Franciscan Assemblage And Ophiolite

Southwest of the Sur-Nacimiento fault zone, the basement of the Southern Coast Ranges is a highly deformed complex of sedimentary and volcanic rocks known as the Franciscan assemblage (or Formation). These rocks are thought to have been deposited in an offshore trench that existed during the time of underthrusting, or subduction, of the Pacific plate under the North American plate during late Jurassic and Cretacous time.

Characteristic rock types of the Franciscan assemblage include graywacke sandstone (sandstone consisting largely of grains of basic volcanic rocks), greenstones· (metamorphosed volcanic rocks), shale, and chert.

Included within the Franciscan basement terrane are isolated fault-bounded masses of a distinctive assemblage of rocks, known as ophiolites, that are thought to be remnants of ocean-floor crust formed about 160 million years ago. These rocks exist in several areas in the Southern Coast Ranges (Figure 10). The presence of like-appearing ophiolite assemblages at Point Sal and near San Simeon has been cited as evidence that these rocks must have been separated by large-scale strike-slip faulting. Such a mechanism, however, is not required to account for the existence of these assemblages at widely separated locations. Little is known of their early structural history, but their relatively widespread, though scattered, distribution in the Coast Ranges shows that they have not been uniquely positioned by strike-slip faulting.

b. Cenozoic Sedimentary And Volcanic Rocks

i. General Features

The Southern Coast Ranges, including offshore basins, constitute a region that intermittently has been the site for accumulation of clastic sedimentary rocks through Cenozoic time. Because of the several episodes of deformation, uplift, and erosion that have affected this area, especially the onshore Coast Ranges part, these rocks are now preserved mainly in structural depressions such as the Pismo-San Luis syncline, the Huasna syncline, and the onshore Santa Maria Basin. The offshore basins have undergone less uplift and consequently less erosion, especially since Middle Miocene time about 15 million years ago, so that the sedimentary accumulations are more widely preserved in them.

Most of these rocks were deposited over wide regions, although they were wedged out over local topographically high areas on the flanks of structurally controlled sub-basins. Consequently, the characteristic formations of from 22 million years ago (Miocene) through 3 million years ago (Pliocene) age occur over areas of many square miles. Differences in thickness and lithology are fairly gradual within most of these formations, although some basin fillings are notable for substantial changes over short distances.

Besides the widely distributed sedimentary formations, some rock units were deposited or emplaced within relatively limited areas. The two chief examples of such units in the Southern Coast Ranges are the coarse clastic units that were laid down in close proximity to lithologically distinctive source terranes; these are represented by parts of the Oligocene Sespe Formation and the Lospe Formation of presumed equivalent age, and by the volcanic-derived rocks of the Obispo Formation of early middle Miocene age. The distribution of such units was controlled by proximity to local source areas; some, notably several of the coarse sedimentary breccias assigned to the Lospe Formation, apparently are local fan deposits derived from nearby high-standing masses of ophiolite rocks. Such areally restricted rock units would provide useful markers for evaluating offset along faults separating them from respectively recognizable source terranes. Occurrences in close proximity of both the source and the derivative rock, on the other hand, cannot by itself have significance regarding possible offset from other more or less similar rocks.

ii. Widespread Sedimentary Units

A succession of clastic sedimentary rock units or formations of mid-Tertiary and younger age is present in the Southern Coast Ranges and offshore basins region. Typically these units were originally deposited under marine conditions over areas of thousands of square miles, with only relatively minor changes of lithologic character and fossil content throughout much of their extent. Such changes commonly are related to variations in water depth and proximity to sediment sources, and are referred to as "facies changes." In the case of formations with original widespread distribution, apparent differences between rocks of the same formation exposed at nearby locations may be suggestive, though usually not demonstrative, of fault movement since the time of deposition. Nor do similarities between rocks exposed at even widely separated locations constitute direct evidence for an originally closer proximity. Sedimentary rocks of originally wide distribution rarely provide strong evidence either for or against post-depositional separation of originally contiguous units.

The principal middle through late Tertiary rock units of originally widespread distribution in the Southern Coast Ranges and offshore basins are noted as follows, beginning with the oldest.

Vaqueros And Rincon Formations. The Vaqueros and Rincon Formations, of Oligocene and early Miocene age, respectively, are the oldest Tertiary Formations of original widespread extent that are now preserved in the Southern Coast Ranges region. The Vaqueros strata typically rest on a surface eroded over Franciscan-assemblage basement rocks, and they are generally overlain conformably by strata of the Rincon Formation. The Vaqueros is chiefly marine sandstone with some conglomerate, whereas the Rincon is predominantly shale and mudstone. These rocks occur in scattered areas of the Coast Ranges and Western Transverse Ranges, at the base of a succession of Tertiary formations. In some areas, notably in the onshore Santa Maria Basin, the Vaqueros and Rincon are missing, either through non-deposition or because of removal by erosion prior to deposition of the younger Tertiary section.

Monterey Formation. The middle to late Miocene Monterey Formation and its stratigraphic equivalents probably constitute the most widely distributed Tertiary rock unit in California. In the Southern Coast Ranges, rocks of the Monterey Formation are prominent in all remaining Tertiary sections, either as the basal Tertiary unit or as a unit overlying Rincon, Obispo, or Point Sal rocks. In the offshore Santa Maria basin the Monterey forms a seismically distinctive unit that can be traced throughout the basin (Figure 11).

The Monterey Formation is often divided into lower, middle, and upper members, which are differentiated on the basis of lithology and microfauna-defined age. The lower member is rich in silty, phosphatic, and porcelaneous mudstone, with thin interbeds of limestone and with relatively minor amounts of chert, and interbeds of sandstone and sedimentary breccia. The middle member is characterized by abundant chert, with porcelaneous shale and minor limestone. The chert is commonly thin bedded, but it also occurs locally as lenses and pods up to several feet thick. A notable sequence of chert beds of 6 inches to about 10 feet thick is exposed along the coast south of Point Sal and the Lions Head fault, and similarly massive chert is encountered in oil well borings in that area. Shale and porcelaneous shale, which locally grade into diatomaceous shale, are the dominant lithologies in the upper member.

The Monterey Formation is overlain by a sequence of shale, claystone, and sandstone beds that have been assigned different names in different parts of the region. These beds range from late Miocene (about 12 million years) to late Pliocene or early Pleistocene in age. The formation names that have been assigned in the Santa Maria area are the Sisquoc, Foxen, and Careaga Formations, and in the region from Arroyo Grande north, the Pismo Formation. Like the underlying Monterey Formation, the lower part of this sequence of strata was deposited over an area of thousands of square miles, and it can be followed in continuous seismic reflection profiles throughout the offshore Santa Maria basin (Figure 12). Lithologically similar rocks crop out at uplifted points along the coast as far north as Point Sur.

iii. Areally Restricted Units

Tertiary rock units in the Southern Coast Ranges that were deposited or emplaced over relatively limited areas include the shallow igneous intrusive rocks of the Morro Rock-Islay Hill complex, the Cambrua Felsite, the several local accumulations of conglomerate and sedimentary breccia referred to as the Lospe Formation, and the volcanic-related rocks of the Obispo Formation. Other locally occurring intrusive volcanic rocks and intrusive breccias have not been assigned separate names; some have been described with the sedimentary formations into which they were emplaced. The intrusive breccias and tuffs present in the Lospe Formation near Point Sal are notable examples.

The Morro Rock-Islay Hill complex is a series of shallowly emplaced igneous rock masses, which crop out as a line of prominent hills along the southwest side of Los Osros-San Luis Obispo Valley. Hollister Peak, Islay Hill, and Morro Rock are all made up of the resistant dacitic volcanic rock of this complex. This rock has been radiometrically dated in the range of 22-26 million years.

The Cambria Felsite exists in scattered outcrops in the hills east of Cambria, and possibly in a few small patches in Los Osos Valley. It is thought to have been formed as an ash fall associated with an eruption of part of the Morro Rock-Islay Hill complex volcanics. Clasts of Cambria Felsite are present in the conglomerate of the overlying Lospe/Sespe Formation, thereby showing that this unit was at least in part derived from erosion of local source rocks.

Rocks assigned to the Lospe Formation are located near Point Piedras Blancas, in the hills east of Cambria, and in a mostly buried wedge extending east-southeast from an area of outcrop near Point Sal (Figure 13). These rocks have a common stratigraphic position below all other surviving Tertiary rocks except the Cambria Felsite in the Cambria area, and their composition and texture indicate derivation from the local bedrock. Thus, the Lospe near Point Piedras Blancas and part of it near Point Sal is apparently composed entirely of material shed from the distinctive ophiolite bedrock in the corresponding areas. The coarse, bouldery texture and the mostly poorly defined to chaotic bedding in both occurrences indicate a local debris flow or talus mode of deposition of the rocks. At another outcrop near Point Sal the Lospe consists of a basal interbedded sandstone and conglomerate, composed of mixed ophiolite and Franciscan debris, which grades up into a thick section of massive sandstone. The sandstone is overlain in turn by massive claystone. The Lospe near

Cambria consists of conglomerate made up of varying fractions of Franciscan and Cambria Felsite debris, sandstone, and claystone.

The Obispo and Tranquillon Formations represent a lithologically distinctive sequence of volcanic and volcanic-sedimentary rocks that exist in local areas around the Santa Maria Valley, including locations near Point Arguello, northeast of Purisima Point, and in the San Luis-Pismo and Huasna synclines (Figure 14). Tuff, tuffaceous sandstone, intrusive tuff breccia, and basalt are included in various parts of these formations. The Obispo-Tranquillon is of early Miocene age and has been radiometrically dated at 16 million years. It transgressively overlies Franciscan, Vaqueros and Rincon Formations, and it underlies and locally grades into Point Sal or lower Monterey Formation. It underlies the Monterey and may overlie Lospe Formation or Franciscan or ophilite rock in the section penetrated by the offshore Oceano Well.

iv. Comparison Of The Stratigraphic Section In The Offshore Oceano Well With On-Land Stratigraphic Sections East Of The Hosgri Fault

The stratigraphic section that exists at various onshore points from the San Luis Range southward to the Santa Barbara channel varies both in thickness and in character. Certain areally widespread units, especially the Middle Miocene Monterey Formation and the overlying Pismo-Sisquoc-Foxen section, are present throughout this region, although they each vary in thickness and, to some extent, in facies. The lower Miocene Obispo-Tranquillon Formation is present at or near the base of the Tertiary section in specific areas, particularly in the San Luis-Pismo syncline, the Huasna syncline, south of Point Sal, and near Point Arguello.

The Lospe Formation, of presumed Oligocene age, is present in the trough of the onshore Santa Maria Basin in a wedge that extends east-southeastward from Point Sal (Figure 13). From Point Arguello northward, the Oligocene and younger Tertiary section rests on Franciscan or, near Point Sal, ophiolite basement rock. In the main western Santa Ynez Mountains and the Santa Barbara channel, a distinctive section of early Tertiary and Cretaceous sedimentary rocks more than 10,000 feet thick underlies the Oligocene and younger rocks (Figure 15).

The fact that the onshore geologic column, which lies east of the Hosgri fault trend, exhibits a systematically varying thickness of widespread rock units, and also locally contains units of limited areal extent, allows some assessment of the possibility of offset relative to the onshore basin of a section encountered in the offshore Oceano Well, located opposite the Santa Maria Valley west of the Hosgri fault. Comparison of the Oceano Well section with onshore sections shows that the Monterey-Sisquoc-Foxen column in the upper part of the well agrees in thickness with the thickness of these units in the onshore columns located generally opposite the Hosgri fault, but that the Monterey is only about half as thick in the well section as in the western Santa Ynez Mountains column, located 50 km to the south (Figure 15). The Monterey in the well overlies a section of tuff and basalt that corresponds to the Obispo-Tranquillon on shore. The lowermost part of the Oceano Well may, from the available date, have been in either Obispo or Lospe, and the well may have bottomed in either Franciscan or ophiolite basement. Either of these possible combinations corresponds to sections that exist across the Hosgri fault in the subsurface near Point Sal or Casmalia, but not to the western Santa Ynez Mountains or Santa Barbara channel sections, where the thick lower Tertiary-Cretaceous section exists. The conclusion from this comparison of stratigraphic sections at points across the Hosgri fault is that right (or left) fault slip of more than a maximum of about 20 km is precluded, and essentially no lateral slip is required. This precludes a possibility of Neogene right slip on the order of 80 to 100 km, such as has been postulated by Hall (1976).

3. Faults

a. Major Faults Of The Southern Coast Ranges And Offshore Basins

The principal faults of the Southern Coast Ranges and offshore basins tectonic province, shown on Figure 16, are here briefly described as they are located from west to east, starting with the Santa Lucia Bank fault near the westerly boundary of the province. The San Andreas fault, described earlier, forms the east boundary of the province. The Hosgri fault is also discussed in greater detail in Section III of this testimony.

i. Santa Lucia Bank Fault System

Santa Lucia Bank Fault. This fault lies along the east flank of the Santa Lucia Bank, between 40 and 50 km west of the California coastline. The fault is well defined and linear over a distance of about 80 km, but it loses definition northward. It turns toward the east near its southerly end. It clearly exhibits evidence of substantial vertical offset, including an east-facing scarp up to 150 meters high, and it probably has a cumulative horizontal displacement of several kilometers since early Miocene time. Lack of continuity through Miocene strata that lie across its trend to the north and south probably imposes a 5 to 10 km limit for lateral slip along it during the past 20 million years. Shocks of the 1969 earthquake swarm near the southerly end of the Santa Lucia Bank fault zone, with magnitudes up to 5.8 and with focal mechanisms indicating a component of right slip, suggest that some Holocene slip probably is represented along the fault zone.

West of the Santa Lucia Bank fault, between latitudes 34°30' and 35° North, several subparallel faults are characterized by apparent surface scarps. The longest of these faults trends along the upper continental slope for a distance of as much as 45 miles, and generally exhibits a west-facing scarp. Other faults are present in a zone, about 30 miles long, that lies between the 45-mile fault and the Santa Lucia Bank fault. These faults range from 5 to 15 or more miles in length, and have both east- and west-facing scarps. All parts of the Santa Lucia Bank fault system are submerged at depths of more than 1200 feet, and hence they may be relatively old compared to sea floor topographic features that exist at depths of less than about 400 feet.

<u>Hosgri Fault</u>. The Hosgri fault forms the southerly part of the east boundary of the offshore Santa Maria Basin. It lies offshore from the coast at distances ranging from 4 to 20 km, and it extends over a total distance of about 145 km (90 miles), from near Purisma Point on the south to near Cape San Martin on the north. The Hosgri is part of the larger Coastal Boundary zone of flexures and faults that lies between the uplift of the Southern Coast Ranges and the structural depression of the offshore basins.

The central, main reach of the Hosgri fault strikes about N25W and extends over a distance of about 50 miles between Point Sal and Cambria. Most of this reach consists of only one or two major strands, although it is somewhat wider and more complex where it impinges on the Pt. San Luis structural high between San Luis Obispo Bay and Estero Bay.

Northward from the latitude of Cambria, the Hosgri merges into a zone of isolated breaks and folds. It also splays and dies out in a series of several breaks south of Point Sal.

Cumulative vertical displacement along the Hosgri fault, as recorded by seismic reflection profiles, is between 1 and 2 km, east up, in the last 15 million years. Right-lateral displacement, inferred chiefly from indirect evidence, may amount to as much as about 10 km near the central part of the Hosgri. Lateral displacement decreases toward the ends of the fault, in general to 1 or 2 km, i.e., to amounts that can be accommodated or transferred to other nearby faults through folding and local reverse faulting.

The Hosgri fault has no gross topographic expression in the present sea-floor topography, and detailed investigation by high resolution profiling shows that the late Pleistocene sea floor over most of the trace of the Hosgri was smooth and unbroken. There is no clear evidence as to whether some sea-floor displacements are present in the area where the Hosgri extends along and across submerged terraces in the reach between San Luis Obispo Bay and Estero Bay. A possible sea-floor offset, between 1 and 2 meters high, and less than 2,000 feet in maximum length, is present along one fault strand north of Point Buchon. From San Luis Obispo Bay southward, available evidence indicates that both the sea floor and the underlying wave-cut surface beneath several tens of feet of post-Wisconsinan surficial deposits are unbroken over the Hosgri fault.

San Simeon Fault. The San Simeon fault extends from an end point near Point Estero northward about to the latitude of Lopez Point, and is approximately 100 km (60 miles) long. Available evidence does not clearly define a northerly end point for this fault, which may splay partly into the offshore Pfeiffer Point fault to the west and partly into the Serra Hill fault farther north.

The San Simeon fault can be divided into southerly, on-land, and northerly segments for convenience of reference. The southerly segment is mapped mainly on the basis of three lines of indirect evidence. The most obvious but least definitive of these is the existence of a straight reach of coastline between Cambria and Point Estero, which aligns with a southerly projection of the onshore segment of the fault. From San Simeon Bay southward for about 8 km (5 miles), the well-stratified rocks of the Monterey Formation, which lie along the west side of the fault and butt against Franciscan basement rock on the east side, can be traced in seismic reflection records. Thus a continuation of the fault is indicated for at least that distance. Finally, the aeromagnetic map of residual magnetic intensity of the coastal region shows a southerly shoreline continuation of the magnetic trough that exists over the onshore part of the San Simeon fault.

The onshore segment of the San Simeon fault extends 20 km (12 miles) from San Simeon Bay northward to Ragged Point. This segment includes an older major trace along which Franciscan rocks are juxtaposed against ophiolite basement rocks, Mesozoic sedimentary rocks, and rocks of the Tertiary Lospe and Monterey Formations, and an apparently younger trace that lies within the Franciscan section. The older fault trace bends westward along a somewhat irregular trend, and corresponds at Ragged Point to a zone of shearing several hundred feet wide. Linear elements of fabric within the shear zone plunge steeply, indicating high-angle oblique movement along this fault strand. The fault apparently does not break the overlying terrace deposits.

The younger trace, named the Arroyo Laguna fault by Hall (1976), comprises several apparently discontinuous en-echelon segment that are defined by side hill rifts and right-laterally deviated canyon crossings. The trace, which extends northward from Arroyo de la Cruz to an intersection with the coastline 1 km north of Ragged Point, is a nearly straight-line projection of the well-defined southerly reach of the on-land segment of the San Simeon fault. If the right-deviated canyon crossings indeed represent actual strike-slip faulting, rather than fault-line erosion features, late Quaternary right-slip of some 500 meters is indicated along the Arroyo de la Cruz trace. The most recent displacements along this fault, however, were vertical, as shown by the orientation of well-defined grooving and slickensiding in its sea-cliff outcrop.

Evidence relating to possible late Quaternary displacements of faults in the San Simeon area has been sought through detailed mapping by Earth Sciences Associates (Appendix 2.5E to Diablo FSAR, 1975) and by Hall (1976). A more recent investigation by Envicom, Inc. for the Hearst Corporation (Envicom, Inc., 1977) involved trenching at selected localities. The Earth Sciences investigation showed that a branch fault, subsequently named the Arroyo del Oso fault by Hall, has displaced the lower part of the lowest emergent marine terrace by about 3 m (1 foot) in a reverse sense. The same fault also has displaced a higher, older terrace. This investigation further showed that partially cemented dune sand of late Pleistocene or early Holocene age has not been offset along the main trace of the San Simeon fault at San Simeon Bay. The Envicom trenching revealed evidence that the San Simeon fault does not displace land surfaces graded to terrace surfaces, or near surface terrace deposits, that exist at elevations ranging from 80 feet to more than 400 fee above present sea level. However, older terrace deposits underlying, and truncated by, the lowest terrace surface were found to be deformed and faulted. This accords with the impression, gained from photogeologic and surface mapping, that the onshore segment of the San Simeon fault has been active during the last several million years but has not undergone surface rupture during the last 10,000 to 100,000 years.

The northerly segment of the San Simeon fault is known from a few seismic reflection line crossings, as well as from gravity and magnetic data. Along this segment a section of Tertiary strata more than 3,000 meters thick is juxtaposed against Franciscan rocks. The indicated vertical separation is on the order of 5,000 meters along the reach centered opposite Cape San Martin. This represents the thickness of the Tertiary section against the Franciscan rocks, plus the height of the uplifted Franciscan rock east of the fault. Much of the trace of the northerly segment of the San Simeon fault coincides with a steep topographic break. Bedded deposits having the form of an on-land talus accumulation are banked against this slope in places, but evaluation of whether latest Pleistocene or younger surface displacement has occurred along this segment is difficult because of the steepness of the submerged terrain, and because it lies at greater depth than was exposed to subaerial erosion during the Wisconsinan low-stand of sea level. The geologic and topographic relationships suggest, however, that a significant amount of Quaternary vertical displacement may be represented along the northerly San Simeon scarp.

<u>Suey - West Huasna Fault</u>. The Suey and West Huasna faults have been studied by Hall and Corbato (1967)

and by Hall and Prior (1975). Hall and Corbato state (p. 576), "Evidence that most strongly suggests lateral movement along the West Huasna fault is provided by different thicknesses and facies relationships between units of equivalent age on opposite sides of the fault." They make no estimate of the total movement represented, but the distribution of units across the fault suggests about 5 km of right slip since Miocene time, an estimate confirmed by Hall (1977). There is no known evidence of Holocene movement along the West Huasna fault.

<u>Rinconada</u> <u>Fault</u>. The Rinconada fault, as considered here, is the zone of faults that was studied and redefined by Dibblee (1972, 1975). This zone extends northwesterly from a point of truncation by the Big Pine fault in the Transverse Ranges to the vicinity of Arroyo Seco Canyon in the Santa Lucia Range. It comprises principal breaks that have been mapped separately as the Espinosa, San Marcos, and Rinconada faults, along with the southerly part of the Nacimiento fault.

By correlating formations, facies relationships, source terranes, and other features of specific ages that exist at different localities on opposite sides of the Rinconada fault, Dibblee developed a history of increasing cumulative offset along this zone through Cenozoic time. The indicated offset for post-early Miocene time (about the last 20 million years) ranges between limits of 23 and

56 km. A value of 30 km is adopted for this testimony. It should be noted, however, that the amount of cumulative lateral slip along the Rinconada fault decreases toward its end points. Vedder and Brown (1968), for example, showed that there is little difference in the Miocene section on opposite sides of the "Nacimiento segment" of this fault in the San Rafael Mountains.

Regarding the possibility of Holocene or late Pleistocene movement along the Rinconada fault, Dibblee (1975) stated (p. 52), "The Paso Robles Formation, the youngest geologic unit definitely truncated by the faults, is probably not younger than several hundred thousand or possibly a million years old. Except possibly at a few places, there are no surface indications that either fault has moved since deposition of the older alluvium, which is estimated to be about 50,000 to 500,000 years old." Envicom (1974) concluded (p. 2.35), ". . .the most recent movement on the Rinconada fault near Santa Margarita is herein considered pre-Holocene (i.e., at least 10,000 years ago), but possibly late Pleistocene. . ." These conclusions suggest that no movement has occurred along the Rinconada fault during the past 10,000 years; however, the fault is not known to have been explored by trenching, and it is possible that a few meters of Holocene offset actually could be present but not yet detected.

ii. Sur-Nacimiento Fault Zone

The Sur-Nacimiento fault zone has been regarded as the system of faults that extends from the vicinity of Point Sur, near the northwest end of the Santa Lucia Range, to the Big Pine fault in the western Transverse Ranges and that separates the granitic-metamorphic basement rocks of the Salinian Block from the Franciscan basement rocks of the Coastal Block. Page (1970) has made an extensive study of this zone. In an excellent overview statement, he described and discussed the Sur-Nacimiento zone as follows:

> "The structural zone . . . is an arbitrarily delimited, elongate belt of faults of various kinds and ages, extending southeast from the Sur fault zone which is included:
>
> "The Sur fault zone is conspicuously exposed at intervals for 67 km along or near the coast south of Monterey Bay. It visibly separates the pre-Campanian granitic and regionally metamorphosed Sur series rocks of the Salinian block on the northeast from the Upper Jurassic (?) to mid-Cretaceous Franciscan rocks on the southwest. It dips northeast for the most part, and has generally been considered to be a

steep thrust fault, but its original character is not well established.

"The Sur fault meets the Nacimiento fault, which extends southeast from the point of intersection . . .The Nacimiento fault perpetuates the general trend of the Sur fault and continues to form the surficial boundary of the Franciscan rocks, but the basement rocks of the Salinian block are nowhere exposed in the immediate vicinity, being covered by Upper Cretaceous and Tertiary formations. The Salinian basement rocks may or may not be bounded by this fault at depth.

"Although the Nacimiento fault for the most part dips steeply northeast, along its course, low angle faults and klippen have now been recognized . . . .Allochthonous sheets of Cretaceous Great Valley-type clastic sedimentary rocks tectonically overlie the Franciscan assemblage. Windows of Franciscan rocks, bounded on one or both sides by high-angle faults, are found along the zone from the latitude of Lake

Nacimiento to the latitude of San Luis Obispo.

"It is fruitless to argue about which one of the faults south of the latitude of Lake Nacimiento should be called the Nacimiento fault sensu stricto, and the writer prefers not to apply this name to any particular fault except near the Nacimiento River, which is presumed to be the type area. However, the term "Sur-Nacimiento fault zone" is meant to include the southeastward prolongation of the belt of faulting.

"Near Santa Margarita, the Rinconada fault merges with the Sur-Nacimiento fault zone, and for at least a short distance, it is the virtual boundary between the granitic and regionally metamorphosed basement rocks of the Salinian block and the Franciscan rocks of the southwest block.

"Southeast of the latitude of San Luis Obispo, neither the Salinian basement nor the Franciscan rocks are exposed along the fault zone, unless one includes the large window of Franciscan that is crossed by the Cuyama River several kilometers west of the principal fault trace. For approximately 96 km, the Sur-Nacimiento fault zone is represented by a generally northeastward-dipping fault which, for the most part, separates Upper Cretaceous clastic sedimentary rocks on the southwest from Paleocene and Eocene clastic sedimentary rocks on the northeast. . . .

"In the Transverse Ranges, the Sur-Nacimiento fault zone appears to be cut off, with a 16 km left-hand separation, by the Big Pine fault, beyond which is may be represented by the Pine Mountain fault (Vedder and Brown, 1968).

"It is unlikely that the Nacimiento fault proper has displaced the ground surface in Late Quaternary time, as there are no indicative offsets of streams, ridges, terrace deposits, or other topographic features. The Great Valley-type rocks on the northeast side must have been down-dropped against the older Franciscan rocks on the southwest, yet they commonly stand higher in the

> topography. This implies relative quiescence of the fault in Late Quaternary time, allowing differential erosion to take place. In a few localities, the northeast side is the low side, and this inconsistency favors the same conclusion. In addition to the foregoing circumstances, the fault is offset by minor cross-faults in a manner suggesting that little, if any, Late Quaternary near-surface movement had occurred along the main fracture."

Richter (1969) noted that some historic seismicity, particularly the 1952 Bryson earthquake, appears to have originated along the Nacimiento fault. This view is supported by recent work of S.W. Smith (1974), which indicated that the Bryson shock and the epicenters of several smaller, more recent earthquakes were located along or near the trace of the Nacimiento.

La Panza And San Juan Faults. The La Panza and San Juan faults are located between the Rinconada and San Andreas faults. These breaks have been interpreted as predominantly dip-slip features that have been inactive since middle or early Pleistocene time (Envicom, 1974). Hill (1954), however, suggested that right-lateral movement along the San Juan fault since Miocene time could have amounted to several kilometers. Although the available information about possible lateral slip along these faults is poorly defined and contradictory, a value of 3 km for aggregate lateral slip along the La Panza and San Juan faults during the last 20 million years seems reasonable. Slip during the past 10,000 years apparently has been negligible.

b. Major Faults Of The Western Transverse Ranges

The Western Transverse Ranges and Santa Barbara Channel region are characterized by generally east-west structural alignment, and by left-oblique reverse faults, thrust faults, and folds. Many of the faults in this structural province are of major dimensions, and only a few of the most important ones are noted here.

Along the northerly margin of the Western Transverse Ranges, the Big Pine and the Santa Ynez faults are the largest individual breaks. Each is a major left-oblique reverse fault, with rift topography and left-deviated cross canyons along its trace. The Big Pine fault is believed to have ruptured in Lockwood Valley during a strong earthquake in 1852. No historic ground ruptures or large earthquakes have been attributed to the Santa Ynez fault, but it has experienced surface displacement at least as recently as late Pleistocene time, as shown by exploratory trenching across the trace of its south branch in Alegria Canyon.

The axial part of the Western Transverse Ranges is occupied by the structural depression of the Santa Clara River Valley and the Santa Barbara channel. Large, recently active left-oblique reverse and thrust faults extend along the margins of this onshore-offshore depression. The rate of late Quaternary deformation along the north margin of the Santa Clara River Valley, as expressed by folding, uplift, and fault slip, is relatively high.

The southerly margin of the Western Transverse Ranges is defined by north-dipping thrust faults of the Malibu Coast and Sierra Madre fault zones. These faults also are highly active, as indicated by thrusting of Mesozoic and Tertiary rocks over late Quaternary alluvial deposits along them.

Earthquakes and episodes of surface faulting have occurred within the past few decades along the San Fernando fault, the Malibu Coast fault, and faults in the Santa Barbara channel.

C. Cumulative Holocene And Neogene Right Slip Along Faults Of The Southern Coast Ranges

The cumulative amount of right slip that has been reported, or can reasonably be estimated, along those faults that extend across a band transverse to the structural grain of the Southern Coast Ranges at the general latitude of Diablo Canyon is shown in the following table.

Cumulative Right Slip During The Last 10,000 Years And The Last 20,000,000 Years Along Principal Faults In The Southern Coast Ranges

Fault Name	Slip During The Last 10,000 Years (Meters)	Slip During The Last 20,000,000 Years (Kilometers)
Santa Lucia Bank	2*	10*
Hosgri (also applies to San Simeon	2*	10
West Huasna - Suey	1*	5
Rinconada (also applies to Nacimiento)	6*	30
La Panza	-	1
San Juan	-	2
San Andreas	400	280

*Indicated amount of slip has not been reported, but is here considered possible, within the resolution of available exploration data.

For the purpose of graphic comparison, the total Neogene right slip of the San Andreas fault, the faults west of the San Andreas, and the Hosgri fault are all shown on the cumulative lateral slip vs. time plot on Figure 17. These data show that Holocene right slip considered possible for faults west of the San Andreas amounts to about 2.5 percent of that on the San Andreas itself. Holocene slip considered possible for the Hosgri fault amounts to about 0.5 percent of that on the San Andreas.

The relative amount of Neogene right slip considered possible for faults west of the San Andreas, and for the Hosgri in particular, is substantially higher, being about 20 percent and 4 percent, respectively, of the total Neogene slip along the San Andreas. This reflects the relatively high level of activity of second- and third-order faults in the Southern Coast Ranges during late Tertiary time.

C. Seismicity

1. Historical Seismicity Of The Coastal Region

The seismicity of the coastal region of central California is known from scattered historical records extending back about 200 years, and from Instrumental records dating from 1900. Relatively detailed records of earthquake locations and magnitudes became available only following installation of the California Institute of Technology and University of California (Berkeley) seismograph arrays in 1932.

A plot of the epicenters of all instrumentally recorded earthquakes in the coastal and offshore region is shown on Figure 18. The pattern of seismic activity seen on this plot is generally representative of the pattern that has obtained through the approximately 200 years of historic record, with a few significant exceptions. These include the occurrence of the great earthquake of 1857 on the San Andreas fault and the large earthquake of 1852 on the Big Pine fault, both of which involved substantial surface rupture of the causative fault, within the area covered by Figure 18.

The highest levels of seismic activity in the Coastal Region shown on Figure 18 during the period of historical record have been concentrated along the San Andreas fault and in the area including the Western Transverse Ranges, the Santa Barbara channel, and the transition zone along the northerly margin of the Transverse Ranges. West of the San Andreas and north of the Transverse Ranges and transition zone, the largest instrumentally recorded shock is the M 6.0 1952 Bryson earthquake. The identification of the source structure for the M 7.3 1927 Lompoc earthquake is controversial, but is here considered, on the basis of geological evidence, to probably be the offshore Lompoc fault, which breaks the sea floor west of Purisima Point in the transition zone. Numerous smaller shocks have been recorded in the Southern Coast Ranges region, generally along the trends of the larger faults. Thus virtually all of the second- and third-order faults in the coastal region appear to have some level of associated seismicity. The major zones of earthquake-related release of strain energy, however, are primarily directly along the San Andreas fault, and secondarily within the region of the Western Transverse Ranges.

2. Seismologic Characteristics Of The Coastal Region Of Central California

The generation of earthquakes in the crust of the coastal region of central California occurs in response to strain accumulation associated with adjustments within the San Andreas plate-boundary stress-strain system. The thickness of the crust, and the pattern of deformation relative to the regional north-south compression that is associated with this system apparently limits the hypocentral depth of earthquakes in this region to about 12-15 km. Geologic data consisting of observations of fault displacement patterns and seismologic studies consisting of precise locations of earthquake hypocenters and analysis of the orientation and relative sense of seismogenic fault slip, yield complementary determinations showing that right lateral strike-slip fault offsets and earthquake focal mechanisms are dominant along the San Andreas, while right oblique to nearly pure dip-slip fault offsets and earthquake focal mechanisms are characteristic of the continental margin west of the San Andreas. In the Western Transverse Ranges, fault offsets and earthquake focal mechanisms typically range from left oblique to pure thrust dip slip. In both areas, instrumentally well located earthquakes are generally clearly associated with geologically recognizable faults or with areas where high rates of crustal deformation, reflected by local elevation changes, are occurring.

The period of historical record of earthquakes in the coastal region of central California is relatively brief - about 200 years - but the geologic evidence of late Quaternary fault behavior in the region provides a sort of "fossil record" of larger earthquakes over a period ranging from about 10,000 to 17,000 years offshore to as much as 100,000 years or more on land. The geologic evidence appears to indicate that the levels of seismic activity in the Southern Coast Ranges represented by the historical record have in fact been reasonably representative of the seismicity throughout late Quaternary time. This assessment is based on the observation that the cumulative slip along the largest faults in the region west of the San Andreas and north of the Transverse Ranges and transition zone appears to not exceed a maximum of a few meters during the last 10,000 (up to 100,000+) years, and the largest earthquake of record is about M 6.0 (the 1952 Bryson earthquake). Recurrent earthquakes much in excess of this size -- say around M 6.5 or larger -- during a comparable time span should have resulted in greater amounts of recent fault slip than have been reported for the region.

This observed low level of fault slip and earthquake activity in the Southern Coast Ranges region may be attributable to the concentration of fault slip and associated earthquake activity strain release directly along the San Andreas fault. The amount of right slip recorded along the San

Andreas, together with right slip on faults lying east of the Sierra Nevada Range, during the last 200 years of historical record, in fact essentially equals the total current rate of relative movement along the plate boundary. This supports the historical and geologic evidence that the rate of movement along faults in the Southern Coast Ranges west of the San Andreas is very low, with correspondingly moderate seismicity in that region.

The rate of crustal deformation and the level of historical seismicity in the Western Transverse Ranges, and in the transition zone between the Southern Coast Ranges and the Western Transverse Ranges, on the other hand, is much higher, as noted previously in this testimony. This may be attributable to the different orientation of the pattern of geologic structure in this area relative to the regional north-south compression. The tendency toward active east-west left lateral shear in the area may also result in part from the effect of westward extension of the crust located west of the San Andreas and north of the Garlock faults, described earlier.

II

SITE GEOLOGY

A. Geologic Setting

The Diablo Canyon Power Plant Site is located on the coast along the south-western side of the San Luis Range (Figure 1). This peninsula-forming range is underlain by sedimentary, igneous, and tectonically emplaced ultrabasic rocks of Mesozoic age, by sedimentary, pyroclastic, and hypabyssal intrusive rocks of Tertiary age, and by a variety of surficial deposits of Quaternary age. The lithology and distribution of these rocks were studied by Headlee (1965), and more recently the range has been mapped in detail by Hall (1973). The geology of the San Luis Range is shown on Figures 19 and 20.

1. Basement Rocks

A complex assemblage of rocks typical of the Coast Ranges basement terrane west of the Nacimiento fault zone is exposed along the south and northeast sides of the San Luis Range. As described by Headlee (1965), this assemblage includes quartzose and greywacke sandstone, shale, radiolarian chert, intrusive serpentinite and diabase, and pillow basalt. Some of these rocks have been dated as Upper Cretaceous (more than 70 million years old) from contained microfossils, and Headlee suggested that they may represent dislocated parts of the Great Valley sequence. There is contrasting evidence, however, that at least the pillow basalt and associated cherty rocks may be more characteristic of the Franciscan terrane. Further, a potassium-argon age of 156 million years, equivalent to Upper Jurassic, has been determined for a core of similar rocks obtained from the bottom of the Montodoro Well No. 1 near Point Buchon.

2. Tertiary Rocks

Five formational units, ranging in age from about 20 to 6 million years, are represented in the Tertiary section of the San Luis Range. The lower part of this section comprises rocks of the Vaqueros, Rincon, and Obispo Formations, which range in age from lower Miocene through middle Miocene. These strata crop out in the vicinity of Hazard Canyon, at the northwest end of the range, and in a broad band along the south coastal margin of the range. In both areas the Vaqueros rests directly on Mesozoic basement rocks. The core of the western San Luis Range is underlain by the Middle and Upper Miocene Monterey Formation, which constitutes the bulk of the Tertiary section. The Upper Miocene to Lower Pliocene Pismo Formation crops out in a discontinuous band along the southwest flank and across the west end of the range, resting with some discordance on the Monterey section and elsewhere directly on older Tertiary or basement rocks.

The coastal area in the vicinity of Diablo Canyon is underlain by silty and sandy strata that have been variously correlated with the Obispo, Point Sal, and Monterey Formations. Whatever the exact stratigraphic relationships of these rocks might prove to be, it is clear that they lie above the main body of tuffaceous sedimentary rocks of the Obispo Formation and below the main part of the Monterey Formation. The existence of intrusive bodies of both tuff breccia and diabase in this part of the section indicates either that local volcanic activity continued beyond the time of deposition of the Obispo Formation, or that the section represents a predominantly sedimentary facies of the upper part of the Obispo Formation. In either case, the strata underlying the power plant site range downward through the Obispo Formation and presumably include, below levels of present exposure, a few hundred feet of the Rincon and Vaqueros Formations resting upon a basement terrane of Mesozoic rocks.

The Vaqueros Formation consists of resistant, massive, coarse-grained calcareous sandstone, and the overlying Rincon Formation consists of dark gray to chocolate brown calcareous shale and mudstone. The much thicker Obispo Formation (or Obispo Tuff) comprises alternating massive to thick-bedded, medium- to fine- grained vitric-lithic tuffs and tuff breccias (in part intrusive), finely laminated black and brown marine siltstone and shale, and medium-grained light tan marine sandstone. It grades upward into medium- to fine-grained siltstone and silty sandstone that in turn grades upward into siliceous shale characteristic of the Monterey Formation. The Monterey Formation itself is composed predominantly of porcelaneous and finely laminated siliceous and cherty shales. The overlying Pismo Formation consists of massive, medium- to fine-grained arkosic sandstone with subordinate amounts of siltstone, sandy shale, mudstone, hard siliceous shale, and chert.

3. Quaternary Deposits

Deposits of Pleistocene and Holocene age are widespread on the coastal terrace benches along the southwest margin of the San Luis Range, and they are present in areas farther onshore as local alluvial and stream-terrace deposits, landslide debris, and various colluvial accumulations. The coastal terrace deposits include discontinuous thin basal sections of marine silt, sand, gravel, and rubble, some of which are highly fossiliferous, and generally much thicker overlying sections of talus, alluvial-fan debris, and other deposits of landward origin. All of the marine deposits and most of the overlying nonmarine accumulations are of Pleistocene age, but some of the uppermost talus and alluvial deposits are Holocene. Most of the alluvial and colluvial materials consists of silty clayey sand with irregularly distributed fragments and blocks that represent locally exposed bedrock types. The landslide deposits include chaotic mixtures of rock fragments and finer-grained matrix debris, as well as some large masses of nearly intact to thoroughly disrupted bedrock.

4. Structural Features

The geologic structure of the San Luis Range - Estero Bay area and the adjacent offshore area is characterized by a complex system of folds and faults (Figure 19).

These areas lie near the zone of transition between the west-trending Transverse Ranges structural province and the northwest-trending Coast Ranges province. Major structural features within them are the long, narrow downfold of the San Luis - Pismo syncline and the flanking antiformal structural highs of Los Osos Valley on the northeast and Point San Luis and the adjacent offshore area on the southwest. This set of folds trends obliquely into a north-northwest aligned zone of basement upwarping, folding, and high-angle normal faulting that lies a few miles off the coast. The main onshore folds can be recognized offshore, by seismic relection and gravity techniques, in the structure of the buried, downfaulted Miocene section that lies beyond (west of) this zone.

Lesser but nonetheless important structural features in these areas include smaller zones of faulting. The Edna and San Miguelito fault zones disrupt parts of the northeast and southwest flanks of the San Luis - Pismo syncline. A southward extension of the San Simeon fault can be inferred from linearity of the coastline between Cambria Point Estero, and from the gravity gradient in that area; this fault may extend into, and die out within, the rock section beneath the northern part of Estero Bay. An aligned series of plugs and lensoid masses of Tertiary volcanic rocks, which intrude the Franciscan Formation along the axis of the Los Osos Valley antiform, extends from the outer part of Estero Bay southeastward for a distance of 22 miles (Figure 19). These distinctive bodies and their consistent alignment provide a useful reference for assessing the possibility of northwest-trending lateral-slip faulting within Estero Bay. It shows that such faulting has not extended across the trend either from the inferred offshore south extension of the San Simeon fault or from faults in the ground east of the San Simeon trend.

The main synclinal fold system of the San Luis Range, the San Luis - Pismo syncline, trends about N 60 W and forms a structural unit more than 15 miles in length. The system comprises several parallel anticlines and synclines across its maximum onshore width of about 5 miles. Individual folds typically range in length from hundreds of feet to as much as 10,000 feet, and in plunge range from zero to more than 30 degrees. Some of them have flank dips as steep as 90 degrees. Various kinds of smaller folds exist locally, most notably flexures and drag folds associated with tuff intrusions and with zones of shear deformation.

Near Estero Bay, the major fold extends to a depth of more than 6,000 feet. Farther south, in the central part of the San Luis Range, it is more than 11,000 feet deep. Parts of its northeast flank are disrupted by faults associated with the Edna fault zone. Local breaks along the central part of the southwest flank have been referred to as the San Miguelito fault zone.

As shown by extensive marine geophysical surveying, the stratigraphy and the west-northwest-trending structure that characterizes the onshore region from Point Sal to areas north of Point Estero extend into the adjacent offshore area as far as the north-northwest-trending structural zone that forms a boundary of the main offshore Santa Maria Basin. Owing to the irregular outline of the coast, the width of the offshore shelf east of this boundary zone ranges from 2-1/2 miles to as much as 12 miles. The shelf area is narrowest opposite the reach of coast between Point Sal and Point Buchon, and widest in Estero Bay and in areas south of San Luis Bay.

The major geologic features that underlie the near-shore shelf include, from south to north, the Casmalia Hills anticline, the broad Santa Maria Valley downwarp, the anticlinal structural high off Point San Luis, the San Luis - Pismo syncline, and the Los Osos Valley antiform. These features are defined by the outcrop pattern and structure of the lower Pliocene, Miocene, and basement-complex rocks. Upper Pliocene strata that form the upper one to two thousand feet of section in the adjacent offshore Santa Maria Basin are partly buttressed and partly faulted against the rocks that underlie the near-shore shelf, and they unconformably overlap the boundary zone and parts of the shelf in several areas.

B. General Features Of The Site

1. Physiographic Features And Associated Superficial Deposits

The power plant site lies immediately southeast of the mouth of Diablo Canyon, a major westward-draining feature of the San Luis Range, and about a mile southeast of Lion Rock, a prominent offshore element of the highly irregular coastline (Figures 21, 22). It occupies an extensive topographic terrace about 1,000 feet in average width. In its pre-grading, natural state, the gently undulating surface of this terrace sloped gradually southwestward to an abrupt termination along a cliff fronting the ocean; it rose with progressively increasing slope in a landward, or northeasterly, direction to merge with the much steeper front of a foothill ridge of the San Luis Range. The surface ranged in altitude from 65 to 80 feet along the coastline to a maximum of nearly 300 feet along the base of the hillslope to the northeast, but nowhere was its local relief greater than 10 feet. Its only major interruption was the steep-walled canyon of lower Diablo Creek, a gash about 75 feet in average depth. The ridge that flanks the terrace on the northeast has been deeply scored by Diablo Creek, but farther upstream the canyon broadens out as a large, irregular bowl-like feature.

Like many other parts of the California coast, the Diablo Canyon area is characterized by several wave-cut benches of Pleistocene age. These surfaces of irregular but generally low relief were developed across bedrock by marine erosion, and they are ancient analogues of the benches now being cut approximately at sea level along the present coast. They were formed during periods when sea level was higher, relative to the adjacent land, than it is now. Each of the ancient benches is thinly and discontinuously mantled with marine sand, gravel, and rubble similar to the beach and offshore deposits that are accumulating along the present coastline. Along its landward margin each bears thicker and more localized coarse deposits similar to the modern talus along the base of the present sea cliff.

Both the ancient wave-cut benches and their overlying marine and shoreline deposits have been buried beneath silty to gravelly detritus derived from landward sources after the benches were in effect abandoned by the ocean. This nonmarine cover is essentially an apron of coalescing fan deposits, other alluvial debris, and colluvial accumulations that are the thickest adjacent to the mouths of major canyons and along the bases of steep hillslopes.

Where they have been deeply trenched by subsequent erosion, as along Diablo Canyon, these deposits can be seen to have buried some of the benches so deeply that their individual identities are not reflected by the modern (pre-grading) rather smooth terrace topography. Thus the surface of the main terrace is defined mainly by nonmarine deposits that conceal both the older benches of marine erosion and some of the abruptly rising ground that separates them (Figures 23, 24).

The observed and inferred relationships among the terrace surfaces and the wave-cut benches buried beneath them can be summarized as follows:

Wave-Cut Bench		Terrace Surface	
Altitude (Feet)	Location	Altitude (Feet)	Location
170-175	Small remnants on sides of Diablo Canyon	Mainly 170-190	Sides of Diablo Canyon and upper parts of main terrace; in places separated from lower parts of terrace by low scarps
145-155	Very small remnants on sides of Diablo Canyon	Mainly 150-170	
120-130 65-80	Subparallel benches elongate in a northwest-southeast direction but with considerable aggregate width; wholly beneath main terrace surface	Mainly 70-160	Most of main terrace, a widespread surface on a composite section of nonmarine deposits; no well-defined scarps
30-45	Small remnants above modern sea cliff	50-100	Small remnants above modern sea cliff
Approx. 0	Small to moderately large areas along present coastline		No depositional terrace

Within the site area the wave-cut benches increase progressively in age with increasing elevation above present sea level, hence their order in the above list is one of decreasing age. By far the most extensive of these benches slopes gently seaward from a shoreline angle that lies at an elevation of approximately 100 feet above present sea level.

2. Bedrock Units

The entire site area is underlain by a complex sequence of stratified marine sedimentary rocks and tuffaceous volcanic rocks, all of Tertiary (Miocene) age. Diabasic intrusive rocks are locally exposed high on the walls of Diablo Canyon at the edge of the area. Both the sedimentary and volcanic rocks have been folded and otherwise disturbed over a considerable range of scales.

a. Obispo Formation (Obispo Tuff)

Rocks of the Obispo Formation, the oldest bedrock units exposed in the site area, crop out extensively in its coastward parts and form nearly all of the offshore prominences and shoals. They are dense to highly porous, and thinly layered to almost massive. They range in color from white to buff in fresh exposures, and from yellowish to reddish brown on weathered surfaces. Most outcrop surfaces have a characteristic "punky" to crusty appearance, but the rocks in general are tough, cohesive, and relatively resistant to erosion.

The Obispo consists mainly of fine-grained vitric tuff, with locally prominent crystal tuffs. Other observed rock types include pumiceous tuffs, pumice-pellet tuff breccias, perlitic vitreous tuffs, tuffaceous siltstones and mudstones, and fine-grained tuff breccias with fragments of glass and various sedimentary rocks. No massive flow rocks have been recognized anywhere in the exposed volcanic section. Most of the tuffaceous rocks, and especially the more vitreous ones, have been locally to pervasively altered. Products of silicification, zeolitization, and pyritization are readily recognizable in many exposures, where the rocks generally are traversed by numerous thin, irregular veinlets and layers of cherty to opaline material. Veinlets and thin, pod-like concentrations of gypsum also are widespread. Where pyrite is present, the rocks weather yellowish to brownish and are marked by gossan-like crusts.

The various contrasting rock types are simply interlayered in only a few places. Much more typical are abutting, intertonguing, and irregularly interpenetrating relationships over a wide range of scales. Septa and inclusions of shale and sandstone are abundant, and a few of them are large enough to be shown separately on the geologic map (Figure 23). Highly irregular inclusions, a few inches to several feet in maximum dimension, are so densely packed together in some places that they form breccias with volcanic matrices.

The Obispo Formation is underlain by mudstones of early Miocene (pre-Monterey) age, on which it rests with a highly irregular contact that appears to be in part intrusive. This contact lies offshore in the vicinity of the power plant site, but it is exposed along the seacoast to the southeast. In a gross way, the Obispo underlies the basal part of the Monterey Formation, but many of its contacts with these sedimentary strata are plainly intrusive. Moveover, individual sills and dikes of slightly to thoroughly altered tuffaceous rocks appear here and there in the Monterey section, not uncommonly at stratigraphic levels well above its base. The observed physical relationships, together with the local occurrence of microfossils within the principal masses of volcanic rocks, indicate that much of the Obispo Formation in this area probably was emplaced at shallow depths beneath the Miocene sea floor during accumulation of sedimentary strata. The volcanic rocks do not appear to represent a single, well-defined eruptive event, nor are they likely to have been derived from a single source conduit.

b. Monterey Formation

Stratified marine rocks variously correlated with the Monterey Formation, Point Sal Formation, and Obispo Tuff underlie most of the site area, including all of that portion intended for power plant structures. They are almost continuously exposed along the crescentic sea cliff that borders Diablo Cove, and elsewhere they appear in much more localized outcrops. For convenience they are here assigned to the Monterey Formation in order to delineate them clearly from the adjacent more tuffaceous rocks so typical of the Obispo Formation.

The observed rock types, listed in general order of decreasing abundance, are silty and tuffaceous sandstone, siliceous shale, shaly siltstone and mudstone, diatomaceous shale, sandy to highly tuffaceous shale, calcareous shale and impure limestone, bituminous shale, fine- to coarse-grained sandstone, impure vitric tuff, silicified limestone and shale, and tuff-pellet sandstone. Dark-colored and relatively fine-grained strata are most abundant in the lowest part of the section, as exposed along the east side of Diablo Cove, whereas lighter-colored sandstones and siliceous shales are dominant at stratigraphically higher levels farther north. In detail, however the different rock types are interbedded in various combinations, and intervals of uniform lithology rarely are thicker than 30 feet.

The sandstones are mainly fine to medium grained, and most are distinctly tuffaceous. Some of these rocks contain small but megascopically visible fragments of pumice, perlitic glass, and tuff, and a few beds grade along strike into submarine tuff breccia. The sandstones are thinly to very thickly layered; individual beds 6 inches to 4 feet thick are fairly common, and a few appear to be as thick as 15 feet. Some of them are hard and very resistant to erosion, and they typically form subdued but nearly continuous elongate projections on major hillslopes.

The siliceous shales are light colored platy rocks that are moderately hard to extremely hard according to their silica content, but they tend to break readily along bedding and fracture surfaces. The bituminous rocks and the siltstones and mudstones are darker colored, softer, and grossly more compact. Some of them are very thinly bedded or laminated; others appear almost massive or form matrices for irregularly ellipsoidal masses of somewhat sandier material. The tuffaceous rocks are softer, and the diatomaceous ones are soft to the degree of punkiness; both kinds of rocks are easily eroded, but are markedly cohesive and tend to retain their gross positions on even the steepest of slopes.

Stains of iron oxides are widespread on exposures of nearly all the Monterey rocks, and are especially well developed on some of the finest-grained shales that contain disseminated pyrite. All but the hardest and most thick-bedded rocks are considerably broken to depths of as much as 6 feet in the zone of weathering on slopes other than the present sea cliff, and the broken fragments have been separated and displaced by surface creep to somewhat lesser depths.

c. Diabasic Intrusive Rocks

Small, irregular bodies of diabasic rocks are poorly exposed high on the walls of Diablo Canyon at and beyond the northeasterly edge of the site area. Contact relationships are readily determined at only a few places where these rocks evidently are intrusive into the Monterey

Formation. They consist chiefly of calcic plagioclase and augite, with some olivine, opaque minerals, and zeolitic alteration products, and in most places they are considerably weathered.

3. Quaternary Deposits

Coastal Terrace Deposits

The coastal wave-cut benches of Pleistocene age, as described earlier, are almost continuously blanketed by terrace deposits of several contrasting types and modes of origin. The oldest of these deposits are relatively thin and patchy in their occurrence, and were laid down along and adjacent to ancient beaches during Pleistocene time. They are covered by considerably thicker and more extensive nonmarine accumulations of detrital materials derived from various landward sources.

The marine deposits consist of silt, sand, gravel, and cobbly to bouldery rubble. They are approximately 2 feet in average thickness over the entire terrace area and reach a maximum observed thickness of about 8 feet. They rest directly upon bedrock, some of which is marked by numerous holes attributable to the action of boring marine mollusks, and they commonly contain large rounded cobbles and boulders of Monterey and Obispo rocks that have been similarly bored. Lenses and pockets of highly fossiliferous sand and gravel are present locally. All the marine sediments are poorly to very well sorted and loose to moderately well consolidated. They have been naturally compacted, and the degree of compaction is consistently greater than that observed in any of the associated surficial deposits of other types.

Near the inner margins of individual wave-cut benches the marine deposits merge landward into coarser and less well-sorted debris that evidently accumulated along the bases of ancient sea cliffs or other shoreline slopes. This debris is locally as much as 12 feet thick; it forms broad but very short aprons, now buried beneath younger deposits, that are ancient analogues of the talus accumulations along the inner margin of the present beach in Diablo Cove. One of these aprons is well exposed high on the northerly wall of Diablo Canyon.

A younger, thicker, and much more continuous nonmarine cover is present over most of the coastal terrace area. It consistently overlies the marine deposits noted above, and where these are absent it rests directly upon bedrock. It is composed in part of alluvial detritus contributed during Pleistocene time from Diablo Canyon and several smaller drainage courses, and it thickens markedly as traced sourceward toward these canyons. The detritus is chiefly fine- to moderately coarse-grained gravel and rubble characterized by tabular fragments of Monterey rocks in a rather abundant silty to clayey matrix. Most of it is thinly and regularly stratified, but the distinctness of this layering varies greatly from place to place.

Slump, creep, and slope-wash deposits, derived from adjacent hillsides by relatively slow downhill movement over long periods of time, also form major parts of the nonmarine terrace cover. All are loose and uncompacted. They comprise fragments of Monterey rocks in dark-colored clayey matrices, and their internal structure is essentially chaotic. In some places they are crudely interlayered with the alluvial-fan deposits, and elsewhere they overlie these bedded sediments. On parts of the main terrace area not reached by any of the alluvial fans, a cover of slump, creep, and slope-wash deposits, a few inches to nearly 10 feet thick, rests directly upon either marine terrace deposits or bedrock.

b. Stream-Terrace Deposits

Several narrow, irregular benches along the walls of Diablo Canyon are veneered by a few inches to 6 feet of silty gravels that are somewhat coarser but otherwise similar to the alluvial-fan deposits already described. These stream-terrace deposits originally occupied the bottom of the canyon at a time when the lower course of Diablo Creek had been cut downward through the sedimentary cover of the main terrace and well into the underlying bedrock. Subsequent deepening of the canyon has left remnants of the deposits as cappings on scattered small terraces.

c. Landslide Deposits

The walls of Diablo Canyon also are marked by tongue- and bench-like accumulations of loose, rubbly landslide debris that consists mainly of highly broken and jumbled masses of Monterey rocks with abundant silty and soily matrix materials. These landslide bodies represent localized failure on naturally oversteepened slopes, generally confined to fractured bedrock in and immediately beneath the zone of weathering. Individual bodies within the site area are small, with probable maximum thickness no greater than 20 feet. All of them lie outside the area of power plant construction.

Landslide deposits along the sea cliff are associated with small scale failure that represents slippage along bedding and fracture surfaces in siliceous Monterey rocks. Several episodes of sliding are attested by thin, elongate masses of highly broken ground separated from one another by well defined zones of dislocation. Some of these masses are still capped by terrace deposits. The composite accumulations of debris are not more than 35 feet in maximum thickness, and the ground failure does not appear to have resulted in major recession of the cliff. Landsliding along the sea cliff evidently has not been a major process within the site area.

Large landslides, some of them involving substantial thicknesses of bedrock, are present on both sides of Diablo

Canyon not far northeast of the power plant area. These occurrences need not be considered in connection with the plant site, but they have been regarded as significant factors in establishing a satisfactory grading design for the switchyard and other up-canyon installations.

d. Slump, Creep, and Slope-Wash Deposits

As noted earlier, slump, creep, and slope-wash deposits form parts of the nonmarine sedimentary blanket on the main coastal terrace. They also have been considerably concentrated along well defined swales on major slopes, where they are readily distinguished from other surficial deposits.

Angular fragments of Monterey rocks are sparsely to very abundantly scattered through the colluvial deposits, whose most characteristic feature is a fine grained matrix that is dark colored, moderately rich in clay minerals, and extremely soft when wet. Internal layering is rarely observable and nowhere is sharply expressed. The debris seems to have been rather thoroughly intermixed during its slow migration down hillslopes in response to gravity. That it was derived mainly from broken materials in the zone of weathering is showwn by several exposures in which it grades downward through soily debris into highly disturbed and partly weathered bedrock, and thence into progressively fresher and less broken bedrock.

e. Talus And Beach Deposits

Much of the present coastline in the vicinity of the site is marked by bare rock, but Diablo Cove and a few other large indentations are fringed by narrow, discontinuous beaches and irregular concentrations of seacliff talus. The total volume of these coarse grained deposits is small, and they are of interest mainly as modern analogues of Pleistocene deposits at higher levels beneath the main terrace surface.

The beach deposits consists chiefly of well rounded cobbles. They form thin veneers over bedrock, and in Diablo Cove they grade seaward into patches of coarse pebbly sand. The floors of both Diablo Cove and South Cove probably are irregular in detail and are featured by rather hard, fresh bedrock that is discontinuously overlain by irregular thin bodies of sand and gravel. The presumed remnant of the gash cut in the cove area by Diablo Creek during Wisconsin time probably is filled with sand and gravel.

4. Geologic Structure

The rocks underlying the Diablo Canyon site have been subjected to intrusive volcanic activity and to later compressional deformation that has given rise to folding, jointing and fracturing, minor faulting, and local brecciation. The site is situated in a section of moderately to steeply north-dipping strata, about 300 feet south of an east-west trending synclinal fold axis (Figure 23). The rocks are jointed throughout, and they contain local zones of closely spaced high-angle fractures (Figure 27). In addition to these features, cross-cutting bodies of tuff and tuff breccia, and cemented "crackle breccia" could be considered as tectonic structures.

Exact ages of the various tectonic structures at the site are not known. It has been clearly demonstrated, however, that all of them are truncated by and therefore antedate the principal marine erosion surface that underlies the coastal terrace bench. This terrace can be correlated with coastal terraces to the north and south that have been dated as 80,000 to 120,000 years old. The tectonic structures probably are related to the Pliocene-lower Pleistocene episode of Coast Ranges deformation, which occurred more than a million years ago.

a. Folds

The bedrock units within the entire site area form part of the southerly flank of a very large syncline that is a major feature of the San Luis Range. The northerly dipping sequence of strata is marked by several smaller folds with subparallel trends and flank-to-flank dimensions measured in hundreds of feet. One of these, a syncline with gentle to moderate westerly plunge, is the largest flexure recognized in the vicinity of the site. Its axis lies a short distance north of the site and about 450 feet northeast of the mouth of Diablo Canyon (Figures 23, 24). East of the canyon, this fold appears to be rather open and simple in form, but farther west, it probably is complicated by several large wrinkles and may well lose its identity as a single feature. Some of this complexity is clearly revealed along the northerly margin of Diablo Cove, where the beds exposed in the sea cliff have been closely folded along east to northeast trends. Here a tight syncline (Figure 23) and several smaller folds can be recognized, and steep to near-vertical dips are dominant in several parts of the section.

The southerly flank of the main syncline within the site area steepens markedly as traced southward away from the fold axis. Most of this steepening is concentrated within an across-strike distance of about 300 feet as revealed by the strata exposed in the sea cliff southeastward from the mouth of Diablo Canyon; farther southward the beds of sandstone and finer grained rocks dip rather uniformly at angles of 70 degrees or more. A slight overturning through the vertical characterizes the several hundred feet of section exposed immediately north of the Obispo rocks that underlie South Point and the north shore of South Cove (Figure 23). Thus the main syncline, though simple in gross form, is distinctly asymmetric. The steepness of its southerly flank may well have resulted from buttressing, during the folding, by the relatively massive and competent unit of tuffaceous rocks that adjoins the Monterey strata at this general level of exposure.

Smaller folds, corrugations, and highly irregular convolutions are widespread among the Monterey rocks, especially the finest grained and most shaly types. Some of these flexures trend east to southeast and appear to be drag features systematically related to the larger scale folding in the area. Most, however, reflect no consistent form or trend, range in scale from inches to only a few feet, and evidently are confined to relatively soft rocks that are flanked by sections of harder and more massive strata. They constitute crudely tabular zones of contortion within which individual rock layers can be traced for short distances but rarely are continuous throughout the deformed ground. Some of this contortion appears to have derived from slumping and sliding of unconsolidated sediments on the Miocene sea floor during acculation of the Monterey section. Most of it, in contrast, plainly occurred at much later times, presumably after conversion of the sediments to sedimentary rocks, and it can be most readily attributed to highly localized deformation during the ancient folding of a section that comprises rocks with contrasting degrees of structural competence.

b. Faults

Numerous faults with total displacements ranging from a few inches to several feet cut the exposed Monterey rocks. Most of these occur within, or along the margins of, the zones of contortion noted above. They are sharp, tight breaks with highly diverse attitudes, and they typically are marked by 1/16 inch or less of gouge or microbreccia. Nearly all of them are curving or otherwise somewhat irregular surfaces, and many can be seen to terminate abruptly or to die out gradually within masses of tightly folded rocks. These small faults appear to have been developed as end products of localized intense deformation caused by folding of the bedrock section. Their unsystematic attitudes, small displacements, and limited effects upon the host rocks identify them as secondary features, i.e., as results rather than causes of the localized folding and convolution with which they are associated.

Three distinctly larger and more continuous faults also were recognized within the mapped area. They are well exposed on the sea cliff that fringes Diablo Cove (see Figure 23), and each lies within a zone of moderately to severely contorted, fine grained Monterey strata. Each is actually a zone, 6 inches to several feet wide, within which two or more subparallel tight breaks are marked by slickensides, 1/4 inch or less of gouge, and local stringers of gypsum. None of these breaks appears to be systematically related to individual folds within the adjoining rocks. None of them extends upward into the overlying blanket of Quaternary terrace deposits.

One of these faults, exposed on the north side of the cove, trends north-northwest essentially parallel to the flanking Monterey beds, but it dips more steeply than these beds. Another, exposed on the east side of the cove, trends east-southeast and is essentially vertical; thus, it is essentially parallel to the structure of the host Monterey section. Neither of these faults projects toward the ground involved in power plant construction. The third fault, which appears on the sea cliff at the mouth of Diablo Canyon, trends northeast and projects toward ground in the northernmost part of the power plant site. It dips northward somewhat more steeply than the adjacent strata.

Total displacement is not known for any of these three faults on the basis of natural exposures, but it could amount to as much as tens of feet. That these breaks are not major features, however, is strongly suggested by their sharpness, by the thinness of gouge along individual surfaces of slippage, and by the essential lack of correlation between the highly irregular geometry of deformation in the enclosing strata and any directions of movement along the slip surfaces.

The possibility that these surfaces are late-stage expressions of much larger scale faulting at this general locality was tested by careful examination of the deformed rocks that they transect. On megascopic scales the rocks appear to have been deformed much more by flexing than by rupture and slippage, as evidenced by local continuity of numerous thin beds that denies the existence of pervasive faulting within much of the ground in question. That the finer grained rocks are not themselves fault gouge was confirmed by examination of numerous samples under the microscope.

Sedimentary layering, recognized in 27 of 34 samples that were studied, was observed to be grossly continuous even though dislocated here and there by tiny fractures. Moreover, nearly all the samples were found to contain shards of volcanic glass and/or the tests of foraminifera; some of these delicate components showed effects of microfracturing and a few had been offset a millimeter or less along tiny shear surfaces, but none appeared to have been smeared out or partially obliterated by intense shearing or grinding. Thus the three larger faults in the area evidently were superimposed upon ground that already had been deformed primarily by small scale and locally very intense folding rather than by pervasive grinding and milling.

It is not known whether these faults were late-stage results of major folding in the region or were products of independent tectonic activity. In either case, they are relatively ancient features, as they are capped without break by the Quaternary terrace deposits exposed along the upper part of the sea cliff. They probably are not large scale elements of regional structure, as examination of the nearest areas of exposed bedrock along their respective landward projections revealed no evidence of substantial offsets among recognizable stratigraphic units. Seaward projection of one or more of these faults might be taken to explain a possible large offset of the Obispo Formation as this unit is exposed on North Point and South Point. The notion of such an offset, however, would rest upon the assumption that the two outcropping masses are displaced parts of an originally continuous body, for which there is no real evidence. Indeed, the two tuff masses are bounded on their northerly sides by lithologically different parts of the Monterey Formation, hence clearly were originally emplaced at different stratigraphic levels and are not directly correlative.

c. Masses Of Brecciated Rocks

Highly irregular masses of coarsely brecciated rocks, a few feet to many tens of feet in maximum dimension, are present in some of the relatively siliceous parts of the Monterey section that adjoin the principal bodies of Obispo rocks. The fracturing and dislocation is not genetically related to any recognizable faults, but instead seems to have been associated with emplacement of the volcanic rocks; it evidently was accompanied or soon followed by extensive silicification. Many adjacent fragments in the breccias are closely juxtaposed and have matching opposed surfaces, so that they plainly represent no more than coarse crackling of the brittle rocks. Other fragments, though angular or subangular, are not readily matched with adjacent fragments and hence may represent significant translation within the entire rock masses.

The ratio of matrix materials to coarse fragments is very low in most of the breccias, and nowhere was observed to exceed about 1:3. The matrices generally comprise smaller angular fragments of the same Monterey rocks that are elsewhere dominant in the breccias, and they characteristically are set in a siliceous cement. Tuffaceous matrices, with or without Monterey fragments, also are widespread and commonly show the effects of pervasive silification. All the exposed breccias are firmly cemented, and they rank among the hardest and most resistant units in the entire bedrock section.

A few 3 to 18 inch beds of sandstone have been pulled apart to form separate tabular masses along specific stratigraphic horizons in higher parts of the Monterey sequence. Such individual tablets, which are boudins rather than ordinary breccia fragments, are especially well exposed in the sea cliff at the northern corner of Diablo Cove. They are flanked by much finer grained strata that converge around their ends and continue essentially unbroken beyond them. This boudinage, or separation and stringing out of sandstone beds that lie within intervals of much softer and more shaly rocks, has resulted from compression during folding of the Monterey section. Its distribution is stratigraphically controlled and is not systematically related to recognizable faults in the area.

c. Mapping And Exploration Of The Site

The geologic relationships at the Diablo Canyon Units 1 and 2 power plant site have been studied in terms of both local and regional stratigraphy and structure, with an emphasis on relationships that could aid in dating the youngest tectonic activity in the area. Geologic conditions that could affect the design, construction, and performance of various components of the plant installation also were identified and evaluated. The investigations were carried out in three main phases, which spanned the time between initial site selection and completion of foundation construction.

Feasibility Investigations. Work directed toward determining the pertinent general geologic conditions at the plant site comprised detailed mapping of available exposures, limited hand trenching in areas with critical relationships, and petrographic study of the principal rock types. The results of this feasibility program were presented in a report that also included recommendations for determining suitability of the site in terms of geologic conditions. Information from this early phase of studies is included in the preceding four sections and is illustrated by Figures 23 and 24.

Suitability Investigations. The second phase of investigations was directed toward testing and confirming the favorable judgments concerning site feasibility. Inasmuch as the principal remaining uncertainties involved structural features in the local bedrock, additional effort was made to expose and map these features and their relationships. This was accomplished through excavation of large trenches on a grid pattern that extended throughout the plant area (shown on Figure 25), followed by photographing the trench walls and logging the exposed geologic features. Large scale photographs were used as a mapping base, and the recorded data were then transferred to controlled vertical sections at a scale of 1 inch = 20 feet.

During these suitability investigations, special attention was given to the contact between bedrock and overlying terrace deposits in the plant site area. It was determined that none of the discontinuities present in the bedrock section displaces either the erosional surface developed across the bedrock or the terrace deposits that rest upon this surface. An example of the recording of the pertinent data is illustrated by Figure 26.

<u>Construction Geology Investigation</u>. Geologic work done during the course of construction at the plant site spanned an interval of five years, which encompassed the period of large scale excavation. It included detailed mapping of all significant excavations, as well as special studies in some areas of rock bolting and other work involving rock reinforcement and temporary instrumentation. The mapping covered essentially all parts of the area to be

occupied by structures for Units 1 and 2, including the excavations for the circulating water intake and outlet, the Turbine Generator Building, the Auxiliary Building, and the Containment Structures. The results of this mapping are described farther on and are illustrated by Figure 27.

Exploratory Trenching Program. Four exploratory trenches were cut beneath the main terrace surface at the Unit 1 power plant site, as shown on Figure 23. Trench A, about 1,080 feet long, extended in a north-northwesterly direction and thus was roughly parallel to the nearby margin of Diablo Cove. Trench B, 380 feet long, was parallel to Trench A and lay about 150 feet east of the northerly one-third of the longer trench. Trenches C and D, respectively 450 and 490 feet long, were nearly parallel to each other, 130 to 150 feet apart, and lay essentially normal to Trenches A and B. The two pairs of trenches crossed each other to form a # pattern that would have been symmetrical were it not for the long southerly extension of Trench A. They covered the area intended for Unit 1 power plant construction, and the intersection of Trenches B and C coincided in position with the center of the Unit 1 nuclear reactor structure.

Eight additional trenches were cut beneath the main terrace surface south of Diablo Canyon in order to extend the scope of subsurface exploration to include all ground in the Unit 2 plant site. As in the area of the

Unit 1 plant site, the trenches formed two groups; those in each group were parallel with one another and were oriented nearly normal to those of the other group. The excavations pertinent to the Unit 2 plant site can be briefly identified as follows:

1. North-Northwest Alinement:

a. Trench EJ, 240 feet long, was a southerly extension of older Trench BE (originally designated as Trench B).

b. Trench WU, 1,300 feet long, extended southward from Trench DG (originally designated as Trench D), and its northerly part lay about 65 feet east of Trench EJ. The northernmost 485 feet of this trench was mapped in connection with the Unit 2 trenching program.

c. Trench MV, 700 feet long, lay about 190 feet east of Trench WU. The northernmost 250 feet of this trench was mapped in connection with the Unit 2 trenching program.

d. Trench AF (originally designated as Trench A) was mapped earlier in connection with the detailed study of the Unit 1 plant site. A section for this trench, which lay about 140 feet west of Trench EJ, was included with others in the report on the Unit 1 trenching program.

2. East Northeast Alinement:

a. Trench KL, about 750 feet long, lay 180 feet south of Trench DG (originally designated as Trench D) and crossed Trenches AF, EJ, and WU.

b. Trench NO, about 730 feet long, lay 250 feet south of Trench KL and crossed Trenches AF, WU, and MV.

These trenches, or parts thereof, covered the area intended for the Unit 2 power plant construction, and the intersection of Trenches WU and KL coincided in position with the center of the Unit 2 nuclear reactor structure.

All of the trenches, throughout their aggregate length of about 4000 feet, revealed a section of surficial deposits and underlying Monterey bedrock that corresponded to the "two-ply" sequence of surficial deposits and Monterey strata exposed along the sea cliff in nearby Diablo Cove. The trenches ranged in depth from 10 feet (or less along their approach ramps) to nearly 40 feet, and all had sloping sides that gave way downward to essentially vertical walls in the bedrock encountered 3 to 22 feet above their wide floors. To facilitate detailed geologic mapping, the wall along one side of each trench was trimmed to a near-vertical slope extending upward from the trench floor to a level well above the top of bedrock. These walls subsequently were scaled back by means of hand tools in order to provide fresh, clean exposures prior to mapping of the contact between bedrock and overlying unconsolidated materials.

The geologic sections shown in Figure 26 correspond in position to the vertical portions of the mapped trench walls in the Unit 1 area. Relationships exposed at higher levels on sloping portions of the trench walls have been projected to the vertical planes of the sections. Center lines of intersecting trenches are shown for convenience, but the planes of the geologic sections do not contain the center lines of the respective trenches.

Interface Between Bedrock And Surficial Deposits. As exposed continuously in the exploratory trenches, the contact between bedrock and overlying terrace deposits represents two wave-cut platforms and intervening slopes, all of Pleistocene age. The broadest surface of ancient marine erosion ranges in altitude from 80 to 105 feet, and its shoreward margin, at the base of an ancient sea cliff, lies uniformly within 5 feet of the 100-foot contour. A higher, older, and less extensive marine platform ranges in altitude from 130 to 145 feet, and most of it lies within the ranges of 135 to 140 feet. As noted previously, these are two of several wave-cut benches in this coastal area, each of which terminates eastward against a cliff or steep shoreline slope and westward at the upper rim of a similar but younger slope.

Available exposures indicate that the configurations of the erosional platforms are markedly similar, over a wide range of scales, to that of the platform now being cut approximately at sea level along the present coast. Grossly viewed, they slope very gently in a seaward (westerly) direction and are marked by broad, shallow channels and by upward projections that must have appeared as low spines and "reefs" when the benches were being formed. The most prominent "reefs," which rise a few inches to about five feet above neighboring parts of the bench surfaces, are composed of hard, thick-bedded sandstone that was relatively resistant to the ancient wave erosion.

As shown in the geologic sections (Figure 26), the surfaces of the platforms are nearly planar in some places but elsewhere are highly irregular in detail. The small scale irregularities, generally three feet or less in vertical extent, include knob-, spine-, and rib-like projections and various wave-scoured pits, notches, crevices, and channels. Most of the upward projections closely correspond to relatively hard, resistant beds or parts of beds in the sandstone section. The depressions consistently mark the positions of relatively soft silty or shaly sandstone, of very soft tuffaceous rocks, or of extensively jointed rocks. The surface traces of most faults and some of the most prominent joints are in sharp depressions, some of them with overhanging walls. All these irregularities of detail have modern analogues that can be recognized on the bedrock bench now being cut along the margins of Diablo Cove.

The interface between bedrock and overlying surficial deposits provides information concerning the age of youngest fault movements within the bedrock section. This interface is nowhere offset by faults that were exposed in the trenches, but instead has been developed irregularly across the faults after their latest movements. The consistency of this general relationship was established by highly detailed tracing and inspection of the contact as freshly exhumed by scaling of the trench walls. Gaps in exposure of the interface necessarily were developed at the intersections of trenches. At such localities, the bedrock was carefully laid bare so that all joints and faults could be recognized and traced along the trench floors to points where their relationships with the exposed interface could be determined.

Corroborative evidence concerning age of the most recent fault displacements stems from the marine deposits that overlie the bedrock bench and form a basal part of the terrace section. That those deposits rest without break across the traces of faults in the underlying bedrock was shown by the continuity of individual sedimentary beds and lenses that could be clearly recognized and traced. As in other parts of the site area, some of the faults are directly capped by individual boulders, cobbles, pebbles, shells, and fossil bones, none of which have been affected by fault movements. Thus the most recent fault displacements in the plant site area occurred prior to marine planation of the bedrock and deposition of the overlying terrace sediments.

The age of the most recent faulting in this area is therefore at least 80,000 years. More probably it is at least 120,000 years, the age most generally assigned to these terrace deposits along other parts of the California coastline. Evidence from the higher bench in the plant site area indicates a much older age, as the unfaulted marine deposits there are considerably older than those that occupy the lower bench corresponding to the 100-foot terrace. Moreover, it can be noted that ages thus determined for most recent fault displacements are minimal rather than absolute, as the latest faulting actually could have occurred millions of years ago.

During the Unit 2 exploratory trenching program, special attention was directed to those exposed parts of the wave-cut benches where no marine deposits are present, and hence where there are no overlying reference materials nearly as old as the benches themselves. At such places the bedrock beneath each bench has been weathered to depths ranging from less than an inch to at least ten feet, a feature that evidently corresponds to a lengthy period of surface exposure from the time when the bench was abandoned by the sea to the time when it was covered beneath encroaching nonmarine deposits derived from hillslopes to the east. Stratification and other structural features are clearly recognizable in the weathered bedrock, and they obviously have exercised some degree of control over localization of the weathering. Moreover, in places where upward projections of bedrock have been gradually bent or rotationally "draped" in response to weathering and creep, their contained fractures and surfaces of movement have been correspondingly bent. Nowhere in such a section that has been disturbed by weathering have the materials been cut by younger fractures that would represent straight upward projections of breaks in the underlying fresh rocks. Nor have such fractures been observed in any of the overlying nonmarine terrace cover.

Thus the minimum age of any fault movement in the plant site area is based upon compatible evidence from undisputed reference features of four kinds: (1) Pleistocene wave-cut benches developed on bedrock, (2) immediately overlying marine deposits that are very slightly younger, (3) zones of weathering that represent a considerable span of subsequent time, and (4) younger terrace deposits of nonmarine origin.

Bedrock Geology Of The Plan Foundation Excavations

Bedrock was continuously exposed in the foundation excavations for major structural components of Units 1 and 2. Outlines and invert elevations of these large openings, which ranged in depth from about 5 feet to nearly 90 feet below the original ground surface, are shown on Figure 27. The complex pattern of straight and curved walls with various positions and orientations provided an excellent three-dimensional representation of bedrock structure. These walls were photographed at large scales as construction progressed, and the photographs were used directly as a geologic mapping base. The largest excavations also were mapped in detail on a surveyed planimetric base.

Geologic mapping of the plant excavations confirmed the conclusions based on earlier investigations at the site. The exposed section of Monterey strata was found to correspond in lithology and structure to what had been predicted from exposures at the mouth of Diablo Canyon, along the sea cliff in nearby Diablo Cove, and in the test trenches. Thus the plant foundation is underlain by a moderately to steeply north-dipping sequence of thin- to thick-bedded sandy mudstone and fine-grained sandstone. The rocks at these levels are generally fresh and competent, as they lie below the zone of intense near-surface weathering. The appearance of the thick bedded sandstone that was exposed in the excavation for the Unit 2 containment is shown in Figure 21.

Several thin interbeds of claystone were exposed in the southwestern part of the plant site in the excavations for the Unit 2 Turbine Generator Building, intake conduits, and outlet structure. These beds, which generally are less than 6 inches thick, are distinctly softer than the flanking sandstone. Some of them show evidence of internal shearing.

Layers of tuffaceous sandstone and sills, dikes, and irregular masses of tuff and tuff breccia are present in most parts of the foundation area. They tend to increase in abundance and thickness toward the south, where they are relatively near the large masses of Obispo Tuff exposed along the coast south of the plant site. Some of the tuff bodies are comfortable with the enclosing sandstone, but others are markedly discordant. Most are clearly intrusive. Individual masses, as exposed in the excavations, range in thickness from less than an inch to about 40 feet. The tuff breccia, which is less abundant than the tuff, consists typically of small fragments of older tuff, pumice, or Monterey rocks in a matrix of fresh to highly altered volcanic glass. At the levels of exposure in the excavations, both the tuff and tuff breccia are somewhat softer than the enclosing sandstone.

The stratification of the Monterey rocks dips generally northward throughout the plant foundation area. Steepness of dips increases progressively and in places sharply from north to south, ranging from 10-15 degrees on the north side of Unit 1 to 75-80 degrees in the area of Unit 2. A local reversal in direction of dip reflects a small open fold or warp in the Unit 1 area. The axis of this fold is parallel to the overall strike of the bedding, and strata on the north limb dip southward at angles of 10 to 15 degrees. The more general steepening of dips from north to south may reflect buttressing by the large masses of Obispo Tuff south of the plant site.

The bedrock of the plant area is traversed throughout by fractures, including various planar, broadly curving, and irregular breaks. A dominant set of steeply dipping to vertical joints trends northerly, nearly normal to the strike of bedding. Other joints are diversely oriented with strikes in various directions and dips ranging from 10 degrees to vertical. Many fractures curve abruptly, terminate against other breaks, or die out within single beds or groups of beds.

Most of the joints are widely spaced, ranging from about a foot to 10 feet apart, but within several northerly trending zones, ranging in width from 10 to 20 feet, closely spaced near-vertical fractures give the rocks a blocky or platy appearance. The fracture and joint surfaces are predominantly clean and tight, although some irregular ones are thinly coated with clay or gypsum. Others could be traced into thin zones of breccia with calcite cement.

Several small faults were mapped in the foundation excavations for Unit 1 and the outlet structure. A detailed discussion of these breaks and their relationship to faults that were mapped earlier along the sea cliff and in the exploratory trenches is included in the following section.

<u>Relationships Of Faults And Shear Surfaces</u>

Several subparallel breaks are recognizable on the sea cliff immediately south of Diablo Canyon, where they transect moderately thick-bedded sandstone of the kind that was exposed in the exploratory trenches to the east. These breaks are nearly concordant with the bedrock stratification, but in general they dip more steeply and trend more northerly than the stratification. Their trend differs significantly from much of their mapped trace, as the trace of each inclined surface is markedly affected by the local steep topography. The indicated trend, which projects eastward toward ground north of the Unit 1 reactor site, has been summed from numerous individual measurements of strike on the sea cliff exposures, and it also corresponds to the trace of the main break as observed in nearly horizontal outcrop within the tidal zone west of the cliff.

The structure section shows all recognizable surfaces of faulting and shearing in the sea cliff that are continuous for distances of ten feet or more. Taken together, they represent a zone of dislocation along which rocks on the north have moved upward with respect to those on the south as indicated by the attitude and roughness sense of slickensides. The total amount of movement cannot be determined by any direct means, but it probably is not more than a few tens of feet and could well be less than ten feet. This suggested by the following observed features:

As indicated earlier, bedrock was continuously exposed along several exploratory trenches. This bedrock is traversed by numerous fractures, most of which represent no more than rupture and very small amounts of simple separation. The others additionally represent displacement of the bedrock.

That the surfaces of movement along these faults constitute no more than minor elements of the bedrock structure was verified by detailed mapping of the large excavations for the plant structures. Detailed examination of the excavation walls indicated that the faults exposed in the sea cliff south of Diablo Canyon continue through the rock under the Unit 1 Turbine Generator Building, where they are expressed as three subparallel breaks with easterly trend and moderately steep northerly dips. Stratigraphic separation along these breaks ranges from a few inches to nearly 5 feet, and in general decrease eastward on each of them. They evidently die out in the ground immediately west of the containment excavation, and their eastward projections are represented by several joints along which no offsets have occurred. Such joints, with eastward trend and northward dip, alos are abundant in some of the ground adjacent to the faults on the south (Figure 27).

The easterly reach of the Diablo Canyon sea cliff faults apparently corresponds to the two most northerly of the north-dipping faults mapped in Trench A (Figure 23 and 26). Dying out of these breaks, as established from subsequent large excavations in the ground east of where Trench A was located, explains and verfies the absence of faults in the exposed rocks of Trenches B and C. Other minor faults and shear surfaces mapped in the trench exposures could not be identified in the more extensive exposures of fresher rocks in the Unit 1 containment and turbine generator building excavations. The few other minor faults that were mapped in these large excavations evidently are not sufficiently continuous to have been present in the exploratory trenches.

1. All individual breaks are sharp and narrow, and the strata between them are essentially undeformed except for their gross inclination.

2. Some breaks plainly die out as traced upward along the cliff surface, and others merge with adjoining breaks. At least one well-defined break butts downward against a cross-break, which in turn butts upward against a break that branches and dies out approximately 20 feet away (see structure section for details).

3. Nearly all the breaks curve moderately to abruptly in the general direction of movement along them.

4. Most of the breaks are little more than knife-edge features along which rock is in direct contact with rock, and others are marked by thin films of gouge. Maximum thickness of gouge anywhere observed is about half an inch, and such exceptional occurrences are confined to short curving segments of the main break at the southerly margin of the zone.

5. No fault breccia is present; instead, the zone represents transection of otherwise undeformed rocks by sharply-defined breaks. No bedrock unit is cut off and juxtaposed against a unit of different lithology along any of the breaks.

6. Local prominence of the exposed breaks, and especially the main one, is due to slickensides, surface coatings of gypsum, and iron-oxide stains rather than to any features reflecting large-scale movements.

This zone of faulting cannot be regarded as a major tectonic element, nor is it the kind of feature normally associated with the generation of earthquakes. It appears instead to reflect second-order rupturing related to a marked change in dip of strata to the south, and its general sense of movement is what one would expect if the breaks were developed during folding of the Monterey section against what amounts to a broad buttress of Obispo Tuff farther south (see geologic map, Figure 23). That the fault and shear movements were ancient is positively indicated by upward truncation of the zone at the bench of marine erosion along the base of the overlying terrace deposits.

III

THE HOSGRI FAULT

A. Overview

The Hosgri fault zone is present in the area offshore from the coast of south-central California, where it extends for a distance of about 145 km (90 miles) between end points near Purisima Point on the south and near Cape San Martin on the north (Figure 29). The fault zone is part of a larger zone of flexurng and faulting, referred to here as the Coastal Boundary zone, that is a boundary feature between the uplift of the Southern Coast Ranges and the structural depression of the adjacent offshore Santa Maria and Sur Basins.

The Hosgri fault is a basin boundary structure that has a complex history of generally east-up displacements with a large component of dip-slip. Several lines of geologic and seismologic evidence also suggest that significant amounts of lateral movement have occurred along it. The most recent movements along both the Hosgri fault and other faults of the Coastal Boundary zone have been characterized by oblique-slip displacements with dominantly dip-slip components.

The Hosgri fault is nowhere exposed on land, as are some other major elements of the Coastal Boundary zone such as the San Simeon fault and the Serra Hill fault which are exposed locally in uplifted areas near Point Piedras Blancas and Point Sur. The Hosgri fault underlies the sea floor at water depths ranging from 150 feet to 500 feet. The part of the sea floor above about 400 feet depth was exposed subaerially during the late Pleistocene Wisconsinan glacial maximum, but it has been submerged during the gradual rise of sea level to its present elevation during the past 17,000 years or so. Since erosion is minimal below the depth of active wave disturbance, the sea floor provides a generally good morphologic record of the cumulative total of any surface faulting episodes that have occurred during this time span. Along the trace of the Hosgri, several topographic features are associated with different fault strands at scattered localities, and these could represent local surface breaks during the 17,000-year time span. The generally featureless character of the sea floor along the Hosgri fault trace, however, precludes the possibility of either large-scale or recurrent surface offsets along it during the last 10,000 to 17,000 years. In the event that such offsets had occurred during this time span, detectible rift and scarp topography, similar to that along the San Andreas fault, should be present along long reaches of the submerged Hosgri trace.

The feature now referred to as the Hosgri fault evidently was first mapped by geologists and geophysicists of the Shell Oil Company during the course of a program of exploration along the offshore margin of central and northern California for hydrocarbon potential. This work was done in the mid-1960's, and a paper that includes maps showing the faults, other structural features, and locations of offshore borings was published by Ernest G. Hoskins and John R. Griffiths of the Shell Company in 1971 (Figure 30). The zone of structural disturbance that includes the Hosgri fault also was noted in 1970 by the U.S. Geological Survey during the course of offshore geophysical profiling related to the Survey's review of the construction license application for Diablo Canyon Unit 2. This zone was not then considered to represent a potential for a level of seismic activity beyond that for which the plant was designed.

In 1973, the USGS carried out a much more detailed and extensive geophysical survey of the offshore region between Point Sal and Cape San Martin. This, together with a reevaluation of seismicity data for the corresponding region, led the Survey to a view that the fault, now named the Hosgri after its discoverers, probably is seismically capable. The USGS further concluded that the 7.3 magnitude Lompoc or Pt. Arguello earthquake of 1927 could have originated along the southerly part of the Hosgri fault. This conclusion apparently was a principal factor in the Survey's postulation of a 7.5 magnitude earthquake on the Hosgri fault as the design earthquake for the Diablo Canyon site.

In 1975, Clarence A. Hall published an hypothesis that there has been 80 km or more of right slip on a combined San Simeon - Hosgri fault system during the past 5 to 13 million years. This hypothesis of major slip was based upon the proposed correlation of an assemblage of rocks exposed near Point Sal with an assemblage exposed near San Simeon. Hall apparently made no independent study of the actual geometry of the Hosgri and San Simeon faults, and his map, derived from the then current USGS map, does not show these faults to be joined. Neither does it show the Hosgri fault to extend south of Point Sal in a way that would permit accommodation of the postulated amount of slip.

In 1977, Steven Graham and William R. Dickinson published an hypothesis based on a series of correlations inferred by them and by Clarence Hall and Eli Silver. They suggested that about 115 km of right slip has occurred along a series of breaks extending from the San Andreas north of San Francisco through the San Gregorio fault to the Hosgri. This hypothesis assumed the existence of through-going links between the known faults, thereby providing a continuous fault of at least 400 km in length. In contrast, studies at various points along this series of faults by D.H. Hamilton and C.R. Willingham indicate that the total amount of right slip along any of these faults in the area extending southward from the Santa Cruz Mountains cannot have exceeded a maximum value of approximately 20 km. Moreover, they found that the Hosgri and San Simeon faults are not connected by a through-going link, an interpretation consonant with the map prepared earlier by Hoskins and Griffiths.

Other work, including seismologic studies by Stewart W. Smith and detailed high resolution geophysical surveys of the ocean floor in the epicentral area of the 1927 earthquake, has led to a conclusion that the earthquake did not occur on the Hosgri fault, but instead probably originated on a currently active fault associated with a large anticline located offshore from Purisima Point, southwest of the Hosgri fault. The Hosgri fault itself terminates in this area, where its trace is overlain by apparently undisturbed sea-floor deposits of from around 10,000 to 100,000 years of age.

B. Exploration; Geophysical Manifestations

Throughout its known length, the Hosgri fault underlies the ocean floor, along which it has no consistent topographic expression. Thus exploration of this feature necessarily has been accomplished chiefly through use of various geophysical techniques. Methods that have been employed include several types of seismic or acoustic reflection profiling systems, as well as mapping of the earth's gravity and magnetic fields in the region traversed by the fault. Samples of the rocks and surficial deposits that underlie the sea floor near the fault trace have been gathered by means of dart coring techniques. One deep test well, drilled earlier at a location west of the fault, provides for comparison of the stratigraphic section there with the onshore section east of the fault at various places.

Maps showing some of the regional and local geophysical survey track lines that have yielded data applied to the Hosgri fault investigation are shown on Figures 31 and 32. The several techniques that have been applied in exploration of the Hosgri fault are described briefly as follows:

Seismic-Accoustic Reflection Techniques

Three major categories of reflection-surveying procedures have been used in the investigations along the

Hosgri fault. All involve receiving and recording energy reflected from the sea floor and from various horizons within the geologic section beneath the sea floor. The resulting data define a seismic cross section through the ground along the survey line; this section usually resembles a geologic cross section through the corresponding area. The three systems can be described as single-channel, multichannel, and shallow high-resolution.

Single channel systems are commonly referred to as sparker or airgun, according to the source used for input energy. The reflected energy is picked up by hydrophones, then recorded by a one-channel analogue procedure that usually employs a strip-chart recorder. Energy penetration beneath the sea floor varies according to geologic conditions; it also varies with power and frequency of the energy input, higher power and lower frequency giving deeper penetration but also lower resolution. Horizontal or gently inclined layered sedimentary sections give the best energy returns; massive or complexly deformed bedrock generally gives little in the way of useful returns.

The earliest and most extensive surveys of the Hosgri fault employed single-channel sparker systems. Fault breaks tend to appear in the resulting records as disruptions or truncations within the section, as zones of disturbance indicated by confused or incoherent seismic returns, as sharp changes in apparent dip of strata, as changes in the character of adjacent sections, or as zones where diffraction patterns originate. Figure 33 shows an example of the appearance of the Hosgri fault on a single-channel sparker record.

A more advanced type of reflection surveying involves recording the seismic returns on several channels, usually in digital form on magnetic tape. This allows use of the "common depth point" (CDP) technique of data processing, which greatly improves the accuracy and usefulness of the seismic information. Fault breaks have the same general manifestations in multichannel CDP records as in single channel records. Energy sources commonly used for multichannel reflection surveying include sparker, air gun, expanding sleeve explosion chamber, and explosives. Most of the multichannel CDP surveying of the Hosgri fault has yielded data proprietary to oil companies and contract geophysical surveying firms, but data from two surveys have been acquired for use during the investigations relating to the Diablo Canyon site.

Shallow penetration, high-resolution survey procedures are used to investigate the details of sea floor morphology, surficial deposits, and structure in the uppermost few tens of feet of the underlying rock section. Most high resolution systems employ a single-channel analogue recording system.

Other systems for investigating details of the surface morphology include precision fathometer profiling, which is similar to the high resolution shallow penetration system except that it does not penetrate beneath the sea floor; the side-scan sonar system; and underwater photography. Both fathometer and side-scan sonar records of the sea floor over the Hosgri fault have been obtained during various surveys. Underwater photography has not been attempted because of the generally high turbidity of the water in the region of interest.

Magnetic Field Mapping

The earth's magnetic field can be mapped by plotting and contouring measurements taken along a grid of traverses. Magnetic surveys of regional extent are usually accomplished by ship- or aircraft-borne magnetometers. The resulting data, after appropriate corrections are made, can be plotted to yield a map showing local variations, or anomalies, in the earth's magnetic field. For geologic purposes this is most useful if rocks containing magnetic minerals are present at or near the surface. Faults usually are best inferred where intact blocks of ground composed of rocks with relatively high but different magnetic signatures are juxtaposed. Fault breaks in rocks of low magnetism, such as much of the basin fill section that is cut by the Hosgri fault, may not be detectable by magnetic mapping. For the areas of shallow, magnetic basement rocks near the Point Piedras Blancas and

Point Sur uplifts, in contrast, the magnetic anomaly map pattern can show both faults and unfaulted blocks of rock between faults. Figure 34 shows the magnetic map of the coastal margin and its relationship to mapped faults of the Hosgri and San Simeon zones.

Gravity Field Mapping

The earth's gravity field can be mapped using procedures similar to those employed in magnetic mapping. Data from scattered points or traverses of gravity-field measurements are plotted and contoured. The measurements are made from shipboard or with land-sited gravity meters. The resulting map of gravity anomalies essentially shows areas of contrasting density in the upper part of the crust. As with magnetic mapping, this data can reveal, under conditions where rocks of differing density are structurally juxtaposed, useful information about geologic structure.

C. Geology Of The Main Reach, Point Sal To Cambria

The main or central reach of the Hosgri fault (Figure 35) extends over a distance of about 60 miles, between the approximate latitudes of Point Sal on the south and Cambria on the north. Beyond this reach the fault extends about 10 miles farther south and about 20 miles farther north, to give a total length of about 90 miles for the entire zone.

Within the main reach, the fault zone is fairly straight and trends about N25W. North of Estero Bay, the strike bends westward and the zone widens and evolves into separate splays and isolated breaks. Folding of the strata within and adjacent to the fault zone becomes prominent near the ends of the main reach.

The Hosgri fault, in its main reach, is a nearly vertical planar break or a narrow zone of such breaks that appears as segments within thick sections of late Tertiary sedimentary rocks opposite the Santa Maria River Valley and opposite Morro Bay. These geometrically simple segments are separated by a more complex zone, comprising at least four large breaks, where the fault cuts across the more resistant rocks of the Point San Luis structural high. The area of multiple breaks includes a graben, or down-dropped slice, between the two dominant fault strands.

Sections across the Hosgri fault to a depth of about 5000 feet show that Pliocene and older rocks are displaced downward to the west along it (Figure 36). Commonly the displacement can be seen to have been progressive through late Miocene and subsequent time. Evidence of at least local, deeply buried, pre-late Miocene reverse faulting is preserved along the reach of the zone opposite the Point San Luis high (Figures 36, 37). Within the upper two to three thousand feet of section, the fault planes of the Hosgri zone are relatively narrow, clean breaks, apparently with minimal development of gouge (crushed rock in the fault) and little severe distortion or fracturing of the adjacent rocks. The relationships seen in cross section suggest long-term incremental displacements in a vertical sense.

Evidence of strike-slip (horizontal) movements along the Hosgri fault is less definitive than is the obvious evidence of vertical separation. The three main lines of evidence that indicate or suggest a component of strike slip movement are:

1. Focal mechanism solutions of small earthquakes on the Hosgri show a right oblique sense of fault slip.

2. The fault zone is nearly straight along its central reach, which is a characteristic of lateral-slip faults.

3. Some onshore parts of the San Simeon fault and the Sur fault zone members of the Coastal Boundary zone show geomorphic evidence of right-lateral offsets.

H. Wagner of the USGS has cited, as possible evidence of lateral slip along the Hosgri fault, observed differences in thickness of Tertiary rock sections on opposite sides of the fault, along with inferred differences in character of juxtaposed Tertiary and Quaternary units as seen in seismic reflection records (Wagner, 1974). Although some lateral slip may well have occurred, these conditions might better be attributed to successive episodes of vertical offset combined with continuing sedimentation on the down-dropped side and erosion on the up-thrown side of the fault, and also to changes in the seismic registration of similar but differently oriented strata.

The large amount of right-lateral slip along the Hosgri fault, as proposed by C.A. Hall (Hall, 1976), apparently reflects an hypothesis that was developed independently of any direct study of the actual fault zone geometry or characteristics. The hypothesis was based on an inferred correlation of rocks exposed at Point Sal and near San Simeon, and on an inference that the two rock assemblages were originally together and subsequently separated by more than 80 km of right slip along the Hosgri fault. The hypothesis has been challenged on both stratigraphic and structural grounds, and it is here regarded as invalid. Consideration of all available evidence leads instead to a conclusion that not more than about 20 km of right-lateral slip could have occurred along the central reach of the Hosgri fault since early Miocene time (about 20 million years ago); the actual amount could be as little as a few kilometers. Vertical movement displacement along this part of the fault zone has ranged between 1 and 2 km during the same time span.

Considerations that appear to limit the amount of possible lateral slip along the Hosgri fault include the following:

1. The fault is not through-going in the sense of connecting with other faults in a way that would permit transmission of tens of kilometers of lateral offset.

Instead, it dies out longitudinally in folds and in groups of separate, isolated fault breaks.

2. The stratigraphic section penetrated by the Oceano Well, located west of the fault, is similar to the stratigraphic section of the adjacent Santa Maria - Casmalia region east of the fault. Further, it is unlike the stratigraphic section south of the Santa Ynez River, with which it should correlate if many tens of kilometers of right slip had occurred along the Hosgri fault. The similarity of sections between the Oceano Well and the onshore Santa Maria region appears to limit possible lateral slip to a maximum of about 20 km, although it actually could have been much less.

3. The existence of a wider, more complex pattern of faulting in the Hosgri zone directly opposite the Point San Luis structural high strongly suggests that lateral slip in that region has not exceeded a few kilometers, at least since Pliocene time. Otherwise, lateral movement of the seaward block would have carried the wide zone progressively northward across Estero Bay.

The sea-floor morphology along the main reach of the Hosgri fault varies chiefly in accordance with recency of uplift in local areas and with differential resistance to erosion of rocks juxtaposed across the fault. Opposite and south of San Luis Obispo Bay, the fault lies within younger Tertiary rocks and has no surface expression (Figure 38).

Where they are adjacent to the Point San Luis high, the more easterly fault strands locally coincide with submerged marine terrace steps (Figure-39). The steps in places are localized at the fault where it forms a boundary between rocks of lesser and greater resistance, which makes it difficult to determine whether some of the slip differential elevation could represent vertical fault movement. Opposite Estero Bay, the Hosgri fault locally coincides with small sea-floor ridges or steps, including one that faces landward. Some of these features are interpreted to represent possible local sea-floor offsets. The existence of an undisturbed sea-floor across the fault at other nearby points, however, precludes any possible Holocene rupture along the north-central reach of the Hosgri from exceeding a few thousand feet length.

D. Geology Of The Hosgri Zone North Of Point Estero; Relationship To The San Simeon Fault

The Hosgri fault zone can be traced for a distance of about 30 miles, 50 kilometers, north of Estero Bay. Within this northerly reach, it changes progressively northward from a narrow zone with large vertical offset to a wide zone of folds with less well-defined fault breaks, and thence to an unbroken fold structure (Figures 40, 41).

The general trend of the Hosgri zone curves gradually toward the west between Estero Bay and Point Piedras Blancas, thence back to a trend similar to that of the central reach.

The broad, convex-to-the-west broad arch described by this trend follows the southwest flank of the Point Piedras Blancas antiform or upwarp. The uplift lies between the northerly part of the Hosgri zone and the central and southerly part of the en-echelon San Simeon fault, and it has effected much of the transfer of vertical and lateral offset between these faults. From the vicinity of this uplift northward nearly to Pfeiffer Point, the San Simeon fault forms the main break of the Coastal Boundary zone.

A question of some importance in evaluating the structural relationship of the Hosgri fault to the San Simeon fault is whether a direct, through-going connection may exist between the two faults. It seems clear that the existence of such a connection would be necessary to permit transfer of a substantial amount of slip from one fault to the other, either cumulatively through geologic time or during one earthquake - fault rupture event.

Evidence bearing on this issue has been reviewed previously (FSAR Appendix 2.5.E, p. 2.5.E 38-39) and is here summarized as follows:

1. Seismic reflection lines that cross the Hosgri fault between Point Estero and San Simeon Point do not show any major branches of the Hosgri extending toward the projected southerly extension of the San Simeon fault.

2. These reflection lines show that the contact between late Tertiary rocks and acoustic basement rocks that

approximately parallels the shore line between Point Estero and San Simeon Point is not displaced as it should be if offset by major vertical or lateral faulting.

3. The Monterey cherty shale that lies along the southwest side of the San Simeon fault at San Simeon Point can be traced 4 miles to the southeast in seismic reflection records, indicating that the San Simeon fault does not veer toward the Hosgri in that reach.

4. The splay faults that branch westward from the San Simeon fault north of San Simeon Point form a distinctive structural pattern. These faults may well extend to the northernmost part of the Hosgri fault, but their orientation precludes significant transference of strain (especially right-lateral strain) between the major parts of the two faults.

5. The Hosgri fault dies out north of Point Piedras Blancas. It does not veer toward the San Simeon fault, but instead gradually dies out along a trend that is subparallel to that of the San Simeon fault.

Additional evidence regarding the possibility of a Hosgri - San Simeon fault link, not dependent on interpretation of seismic reflection profiles, is provided by the aeromagnetic map of the Point Estero - San Simeon region (Figure 42). This map of residual magnetic intensity clearly shows the San Simeon fault as a linear magnetic low, or trough, between the pronounced magnetic high associated with the ophiolite basement rocks west of the fault and the more scattered magnetic highs of the mixed Franciscan and ultramafic terrane east of the fault. The Hosgri fault, as mapped from seismic reflection data, is associated with the gradient along the southwesterly, seaward side of the San Simeon area magnetic high. This magnetic high appears to be associated with a block of basement rocks that extends unbroken between the Hosgri and the San Simeon faults in the area that would contain any linking break that could permit through-going transfer of slip from one fault to the other. The magnetic anomaly pattern indicates that no such break exists, and reinforces the conclusion that the Hosgri and San Simeon faults are distinct, unconnected breaks.

E. Geology Of The Hosgri Zone South Of Point Sal; Relationship To The Western Transverse Ranges

From about the latitude of Point Sal southward, the Hosgri fault progressively loses definition as a separate major break and merges into a zone of complex folding that generally characterizes this region (Figure 43).

The southernmost extension of the Hosgri zone may continue for a distance of about 10 miles south of Point Sal. At its extreme southerly end it apparently dies out within a zone of tight folding that extends seaward from the vicinity of Purisima Point. This interpretation agrees closely with the original Shell Oil Company map of the Hosgri fault published by Hoskins and Griffiths, and more generally with the map included with Appendix 2.5.E of the Diablo FSAR. An early interpretation by the USGS (e.g., Figure 2 of USGS open-file report 77-593, McColloch et al., 1977) that the Hosgri fault continued southward as far as Point Arguello evidently has been revised, and the most recently released USGS map of the fault (Map MF-910, Buchanan - Banks, et al., 1978) shows the break as ending just south of Purisima Point.

The substantial displacement across the central reach of the Hosgri fault diminishes southward, and strain in its southerly reach evidently has been accommodated by folding distributed throughout the region, as well as by local reverse faulting. Some movement probably has been taken up along the Lions Head fault, which extends onshore south of Point Sal. This fault has the same east-up sense of vertical displacement as the Hosgri farther north, whereas the southernmost break along the Hosgri trend is east-down.

The southerly end of the Hosgri is in the region where mutually interfering strain systems are present. These are the dominantly right-oblique system extending from the Coast Ranges and offshore basin to the north, and the left-oblique system extending from the Western Transverse Ranges to the east. The major structural feature that shows evidence of late Quaternary tectonic activity, indicated geologically by fold arching and fault disruption of the sea floor, is the offshore Lompoc anticline and reverse fault system, located several miles west of the Hosgri trend. The Hosgri itself offsets rocks of Pliocene age, as it does along its central reach to the north, but it has not been found to exhibit evidence of late Quaternary (post-Wisconsinan) surface displacement.

F. Overall Structural Relationships Of The Hosgri Fault

As has been noted earlier in this testimony, the Hosgri fault forms the southerly part of the Coastal Boundary zone of features and faults that lies between the uplift of the Southern Coast Ranges and the structural depression of the offshore basins. Because of its location at the south end of the Coast Ranges it is also involved in the transition from Coast Ranges to Transverse Ranges structure. The overall structural relationships of the Hosgri can be generalized into three regions, each characterized by a particular set of relationships. These are, first, northerly region, where strain is transferred across the Piedras Blancas antiform between the Hosgri fault and the next major member of the Coastal Boundary zone to the north, the San Simeon fault. Second, the central region, where west-northwesterly trending folds and faults in the uplifted ground east of the Hosgri are detached across it from north-northwesterly folds in the downdropped basin on its west side. Lastly is the southerly zone where the Hosgri enters and dies within the region of merging between the northwesterly, right lateral structure trends of the Southern Coast Ranges and the east-west, left-lateral structure trends of the Western Transverse Ranges. These general relationships are illustrated on Figure 44.

In the central regions of both the Hosgri and the San Simeon faults, vertical strain is accommodated chiefly by high angle dip slip displacement, so that sections of early Miocene and younger strata ranging between 1 and 3 km in thickness are buttressed against the faults. Right lateral slip is also at a maximum along the central regions of each of these faults, although it probably does not exceed about 10 km, and it may amount to only a few km. Along the central part of the Hosgri, the structural trends across the fault differ in orientation by about 30 degrees, and the folds in the ground on the east side are large, long established features that show evidence of progressive evolution since upper Miocene time. This pattern of large folds oriented oblique to the trend of the Hosgri fault may, at least in part, represent accommodation by folding of the right lateral strain along the central reach of the fault - essentially in effect of "wrinkling" the crust on one side of a set of horizontally sliding blocks.

In the northerly region of the Hosgri, the vertical strain is mainly taken up by the large complex upwarp of the

Piedras Blancas antiform. This fold, together with a series of reverse fault splays contained within it, apparently effects the transfer of both horizontal and lateral strain between the Hosgri and San Simeon faults, and the faults themselves are less developed in this region. The antiformal transfer region nonetheless appears to be a zone of relatively higher stress concentration, since it has been the source of frequent small to moderate earthquakes throughout the time of historic record.

The southerly region of the Hosgri fault lies within the transition zone between the Southern Coast Ranges and the Western Transverse Ranges structural provinces. Here the main east-up vertical strain from the central reach of the Hosgri is partly taken up along the Lions Head fault, which extends onshore south of Point Sal as a steeply dipping north-up right-oblique fault with at least 1000 meters of vertical displacement, and which dies out to the east. The remainder of the vertical strain is apparently dispersed in the series of tight folds that exist in the strata adjacent to the Hosgri fault. Right -lateral slip that extends southward from the central reach of the Hosgri fault partly transfers to the Lions Head fault, and partly is accommodated in folds and isolated faults along both sides and across the end of the southernmost break of the Hosgri zone, along the reach between Point Sal and Purisma Point.

G. Evidence Relating To Late Pleistocene And Holocene Displacements

The Hosgri fault underlies the gently seaward-sloping, near-shore margin of the continental shelf area. The nearest abrupt topographic rises lie 2.5 miles (4 km) east of the fault trace at Point Buchon and along the mountainous coastline between Point Estero and Cambria. There is no overall topographic expression of the fault, and there is little associated micro-topography such as commonly exists along traces of active late Quaternary faults on land. It can be suggested that either the latest large-scale offsets along the Hosgri fault occurred far enough back in time -- at least hundreds of thousands of years ago -- to have been obliterated by successive episodes of marine and coastal erosion, or that late Quaternary movement has been dominantly horizontal.

In considering the significance of the fine details of sea-floor morphology and of relations of faulting to surficial deposits underlying the sea floor, it is important to note that the sea floor to depths of about 400 feet was exposed to subaerial erosion during the late Pleistocene Wisconsinan low stand of sea level and was then subjected to marine planation during the succeeding rise in sea level to its present elevation. The rise, which occurred mainly between about 17,000 and 5,000 years ago, resulted in obliteration of earlier small-scale topographic evidence of surface fault movements during the past 10,000 to 17,000 years, after submergence exceeded the depth of active wave erosion.

Surface displacements that have occurred since this resubmergence should have created detectable disturbance of the sea floor and of the late Pleistocene and Holocene deposits that locally underlie. Seismologic evidence that earthquakes in the region have right-oblique mechanisms, and geologic evidence that the Hosgri fault has a history of vertical offset, and geologic evidence that the most recent movements of faults in the San Simeon zone have been high-angle reverse or vertical strongly indicate that any recent surface movements along the Hosgri should have had significant vertical components and therefore should have created scarps and vertical offsets of contacts that would be detectible on high-resolution seismic reflection profiles. Furthermore, any recent surface faulting associated with large earthquakes should have produced topographic effects along substantial reaches of the fault trace.

The entire length of the Hosgri fault zone has been surveyed by intermediate and high-resolution systems. The density of survey coverage is greatest along the reach between Estero Bay and San Luis Obispo Bay, but good reconnaissance coverage exists for the fault zone as far as its north and south ends. The results of this exploration show that both the sea floor and the wave-cut rock surface beneath the post-Wisconsinan surficial deposits are unbroken along any survey line south of San Luis Obispo Bay (e.g., Figures 38, 45). From San Luis Obispo Bay northward to Estero Bay, the Hosgri extends across an area of submerged marine terrace steps in the sea floor (Figure 39). These steps show the form that is characteristic of a sea cliff formed by retreat of the coastline; that is, the slope of the sea floor flattens in a wave-cut bench at the base of the step. Some of the steps are cut into unfaulted ground, thus demonstrating that they were formed independently of any faulting. At some places, however, the terrace steps are essentially coincident with well-defined fault breaks in the underlying rock section. These localities represent uncertainties as to whether some vertical fault offset may be involved in addition to the erosionally developed topographic relief. The fact that no similar topographic steps exist along the fault at points north and south of the area of submerged terraces strongly suggests that the terrace steps are wholly erosional in origin, whether or not they correspond in general position to the trace of a fault. In the absence of proof to the contrary, however, it must be considered possible that some late Pleistocene or Holocene vertical surface displacements may exist for short distances along some strands of this reach of the Hosgri zone.

Opposite Point Buchon, a high-resolution profile indicates a low land-side-down step in the sea floor over the seaward trace of the Hosgri fault along the west side of the graben structure in that area. Because this step faces landward instead of seaward, and has the same topographic sense as the sense of offset along the underlying fault, it is considered to have significant probability of being a young fault scarp. It is between 1 and 2 meters in height, but no such feature can be detected in high-resolution profiles located at distances of 1000 feet to the north and south, across the Hosgri trace.

IV

CONCLUSIONS

1. The Diablo Canyon area is underlain by sedimentary and volcanic bedrock units of Miocene age. Within this area, the power plant site is underlain almost wholly by sedimentary strata of the Monterey Formation, which dip northward at moderate to very steep angles. More specifically, the reactor sites are underlain by thick-bedded to almost massive Monterey sandstone that is well indurated and firm.

2. The bedrock beneath the power plant site occupies the southerly flank of a major syncline that trends west to northwest. No evidence of a major fault has been recognized within the immediate vicinity of the site, and bedrock relationships in the exploratory trenches positively indicate that no such fault is present within the area of the power plant site.

3. Minor surfaces of disturbance, some of which plainly are faults, are present within the bedrock that underlies the power plant site. None of these breaks offsets the interface between bedrock and the cover of terrace deposits, and none of them extends upward into the surficial cover. Thus the latest movements along these small faults must have antedated erosion of the bedrock section in Pleistocene time, at least 80,000 to 120,000 years ago.

4. Larger faults in the region of the Diablo Canyon site, including the Hosgri fault, exhibit evidence of no more than small or negligible amounts of displacement of the ground surface during latest Pleistocene and Holocene time, indicating that the level of seismic activity in the region has been such that no large offsets have occurred, either as single events or cumulatively, along potentially seismogenic faults during a span of time ranging back at least to late Pleistocene.

5. The Hosgri fault is about 145 km in length, its end point lies within complex zones of folding and minor faulting that die out into unbroken strata. It is part of a larger system of faults and flexures that form a boundary zone between the relatively rising and subsiding blocks of the Southern Coast Ranges and the offshore Santa Maria Basin, but it is not a primary element of a transitional plate boundary system.

REFERENCES

Asquith, Donald O., 1977. Trenching of San Simeon fault zone at San Simeon, Presentation at Symposium Geology, Geophysics, and Tectonics of the San Gregorio-Hosgri fault system, California State Department of Conservation.

Bell, Elaine J., 1977. Recent crustal movements in the Central Sierra Nevada-Walker Lane region of California-Nevada : Part II, The Pyramid Lake right-slip fault zone segment of the Walker Lane : Stanford Univ. Press, Abstracts of the 1977 International Symposium on recent crustal movements.

Benioff, Hugo, (1955). Relation of the White Wolf fault to the regional tectonic pattern, <u>in</u> Oakeshott, G. B. (editor), Earthquakes in Kern County, California during 1952: California Div. Mines Bull. 171, pp 203-204.

Berggren, W. A., 1969. Cenozoic chronostratigraphy, planktonic foraminiferal zonation and radiometric time scale : Nature, vol. 224, pp 1072-1075.

Clarke, S. H., Jr., and T. H. Nilsen, 1973. Displacement of Eocene strata and implications for the history of offset along the San Andreas fault, central and northern California, <u>in</u> Kovach and Nur, eds., Proc. of conference on tectonic problems of the San Andreas fault system.

Cummings, J. C., 1968. The Santa Clara Formation and possible post-Pliocene slip on the San Andreas fault in central California, *in* Dickinson, W. R., and Arthur Grantz (eds), Proceedings of conference on geologic problems of the San Andreas fault system : Stanford Univ. Pubs. in the Geol. Sciences, vol. XI, pp 191-206.

Dibblee, T. W., Jr., 1966. Evidence for cumulative offset on the San Andreas fault in central and northern California *in* E. H. Bailey, ed., Geology of northern California : Calif. Div. Mines and Geol. Bull. 190, pp 375-384.

Dibblee, T. W., Jr., 1968. Displacements on the San Andreas fault system in the San Gabriel, San Bernardino, and San Jacinto Mountains, southern California, *in* Dickinson, W. R., and Arthur Grantz, eds. Proc. conf. geologic problems of San Andreas fault system : Stanford Univ. Pubs. Geol. Sci., vol. 11, pp 260-278.

Dibblee, T. W., Jr., 1972. The Rinconada fault in the southern Coast Ranges, California, and its significance, Unpublished abstract of talk given to the AAPG, (Pacific Section).

Dibblee, T. W., Jr., 1975. The Rinconada and related faults in the Southern Coast Ranges, California, and their tectonic significance, U. S. Geol. Survey Prof. Paper 981, p. 55.

Envicom, Inc., 1974. Seismic Safety Element, San Luis Obispo County, Report prepared for San Luis Obispo County Planning Department by Envicom, Inc.

Envicom, Inc., 1977. Report on the San Simeon area to the Hearst Ranch Corporation.

Gawthrop, W., (1975). Seismicity of the Central California Coastal Region, USGS Open-file Report 75-134.

Graham, S. A., 1976. Tertiary Sedimentary Tectonics of the Central Salinian Block of California : Unpublished Ph.D. Thesis, Stanford University, Stanford, California.

Graham, S. A,. and W. R. Dickinson, 1978. Evidence for 115 kilometers of right-slip on the San Gregorio-Hosgri fault trend Seismic, Vol. 199, 13 January 1978.

Greensfelder, R. W., 1972. Crustal Movement Investigations in California; their history, data, and significance : Calif. Div. of Mines and Geology Special Publ. 37, p. 25.

Hall, C. A., Jr., and C. E. Corbato, 1967. Stratigraphy and structure of Mesozoic and Cenozoic rocks, Nipomo quadrangle, Southern Coastal Ranges, California : Geol. Soc. America Bull., Vol. 78, pp 559-582.

Hall, C. A., Jr., 1973a, Geologic map of the Morro Bay South and Port San Luis quadrangles, San Luis Obispo County, California : U. S. Geol. Survey Misc. Field Studies Map 511.

Hall, C. A., Jr., 1975. San Simeon-Hosgri fault system, Coastal California : Economic and Environmental Implications, Science, Vol. 190, pp 1291-1294.

Hall, C. A., Jr., 1976. Geologic map of San Simeon-Piedras Blancas Region, California, USGS Map MF-784.

Hall, C. A., Jr., 1977. Oral communication to C. R. Willingham.

Hall, C. A., Jr., and S. W. Prior, 1975. Geologic map of the Cayucos-San Luis Obispo region, San Luis Obispo County, California : U. S. Geol. Survey Misc. Field Studies Map MF-686, scale 1:24,000.

Hall, N. Timothy, and Kerry Sieh, 1977. Late Holocene rate of slip on the San Andreas fault in the northern Carrizo Plain, San Luis Obispo County, California : Geol. Soc. America, Abs. with programs, Vol. 9, No. 4, pp 428-429.

Hamilton, D. H., and C. R. Willingham, 1977. Hosgri fault zone; structure, amount of displacement, and relationship to structures of the Western Transverse Ranges, Geol. Soc. of America, abs. with programs, Vol. 9, No. 4, p 429.

Headlee, L. A., 1965. Geology of the Coastal Portion of the San Luis Range, San Luis Obispo County, California; Unpubl. M. S. Thesis, Univeristy of Southern California.

Hill, M. L., 1954. Tectonics of Faulting in Southern California, in Jahns, R. H. (editor), Geology of Southern California, Calif. Div. Mines and Geol., Bull. 170, Ch. 4, pp 5-13.

Howell, David G., 1977. How equivocal are the data that suggest 80 km of right-slip on the Hosgri fault? Presentation at Symposium Geology, Geophysics, and Tectonics of the San Gregorio-Hosgri fault system, California State Department of Conservation.

Huffman, O. F., D. L. Turner, and R. N. Jack, 1973. Offset of late Oligocene - early Miocene volcanic rocks along the San Andreas fault in central California, in Kovach, R. L., and Amos Nur (eds.), Proc. of the conference on tectonic problems of the San Andreas fault system : Stanford Univ. Pubs. in the Geol. Sciences, Vol. XIII, pp 368-373.

Jennings, C. W., 1958. San Luis Obispo sheet : Calif. Div. Mines and Geology Geologic Map of California, Olaf P. Jenkins edition.

Jennings, C. W., 1975. Fault Map of California, California Division of Mines and Geology.

Lajoie, K. R., and others 1978. Paper in review describing recent research on tectonism in the Ventura region.

Maddock, M. E., and T. L. Hudson, 1968. Implications of Franciscan rocks near Pajaro Gap regarding movement along the San Andreas fault, in Dickinson, W. R., and Arthur Grantz (eds.), Proceedings of conference on geologic problems of the San Andreas fault system : Stanford Univ. Pubs. in the Geol. Sciences, Vol. XI, pp 121-122.

McCollock, D. S. and R. H. Chapman, 1977. Maps showing residual magnetic intensity along the California Coast Lat. 37° 30' N to 34° 30' N. USGS open file report 77-79.

McCullock, D. S., S. H. Clark, Jr., M. E. Field, E. W. Scott, and P. M. Utter, 1977. A summary report on the regional geology, petroleum potential, and environmental geology of the southern proposed lease sale 53, central and northern California outer continental shelf. USGS open file report 77-593.

Page, B. M., 1970a. Sur-Nacimiento Fault Zone of California : Continental Margin Tectonics, Geol. Soc. Amer., Bull., Vol. 81, pp 667-690.

Richter, C. F., 1969. Possible Seismicity of the Nacimiento Fault, California; Geol. Soc. Amer., Bull., Vol. 80, pp 1363-1366.

Suppe, John, 1970. Offset of Late Mesozoic Basement terrains by the San Andreas fault system : Geol. Soc. Amer., Bull., Vol. 81, pp 3253-3258.

Seiders, Victor M., 1977. The San Simeon-Pt. Sal correlation -- a word of caution, Presentation at Symposium Geology, Geophysics, and Tectonics of the San Gregorio-Hosgri fault system, California State Department of Conservation.

Seiders, Victor M., 1978. Onshore stratigraphic comparisons across the San Simeon and Hosgri faults, California, Abstr. with Programs, Geol. Soc. Amer. Cordilleran Section Meeting, 1978.

Slemmons, David B., 1977. Recent crustal movements in the central Sierra Nevada-Walker Lane region of California-Nevada : Part I, Rate, style, and historical record of deformation. Stanford Univ. Press, abstracts of the 1977 International symposium on recent crustal movements, Stanford, California.

Smith, S. W., 1974. Analysis of Offshore Seismicity in the Vicinity of the Diablo Canyon Nuclear Power Plant. Report to Pacific Gas and Electric Company.

Smith, Roger S. U., 1977. Holocene offset and seismicity along the Panamint Valley fault zone, Western Basin and Range Province, California : Stanford Univ. Press, abstracts of the 1977 International symposium on recent crustal movements, Stanford, California.

Vedder, J. G., 1975. Juxtaposed Tertiary strata along the San Andreas fault in the Temblor and Caliente Ranges, California, *in* Crowell, John C. (ed.), San Andreas fault in southern California : Calif. Div. Mines and Geol., Special Report 118, pp 234-240.

Wagner, H. C., 1974b. Marine Geology between Cape San Martin and Pt. Sal, South-Central California Offshore; a Preliminary Report, August 1974; U. S. Geol. Survey open file report 74-252.

Willingham, C. Richard, 1977. The geometry of the Hosgri fault as determined from seismic reflection and aeromagnetic studies, Presentation at Symposium Geology, Geophysics, and Tectonics of the San Gregorio-Hosgri fault system, California State Department of Conservation.

Willott, J., (1972). "Analysis of Modern Vertical Deformation in the Western Transverse Ranges", M. A. thesis, University of California, Santa Barbara.

GLOSSARY

Acoustic Basement - The zone that yields no coherent or useful seismic reflections, at the base of a sequence of reflecting horizons (if any are present).

Acoustic Reflection Technique - (see Seismic Reflection) The process including the receiving and recording of energy reflected from the sea floor and from various horizons beneath the sea floor.

Aeromagnetic - Referring to magnetic measurements taken from an airplane.

Allochthonous - Formed elsewhere; not formed at its present location.

Alluvial - Pertaining to or composed of alluvium (sediment transported by a stream), or deposited by a stream or running water.

Anticline - A convex upward fold, the interior of which contains the oldest rocks.

Antiform - A complex anticlinal structure in which the stratigraphy may not be defined.

Arkosic Sandstone - A sandstone which contains a large percentage of the mineral feldspar.

Augite - A pyroxene rock-forming mineral.

Basalt - A common, dark-colored volcanic rock, often formed by solidification of a lava flow.

Basement - A complex of undifferentiated rocks that underlies the oldest identifiable rocks in the area.

Batholith - A large, generally discordant mass of intrusive igneous rock (such as granite) having more than 100 km^2 of surface exposure.

Bedrock - Any solid rock exposed at the surface or covered by unconsolidated sediment.

Bench - A level or gently sloping erosion surface.

Bituminous - Referring to the content of a mixture of hydrocarbons, or loosely to a material containing much organic or carbonaceous material.

Boudin - One of a series of elongate, sausage-shaped segments occurring in a boudinage structure.

Boudinage - A structure common in deformed rocks in which an originally continuous, competent layer has been stretched and thinned at regular intervals to produce elongate bodies (boudins) parallel to the fold axis.

B.P. - Before the present.

Breccia - Course-grained, clastic (fragmented) rock composed of large, angular, rock fragments cemented together in a find-grained matrix.

Cenozoic - Geologic time from present to about 65 million years before present.

Clastic - Pertaining to fragments·(clasts) composing a rock.

Colluvial - Pertaining to or composed of colluvium (sediment deposited by unconcentrated surface runoff or sheet erosion).

Conformable - Said of sedimentary layers that horizontally overlie one another without deformation, or a long period of erosion, represented between them.

Conglomerate - Sedimentary rock composed primarily of pebble- and gravel-sized material.

Continental Crust - The portion of the earth's crust that forms the continents, distinguished from oceanic crust by its lighter density and (usually) its chemical composition.

Continental Slope - Relatively steep slope usually separating the submerged edge of a continent from a deeper ocean basin.

Cretaceous - The geologic period extending from about 65 to 136 million years before present.

Cross-Fault - A fault which strikes diagonally or perpendicularly to the strike of faults in the area.

Crust - The outermost (100 km ±) layer of the earth.

Crystalline - Said of a rock consisting of crystals or fragments of crystals, formed by crystallization from a melt, or recrystallization under conditions of elevated temperature and/or pressure.

Diabase - A common igneous rock formed by intrusion into the crust of molten volcanic rock at shallow depth; "diabasic" refers to a common igneous texture.

Diatomaceous - Composed of diatoms, a microscopic single-celled marine plant made of silica.

Dike - An intrusive body which cuts across the planar structures (such as bedding) of the surrounding rocks.

Dip-Slip - Component of fault movement or slip that is parallel to the dip of the fault.

Earthquake - Brief motion or shaking in the earth caused by the sudden release of accumulated strain energy, usually through slippage of rock in the earth's crust along a fault.

En-Echelon Segments - Geologic features, such as faults, that are in an overlapping or staggered arrangement.

Eocene - Geologic time from about 38 million to 54 million years before present.

Epicenter - The point on the earth's surface directly above the focus, or hypocenter, of an earthquake.

"Facies Changes" - Minor lithologic and/or fossil changes due to local changes in the environment of deposition.

Fan Deposits - Sedimentary deposits formed at the base of a slope, usually in a fan shape.

Fault - Surface or zone of rock fracture along which there has been displacement.

Fault Creep - Slow deformation of ground along a fault due to continuous application of stress.

Fault Line - The trace of the intersection of a fault plane with the ground surface.

Fault-Line Scarp - A steep slope or cliff formed by differential erosion along a fault line.

Fault Scarp - A steep slope or cliff formed by fault movement at the ground surface.

Focal Mechanism - Process that leads to the generation of seismic waves, usually through fault slippage, during an earthquake.

Fold - A curve or bend of a planar geologic feature, usually due to deformation.

Foraminifera - Unicellular animal usually marine and microscopic in size; fossils of Foraminifera are often useful for determining the approximate geologic age of a sedimentary rock.

Formation - Primary unit for describing and mapping a succession of similar and related rock materials.

Geodetic Data - Data pertaining to the accurate surveying of the earth's surface.

Geomorphic - Of or pertaining to the form of the earth's surface features.

Geomorphic Province - Region whose form or surface features correspond to a particular pattern or range of patterns, and differ significantly from those of adjacent regions.

Graben - An elongate block which has been down-dropped along faults that bound the long sides.

Gypsum - A mineral (hydrous calcium sulfate).

High Resolution Profiling - A type of marine seismic reflection profiling that has good resolution of small-scale features, but can only penetrate to shallow depths in the material beneath the sea floor.

Holocene - Geologic time from present to about 10,000 years before present.

Hypabyssal - Pertaining to an igneous intrusion of intermediate depth in the earth's crust.

Hypocenter (focus) - That point within the earth's crust which is the center of an earthquake and the origin of its energy release.

Igneous - Descriptive term for rocks formed by crystallization from a molten state; includes both volcanic rocks and plutonic (formed at depth in the crust) rocks.

Joint - A surface of fracture or parting in a rock, without displacement.

Jurassic - The geologic period extending from about 136 to 195 million years before present.

Klippen (plural of klippe) - Isolated rock blocks separated from the underlying rocks by a low-angle fault; remnants of a formerly continuous thrust sheet.

Late Miocene - Geologic time from about 5 million to 13 million years before present.

Late Quaternary - Geologic time from present to about 200,000 years before present.

Left-Lateral - Type of motion occurring on a fault along which the side across the fault from the observer appears to have moved to the left.

Lithologic - Of or pertaining to the description of rocks, especially sedimentary clastic rocks.

Mafic - Referring to iron-magnesium minerals generally dark in color.

Magma - Molten rock, usually a large mass.

Magnitude - A measure of the strength of an earthquake or the energy released by it.

Marine Planation - Process of near-shore waves eroding the bedrock down to a planar surface, usually over a fairly long period during a time of gradually rising sea level.

Melt - Molten rock; implies formed through the melting of once solidified rock.

Mesozoic - Geologic time from about 65 million to 225 million years before present.

Metamorphic - Descriptive term for rock formed from pre-existing rocks by mineralogical, chemical, and structural changes, essentially in the solid state, as response to changes in temperature, pressure, shearing stress, and chemical environment at depth; also, textural features associated with metamorphic processes.

Middle Miocene - Geologic time from about 13 million to 16.5 million years before present.

Mineral Assemblage - The minerals that compose a rock.

Miocene - Geologic time from about 5 million to 23 million years before present.

. . .

Modified Mercalli (MM) - Referring to a scale of earthquake intensity having 12 divisions ranging from I to XII, based on increasing felt intensity and degree of damage.

Morphology - Shape of the land (or of some geologic features).

M.Y. - Million years.

Normal Fault - A steeply dipping fault in which the rock above a dipping fault plane moves down with respect to below the fault plane rock; a fault with the opposite sense of movement of a reverse fault.

Oblique Slip - Component of fault movement or slip that is intermediate in orientation between dip slip and strike slip.

Oceanic Crust - The part of the earth's crust which typically underlies the oceans; has different composition and different geophysical properties from continental crust.

Oligocene - Geologic time from 23 million to 38 million years before present.

Olivine - A mineral usually found in igneous rocks.

Opaline - Similar to opal, an amorphous hydrous form of silicon dioxide.

Ophiolite Assemblage - A group of rock types which is characteristic of the oceanic crust.

Paleocene - Geologic time from about 54 million to 65 million years before present.

Perlitic - A texture found in volcanic glass consisting of concentric cracks.

Petrologic - Of or pertaining to the origin, occurrence, structure and history of rock, especially as reflected in the constituent minerals and fabric.

Pillow Basalt - Basalt extruded under water, having an external form characterized by rounded "pillow" shapes.

Plagioclase - One of the feldspar rock-forming minerals.

Plate Boundary - A zone along which two crustal plates interact according to the plate tectonic model of the earth. The most common types of boundaries are: 1) spreading ridges along which new crust is formed; 2) trenches or subduction zones along which crust is consumed; and 3) transform faults, along which crustal plates move passively by each other.

Plate Tectonics - Earth model which divides the surface or crust of the earth into a small number of large "plates" or segments of a spherical surface which "float" on a viscous underlayer or mantle. These crustal plates move relative to one another, and the geological effects that develop along the boundaries between relatively moving plates are said to be related to plate tectonics.

Pleistocene - Geologic time from about 10,000 to 2.5 million years before present.

Pliocene - Geologic time from about 2.5 million to 5 million years before present.

Plunge - The inclination of a fold or other geologic structure, measured by its angle with the horizontal.

Plutonic Rocks - Igneous rocks which solidify at considerable depth beneath the earth's surface.

Post-Wisconsinan - Geologic time extending from about 15,000 to 17,000 years, the last major low-stand of sea level coinciding with maximum extent of late Pleistocene glaciation, to the present.

Potassium-Argon Age - Radiometric age based on analysis of isotopic content and ratio of potassium and argon in a mineral.

Pumice - A very porous, glassy volcanic rock.

Pumiceous - Pumice-like.

Pyritization - The process by which an original mineral is changed into the mineral pyrite through chemical exchange and recrystallization.

Pyroclastic - Pertaining to a clastic (fragmented) rock formed by debris from explosive volcanic eruptions.

Quaternary - Geologic time from present to about 2.5 million years before present.

Radiolarian Chert - A silica-rich sedimentary rock formed primarily of radiolarians, a single-celled marine animal which has a complex siliceous skeleton.

Radiometric Dating - Determining age in years for geological materials by measuring a short-life radioactive element, e.g. carbon-14, or by measuring a long-life radioactive element plus its decay product (e.g. potassium-argon).

Reflector Horizon - In seismic reflection profiling of the ocean floor, a prominent reflecting layer.

Reverse Fault - A fault in which the rock above a dipping fault plane is uplifted relative to the rock beneath the fault plane; similar to a thrust fault but generally steeper dipping.

Richter Magnitude - Numerical scale representing earthquake energy; devised in 1935 by seismologist C. F. Richter.

Right-Lateral - Sense of motion occurring on a fault along which the ground across the fault from the observer appears to have moved to the right.

Rise - Oceanic spreading ridge or zone of crustal formation.

Sea-Floor Spreading - Theory that the oceanic crust is being added to by convective upward movement of molten material along the spreading ridges in the ocean and then moving away from the ridges as new crust.

Sedimentary - Descriptive term for rock formed of particles of other rock transported and deposited at another location; also textural features associated with sedimentary deposition.

Sedimentary Rocks - Rocks formed by the accumulation of particles, usually in water but also from the air, and by chemical precipitation, characteristically in layers called bedding or stratification.

Seismic Activity - Earthquakes.

Serpentine - General term used to describe a group of common rock-forming minerals, or rock composed of these minerals. The minerals are derived from alteration of pre-existing iron-magnesium-rich rocks.

Sill - An intrusive body which is emplaced generally parallel to the planar structure (such as bedding) in the surrounding rocks.

Spreading Ridge - A zone along which new crust is fairly continuously formed, according to the plate tectonics model of the earth, by the upward movement of molten material, its solidification into crustal material, and subsequent lateral movement in opposite directions away from the zone as part of the two plates being created at, and moving away from, the spreading ridge.

Strain - Deformation of materials due to applied forces.

Strandline - The line or level at which a body of water, such as the sea, meets the land; also a former shoreline now elevated above or depressed below the present water level.

Stratigraphic - Pertaining to rock layers or strata.

Strike - The geographic orientation of an imaginary line which is the intersection of a horizontal plane with a bedding plane, fault plane, or other planar surface in question.

Strike-Slip - Component of fault movement or slip that is horizontal.

Structural - Of or pertaining to features that are the result of folding and faulting.

Structural Grain - Predominant orientation or pattern of folds and faults.

Structural Province - Region whose geologic-structural features correspond to a particular pattern or range of patterns, and which differ significantly from those of adjacent regions.

Subaerial Erosion - Erosion occurring on the land surface above sea level.

Subduction - A plate tectonic process occurring along the boundary of two converging crustal plates where one plate is thrust under and sinks beneath the margin of the other plate.

Syncline - A concave upward fold, the interior of which contains the youngest rocks.

Talus - An accumulation of fallen rock fragments forming a slope at the foot of a steeper slope.

Tectonic Pattern - Similar pattern of folding and faulting and implied history which is characteristic of a particular region during a given period of geologic time.

Terrace - Relatively flat to gently inclined surface, often long and narrow, locally present along the coast, as an uplifted (or submerged) bench developed in response to surf-zone marine erosion (wave-cut bench).

Tertiary - Geologic time from about 2.5 million to 65 million years before present.

Thrust Fault - A fault with a dip of 45° or less in which the material above the fault plane has moved upward relative to the material beneath it.

Trace - intersection of a geologic surface, such as a fault, with another surface, usually the ground surface.

Trench - (geologic term) The topographic low created during subduction. (exploration term) An elongate open excavation.

Triple Junction - Area of intersection of three plate boundaries according to the plate tectonics model of the earth. Theoretically, any combination of the three basic plate boundaries (ridges, trenches, transform faults) may intersect to form a triple junction.

Tuff - A rock formed of compacted volcanic fragments, generally smaller than 4 mm.

Ultramafic - Pertaining to igneous rocks composed chiefly of mafic (dark) minerals.

Uncomformity - A surface of erosion or non-deposition that separates younger strata from older rocks.

Underthrusting - Type of fault motion where a lower rock mass is actively moved under an upper, passive rock mass. Used especially to describe a type of plate tectonics boundary condition where one plate is being thrust under an adjacent one. The underthrusting process is referred to as subduction.

Vertical Slip - The vertical component of fault movement.

Vitric-Lithic - Textural term used to describe rocks composed of both glass and rock fragments.

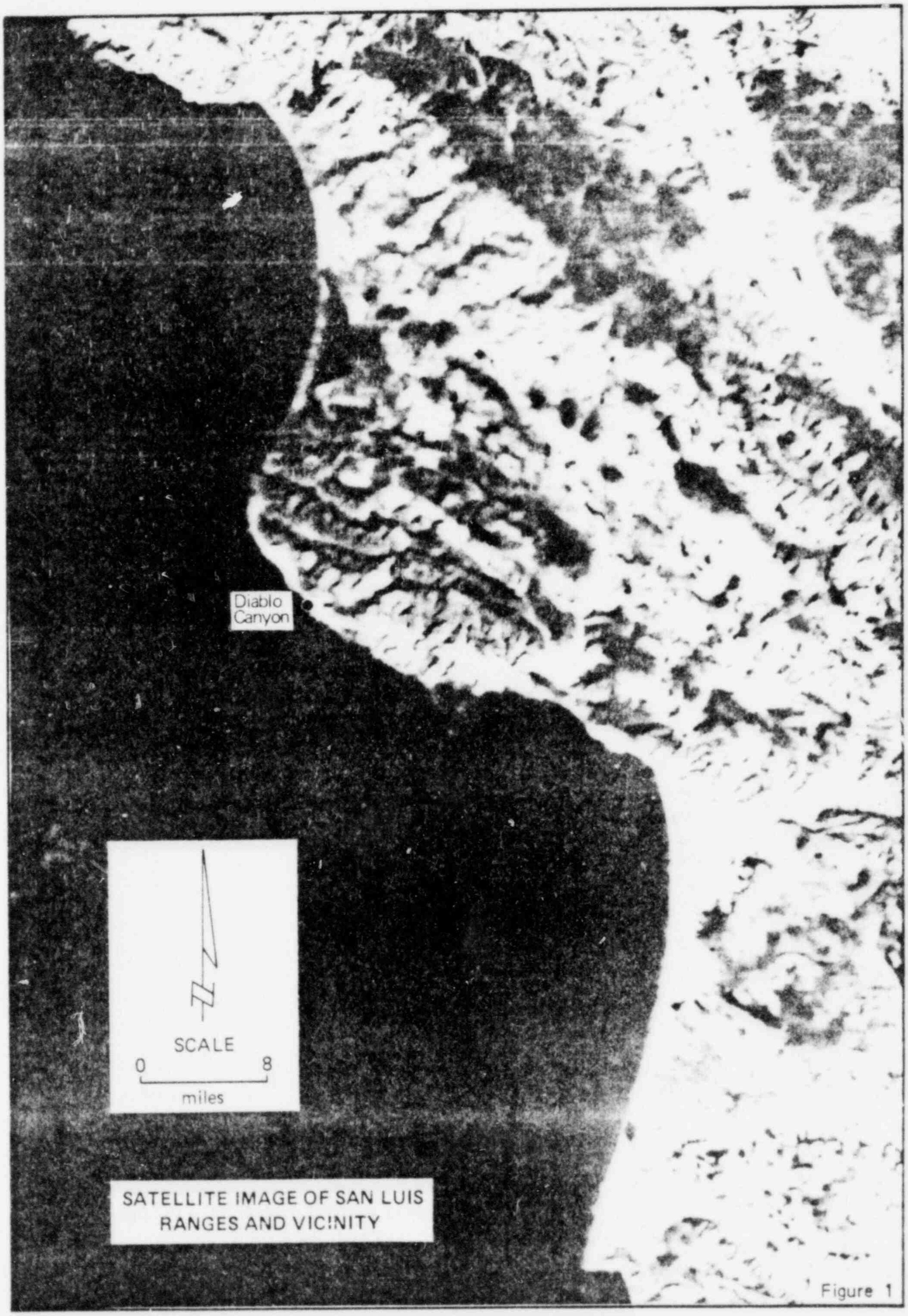
Volcanic - Descriptive term for rock formed by the ejection onto the earth's surface and subsequent solidification of molten or igneous material; also describes processes associated with volcanoes.

Volcanic Rocks - Rocks formed from material erupted from a volcano, which solidified on the surface.

Zeolite - A common secondary mineral, especially in volcanic rocks.

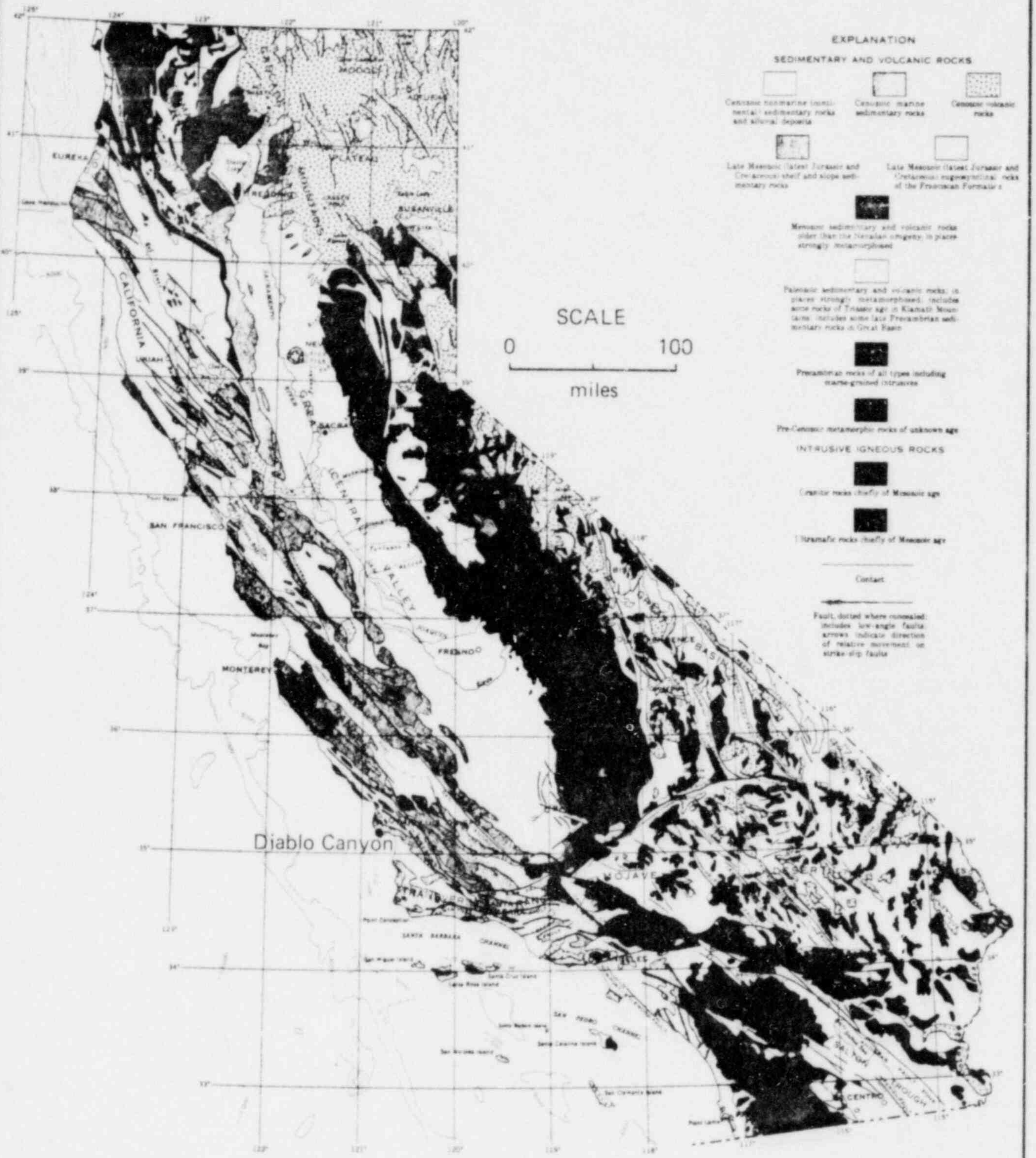
Zeolitization - The process by which an original mineral is changed into a zeolite mineral through chemical exchange and recrystallization.

ILLUSTRATIONS



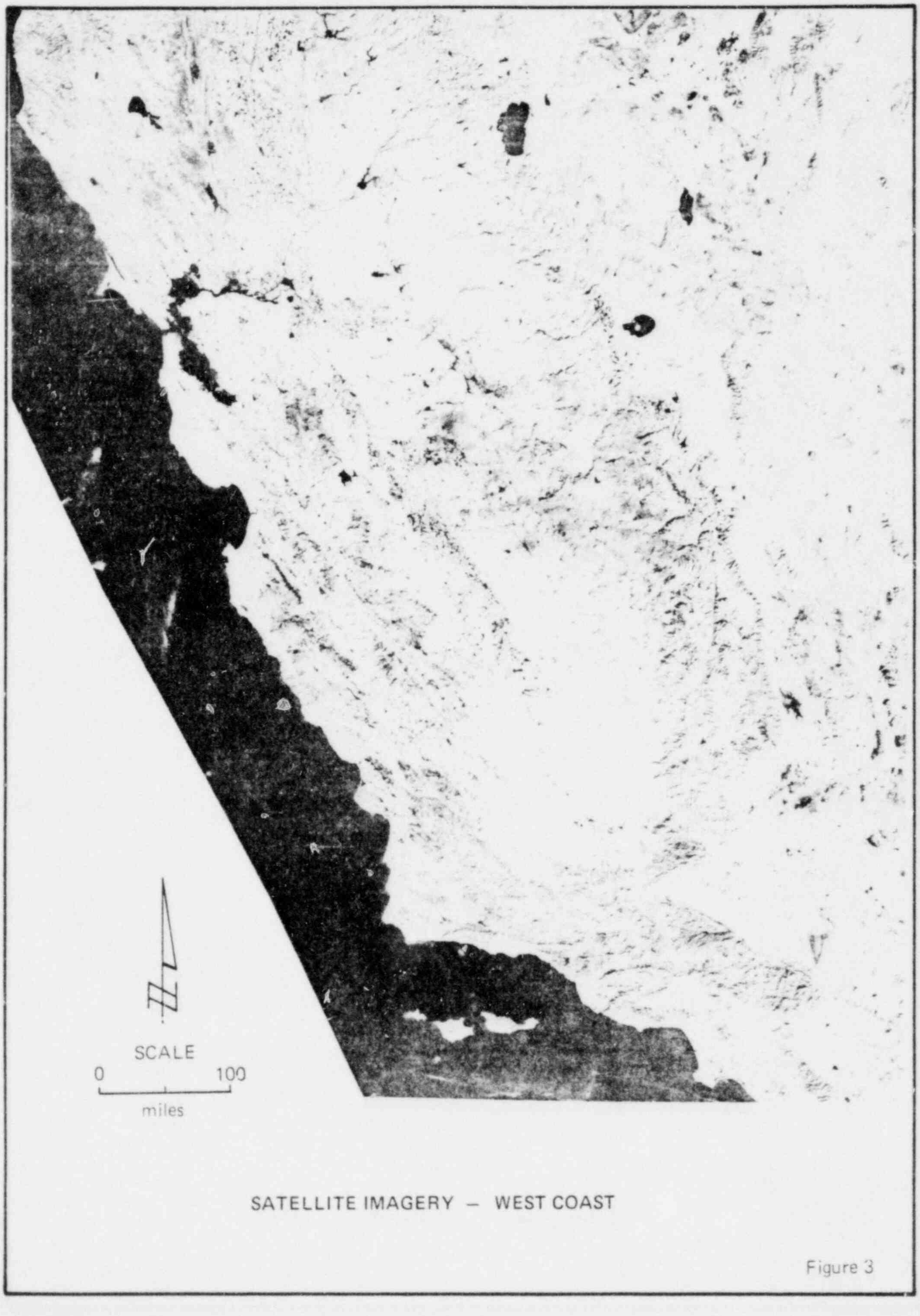
SATELLITE IMAGE OF SAN LUIS RANGES AND VICINITY

Figure 1



GENERALIZED GEOLOGIC MAP OF CALIFORNIA

Figure 2



SATELLITE IMAGERY – WEST COAST

Figure 3

B	Bakersfield	MZ	Mazatlan
CI	Cedros Island	N-IF	Newport-Inglewood Fault
G	Guaymas	Ph	Phoenix
GF	Garlock Fault	R	Reno
LA	Los Angeles	Rd	Redding
LV	Las Vegas	SB	Santa Barbara
M	Monterey	SCI	Santa Cruz Island
MB	Magdalena Bay	SD	San Diego
MD	Mojave Desert	SF	San Francisco

● Mesozoic granitic rocks ans assorted high temperature-low pressure metamorphic rocks

▨ Franciscan rocks; graywacke, shale, mafic volcanics ans serpentines metamorphosed to various high pressure-low temperature mineral assemblages

PLATE TECTONICS MAP: GULF OF CALIFORNIA TO CAPE MENDOCINO

Modified from Suppe, 1970.

Figure 4

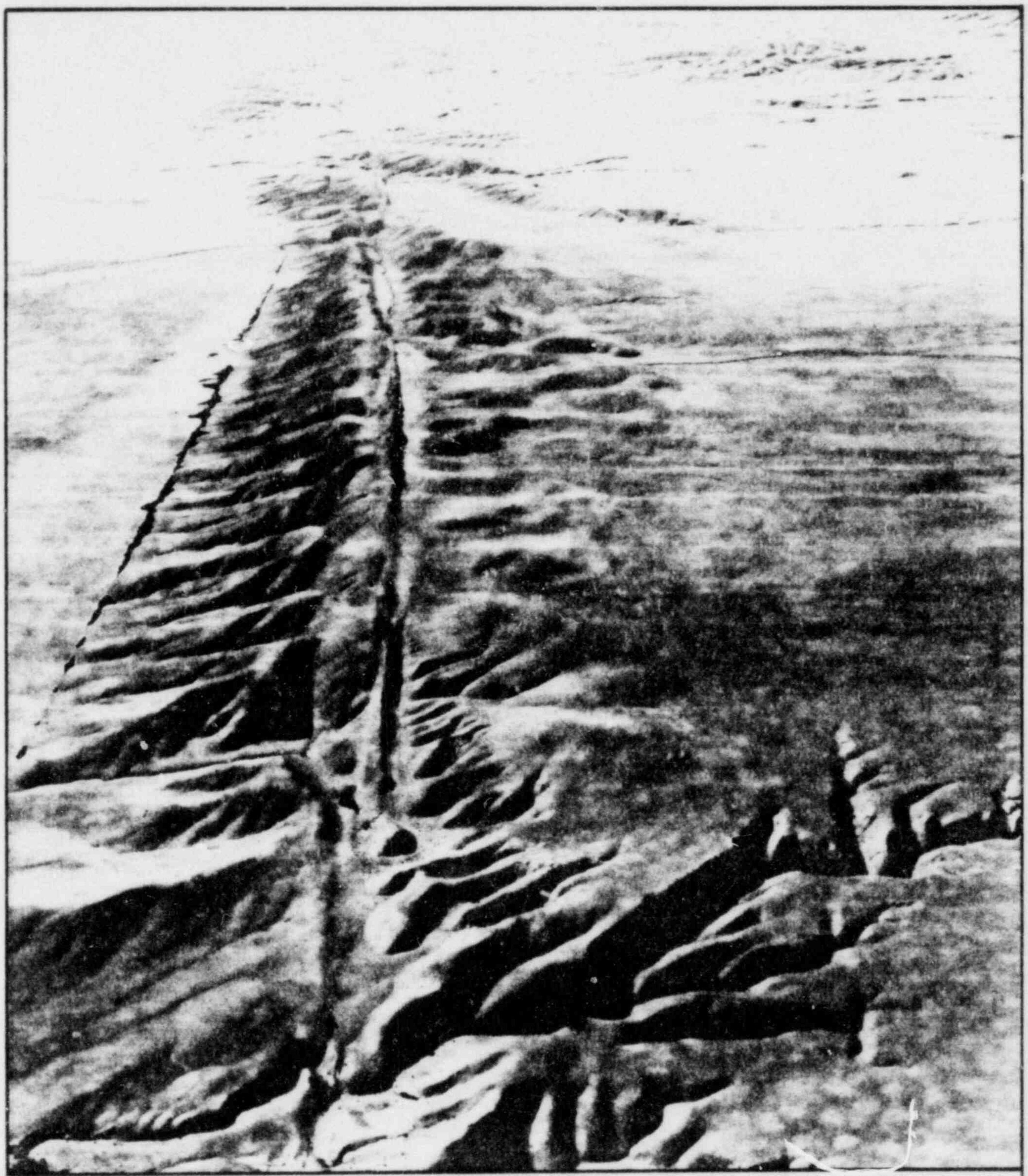
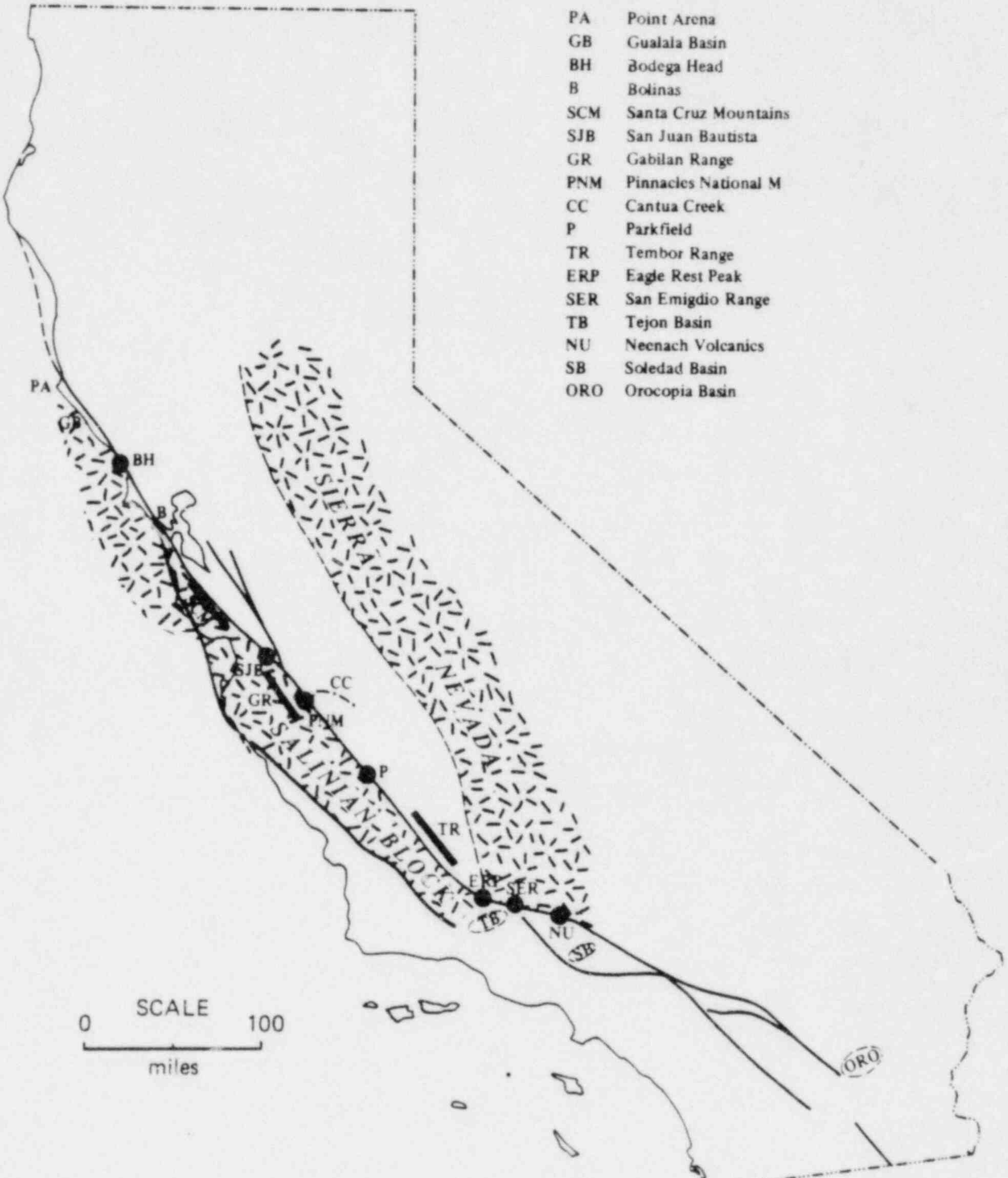


Photo by R. Wallace, USGS

OBLIQUE AERIAL PHOTOGRAPH OF SAN ANDREAS FAULT CROSSING CARRIZO PLAIN, VIEW LOOKING NORTH

Figure 5



SAN ANDREAS FAULT OFFSET POINTS

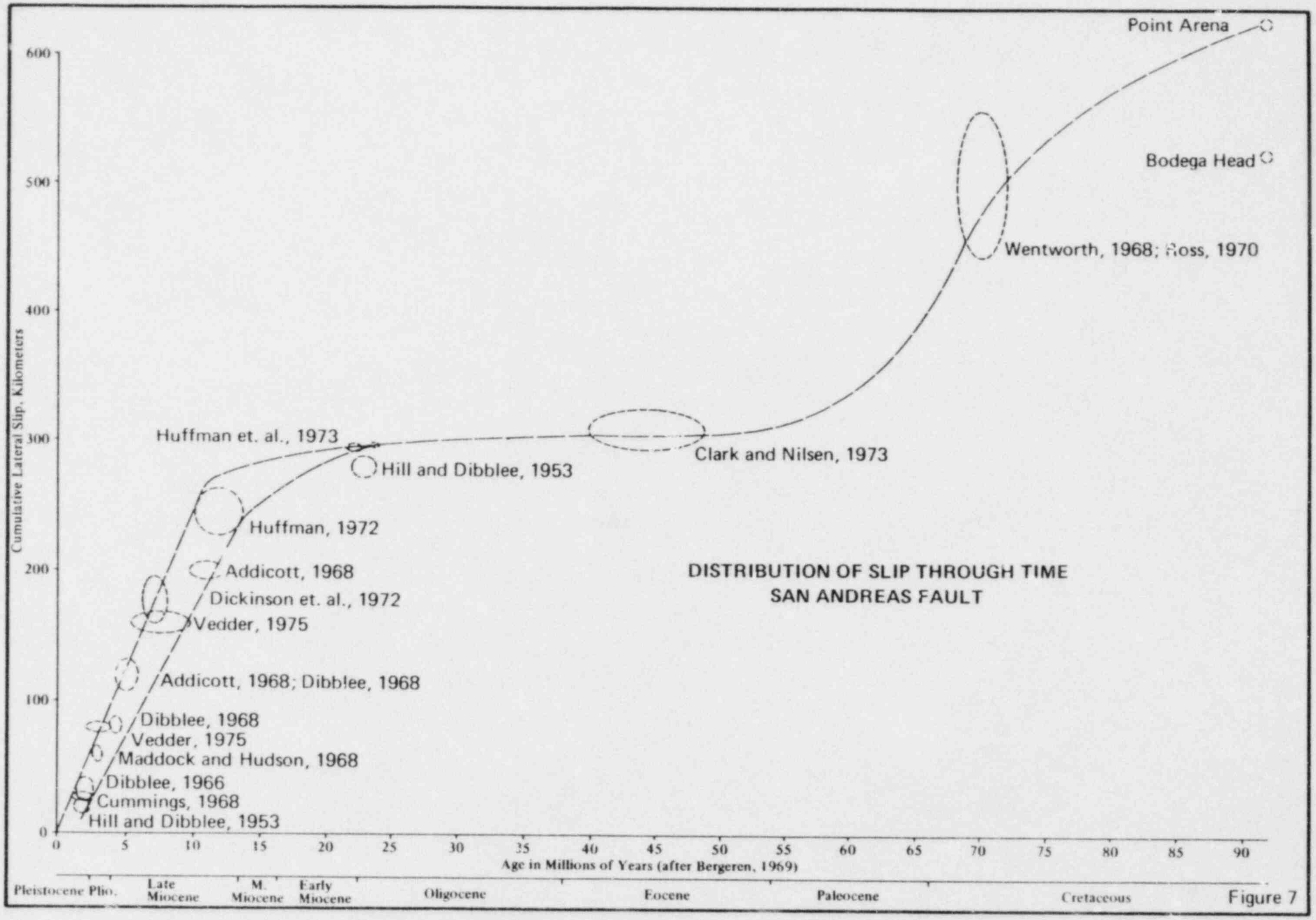
Modified from Graham, 1976.

Figure 6

TABLE FOR FIGURE 6
SAN ANDREAS FAULT OFFSET POINTS

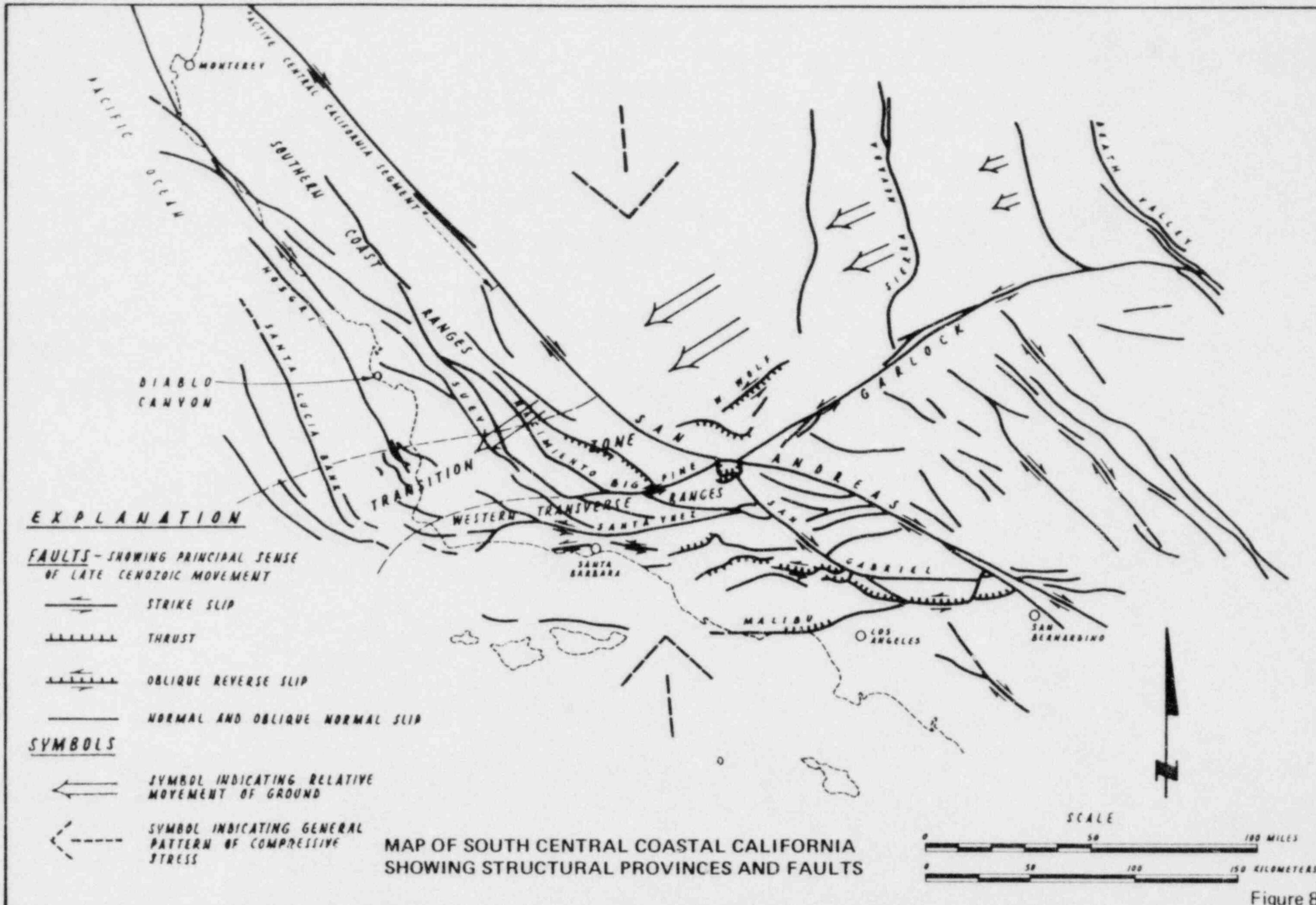
POINTS	AGE	OFFSET, km.
B-BH		70
P-PNM	MIOCENE	80
B-GB		120
TR-GR	POST UPPER MIOCENE	240
ORO-SB-TB	POST OLIGOCENE	260-305
SER-SJB	22 m.y.	280-305
NV-PNM	23.5 m.y.	298-314
TR-SCM	POST EOCENE	305-330
CC-GB	POST EARLY EOCENE	322
ERP-B	CRETACEOUS	450
ERP-GB	CRETACEOUS	435-565
ERP-BH	92 m.y.	525

PA	POINT ARENA
GB	GUALALA BASIN
BH	BODEGA HEAD
B	BOLINAS
SCM	SANTA CRUZ MOUNTAINS
SJB	SAN JUAN BAUTISTA
GR	GABILAN RANGE
PNM	PINNACLES NATIONAL MONUMENT
CC	CANTUA CREEK
P	PARKFIELD
TR	TEMBLOR RANGE
ERP	EAGLE REST PEAK
SER	SAN EMIGDIO RANGE
TB	TEJON BASIN
NU	NEENACH VOLCANICS
SB	SOLEDAD BASIN
ORO	OROCOPIA BASIN



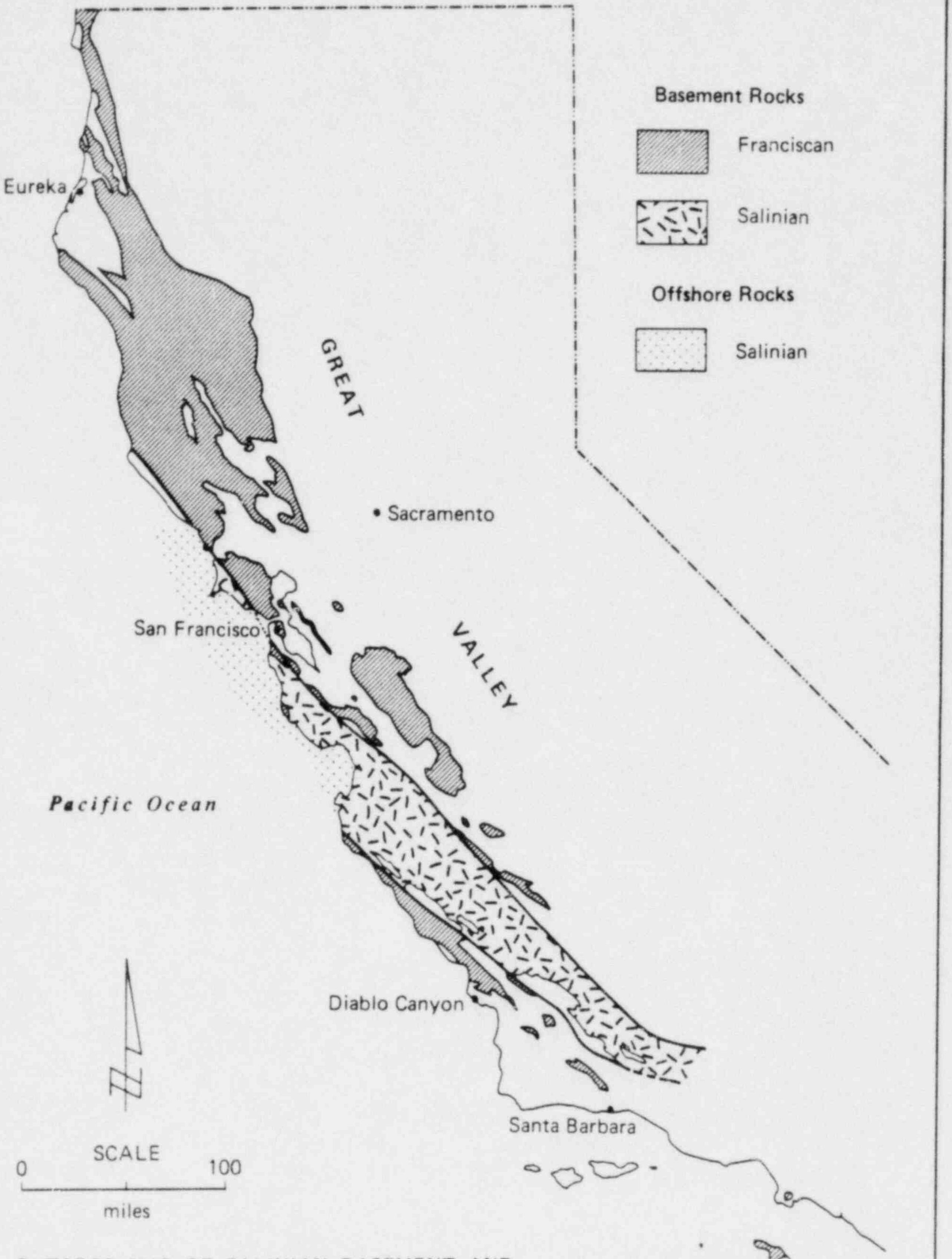
DISTRIBUTION OF SLIP THROUGH TIME
SAN ANDREAS FAULT

Figure 7



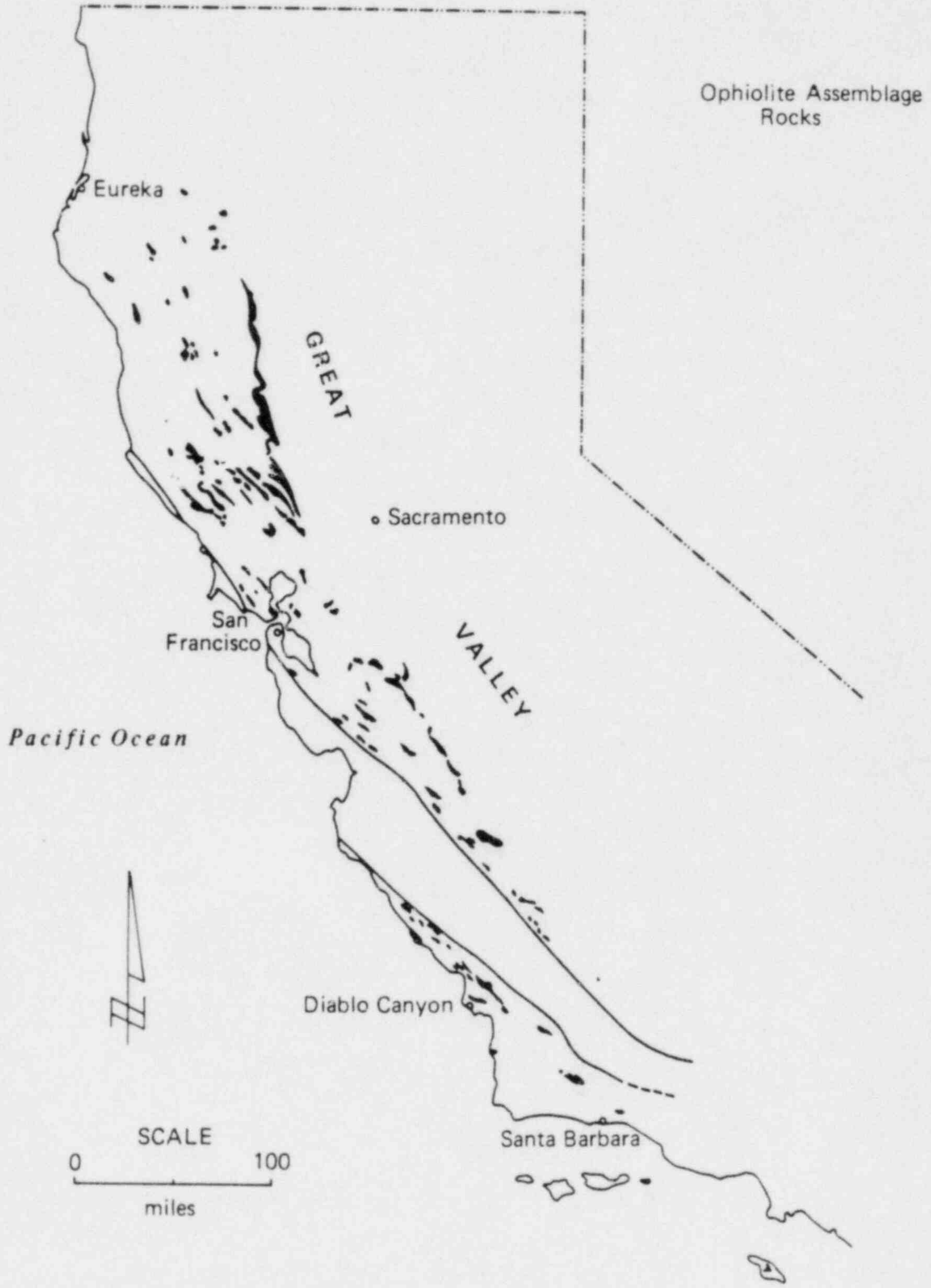
MAP OF SOUTH CENTRAL COASTAL CALIFORNIA
SHOWING STRUCTURAL PROVINCES AND FAULTS

Figure 8



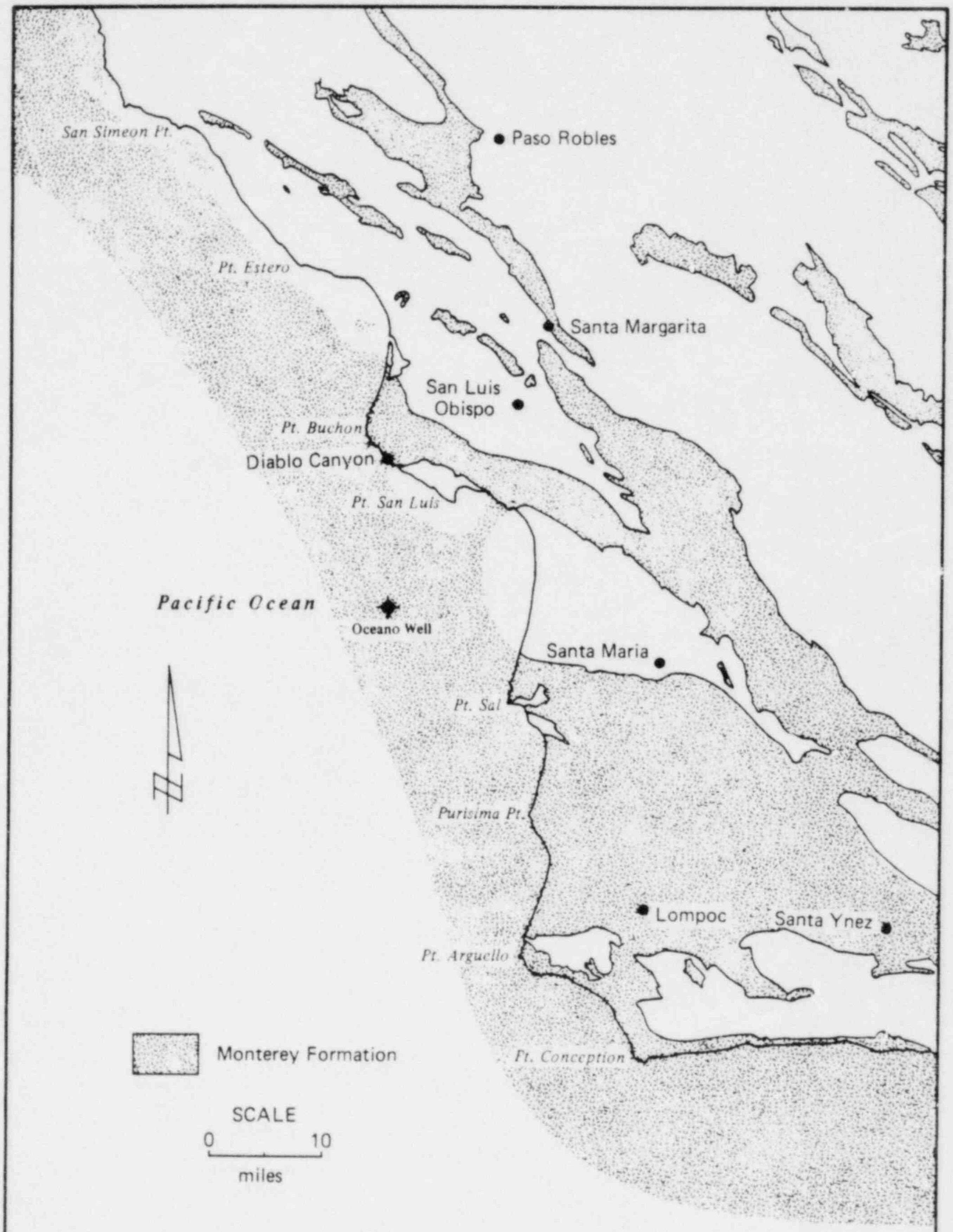
OUTCROP MAP OF SALINIAN BASEMENT AND FRANCISCAN BASEMENT ROCKS

Figure 9



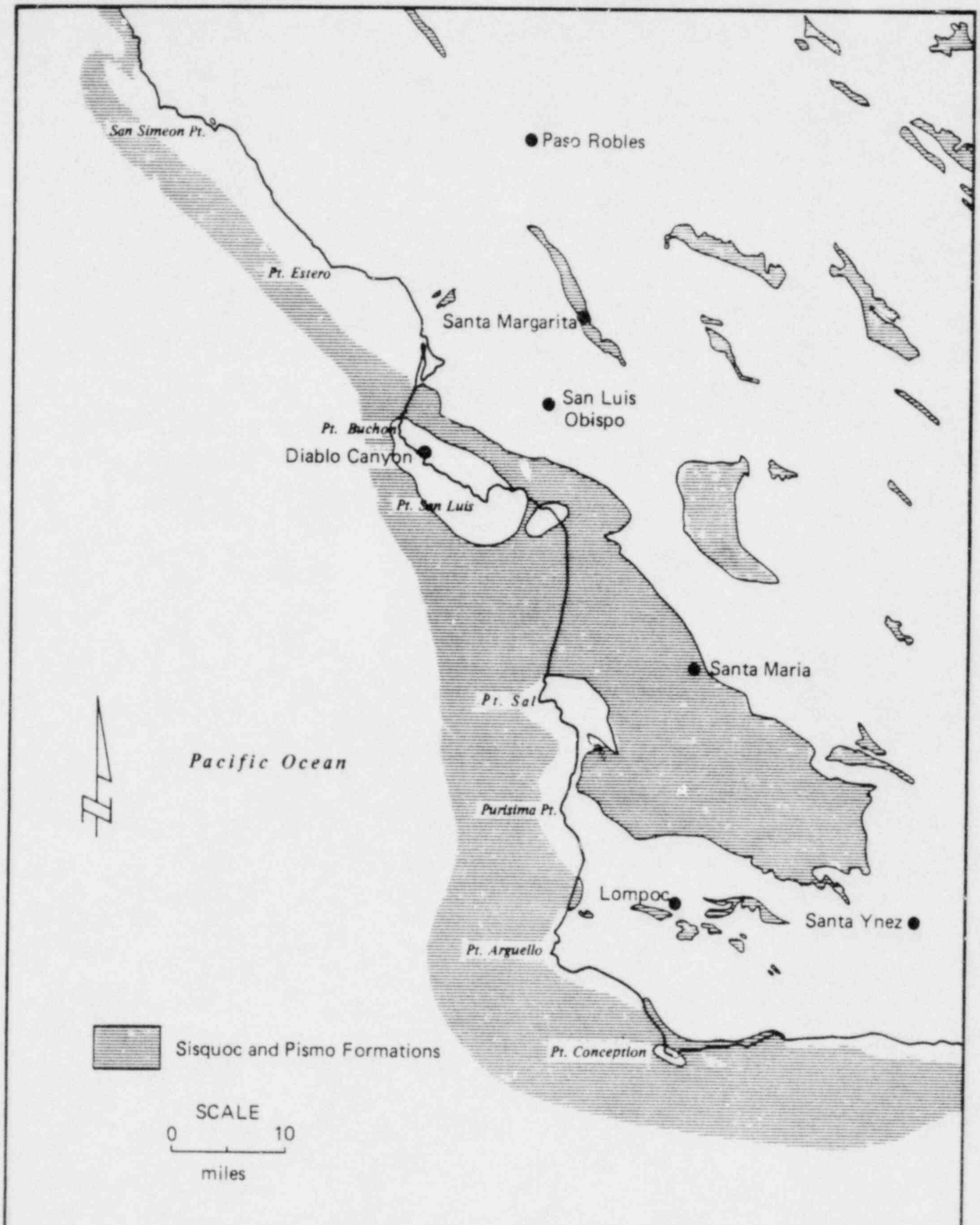
OUTCROP MAP OF OPHIOLITE ASSEMBLAGE ROCKS

Figure 10



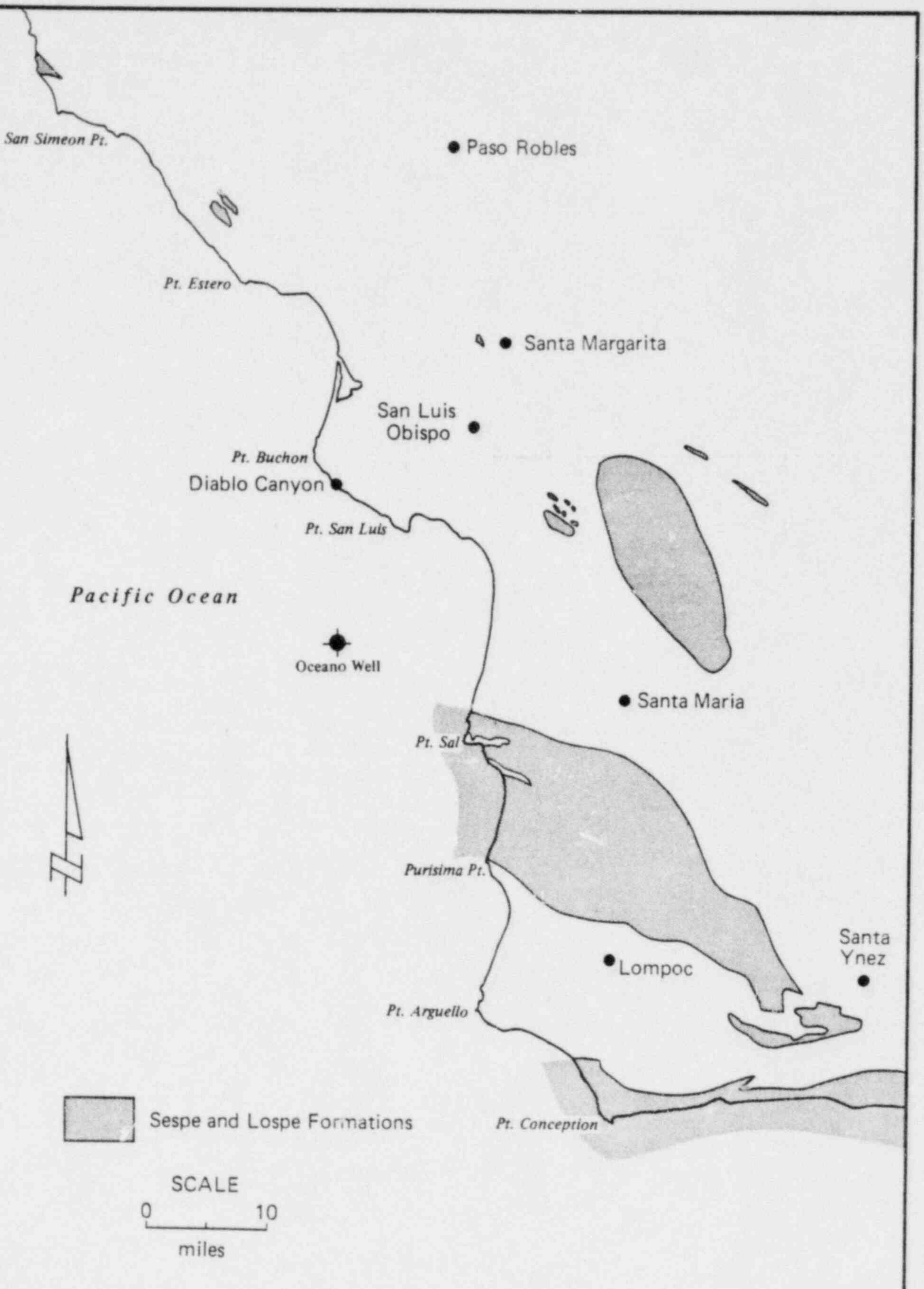
OUTCROP, SUBSURFACE AND OFFSHORE DISTRIBUTION OF MONTEREY FORMATION

Figure 11



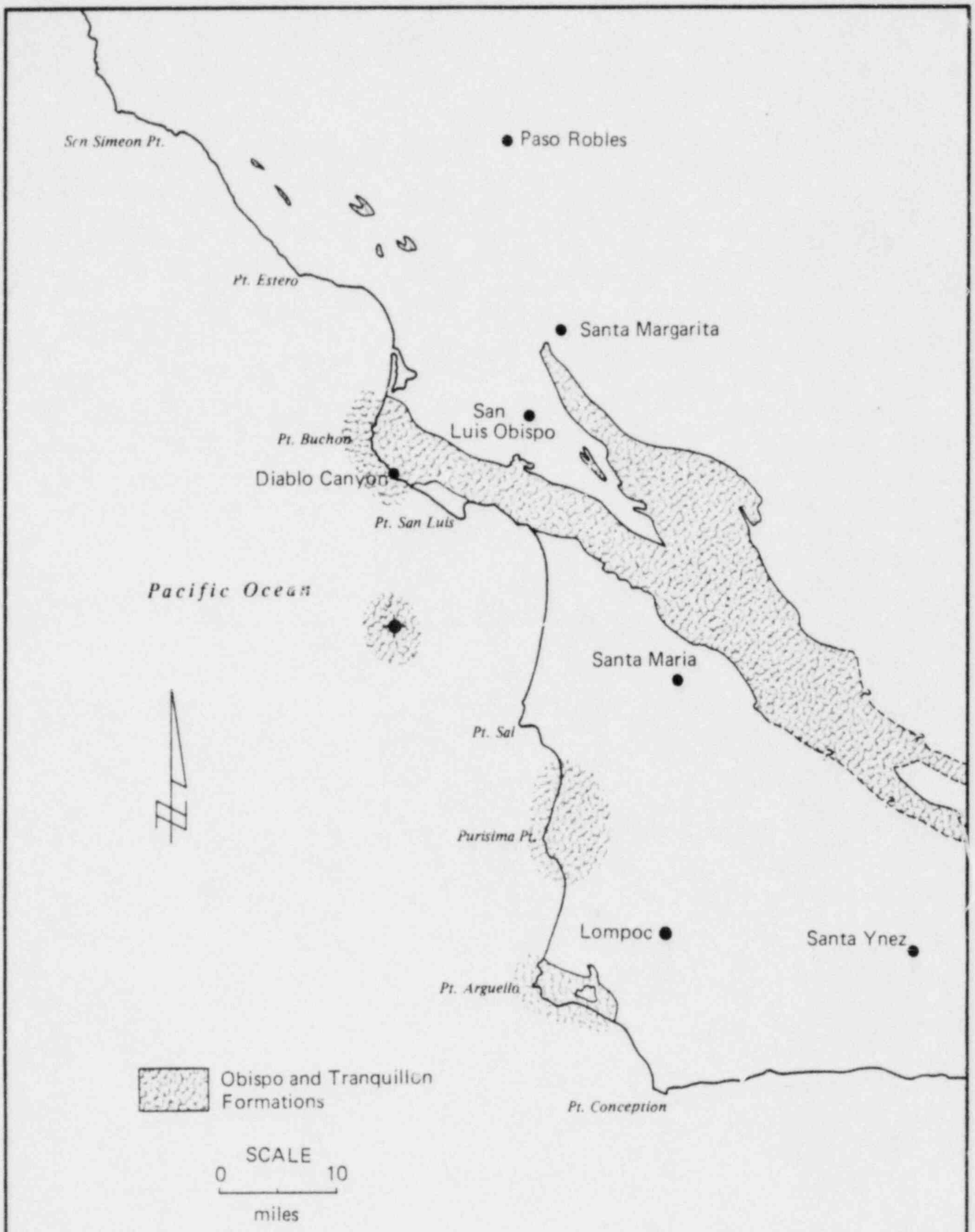
OUTCROP, SUBSURFACE AND OFFSHORE DISTRIBUTIONS
SISQUOC AND PISMO FORMATIONS

Figure 12



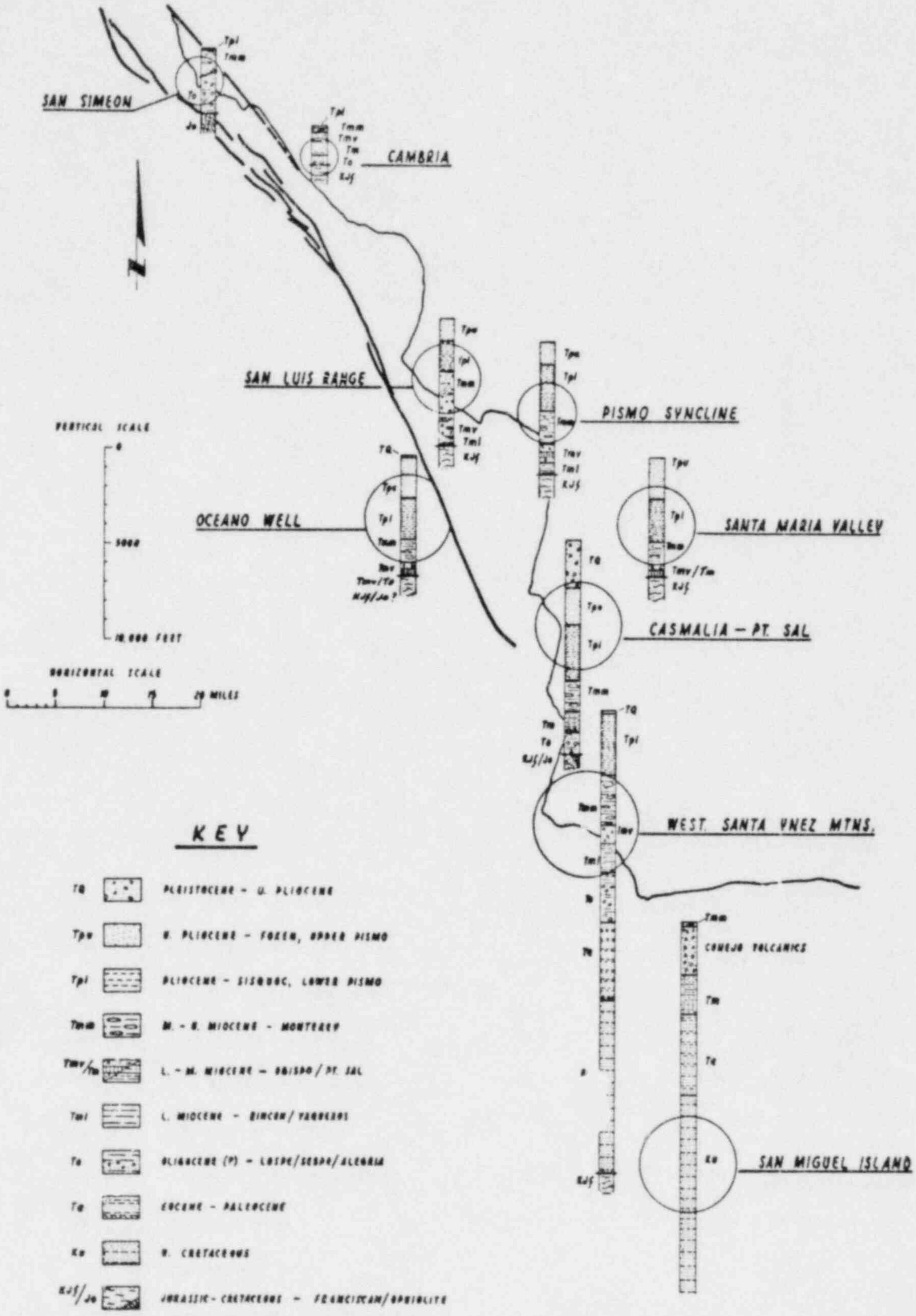
OUTCROP, SUBSURFACE AND OFFSHORE DISTRIBUTIONS OF SESPE AND LOSPE FORMATIONS

Figure 13



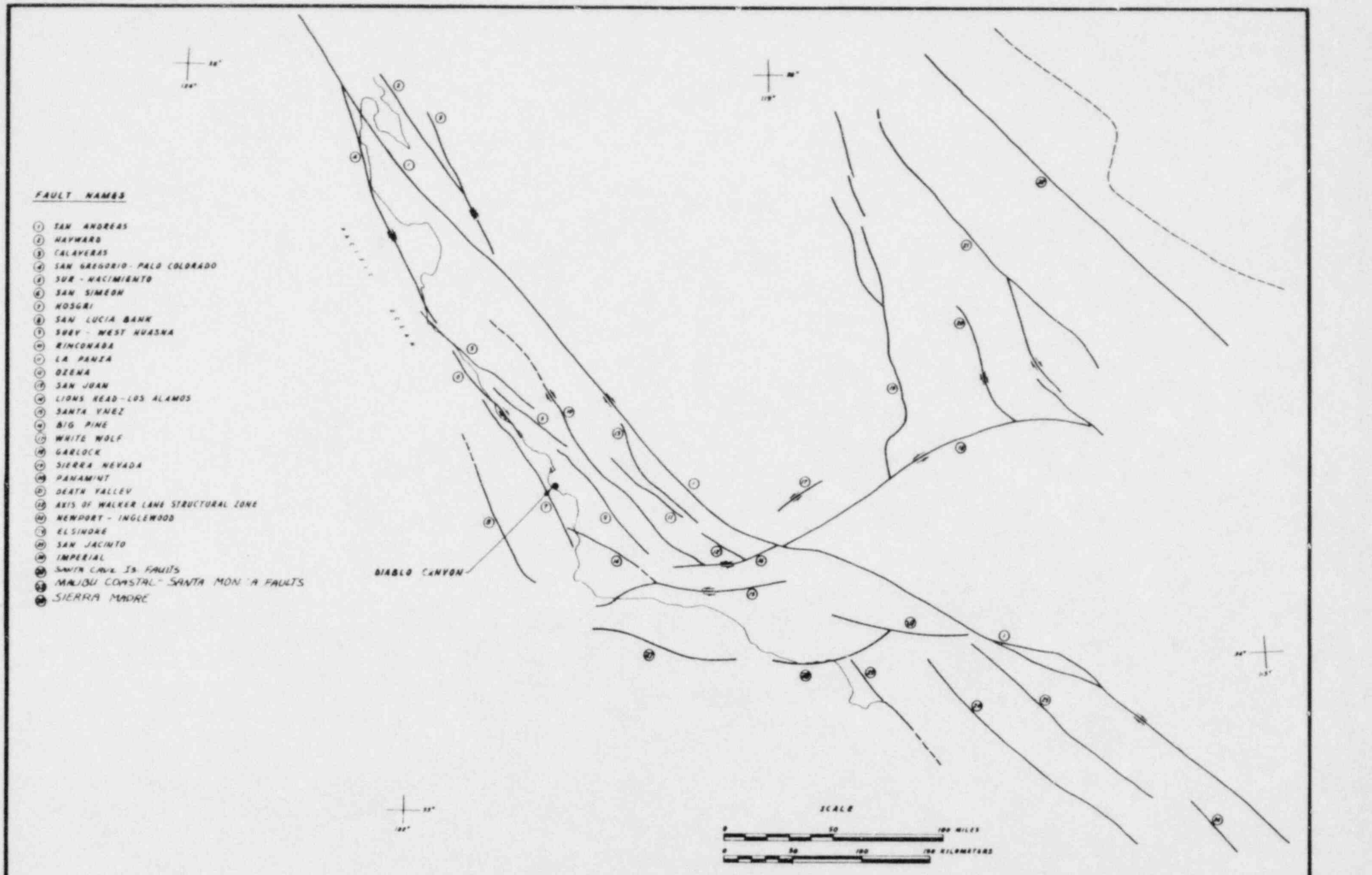
OUTCROP, SUBSURFACE AND OFFSHORE DISTRIBUTION OF OBISPO AND TRANQUILLON FORMATIONS

Figure 14



MAP OF SOUTH CENTRAL COASTAL CALIFORNIA SHOWING SPOT STRATIGRAPHIC SECTIONS

Figure 15



MAJOR FAULTS: SOUTH CENTRAL AND SOUTHERN CALIFORNIA

Figure 16

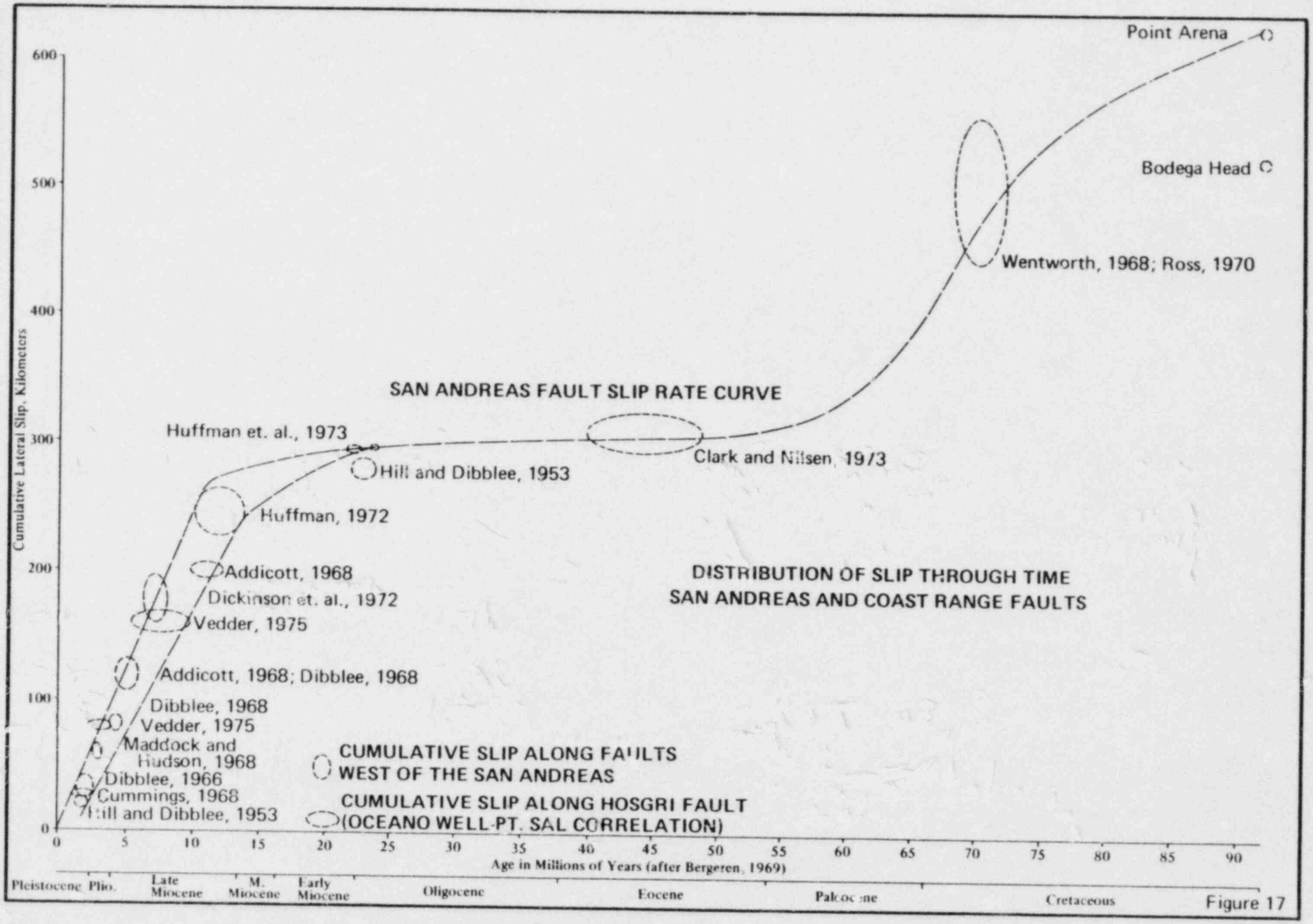
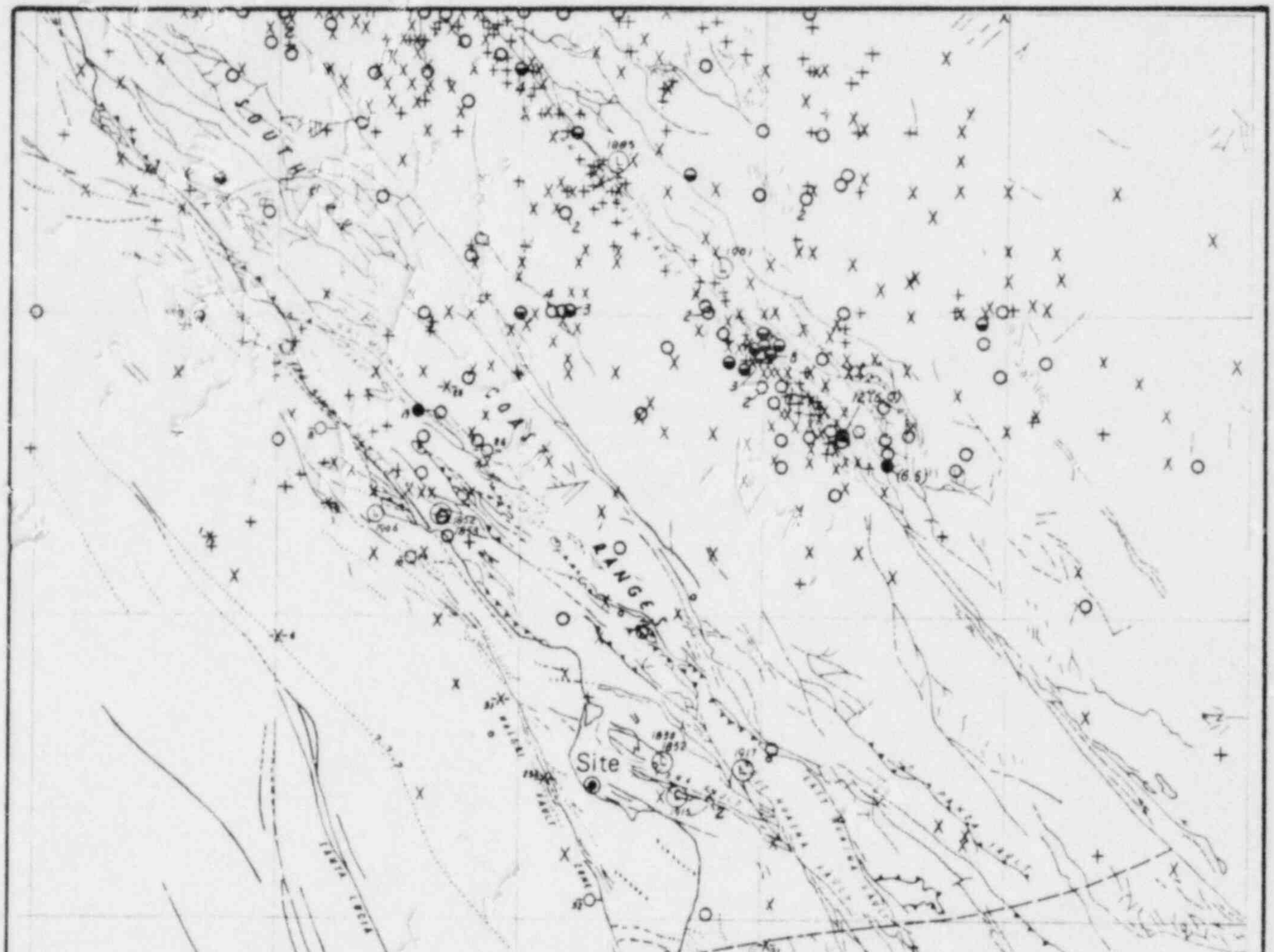

SAN ANDREAS FAULT SLIP RATE CURVE
DISTRIBUTION OF SLIP THROUGH TIME
SAN ANDREAS AND COAST RANGE FAULTS
Point Arena
Bodega Head
Wentworth, 1968; Ross, 1970
Clark and Nilsen, 1973
Huffman et. al., 1973
Hill and Dibblee, 1953
Huffman, 1972
Addicott, 1968
Dickinson et. al., 1972
Vedder, 1975
Addicott, 1968; Dibblee, 1968
Dibblee, 1968
Vedder, 1975
Maddock and Hudson, 1968
Dibblee, 1966
Cummings, 1968
Hill and Dibblee, 1953
CUMULATIVE SLIP ALONG FAULTS WEST OF THE SAN ANDREAS
CUMULATIVE SLIP ALONG HOSGRI FAULT (OCEANO WELL-PT. SAL CORRELATION)
Cumulative Lateral Slip, Kilometers
0
100
200
300
400
500
600
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
Age in Millions of Years (after Bergeren, 1969)
Pleistocene
Plio.
Late Miocene
M. Miocene
Early Miocene
Oligocene
Eocene
Paleocene
Cretaceous

Figure 17



EPICENTER MAP OF WEST-CENTRAL CALIFORNIA

Figure 18

EXPLANATION FOR FIGURE 18
EPICENTER MAP OF WEST-CENTRAL CALIFORNIA

INSTRUMENTALLY LOCATED AND LARGER HISTORICALLY REPORTED EARTHQUAKE EPICENTERS WITHIN 75 MILES OF THE DIABLO CANYON POWER PLANT SITE, 1800 - 1972

SYMBOL	MAGNITUDE	
■	7.9 ≥ M ≥ 7.0	MAGNITUDE AND DATE LISTED.
●	6.9 ≥ M ≥ 6.0	
◒	5.9 ≥ M ≥ 5.0	
○	4.9 ≥ M ≥ 4.0	
X	3.9 ≥ M ≥ 3.0	
+	2.9 ≥ M ≥ 2.0	

(FIGURE ○^{2} INDICATES NUMBER OF EPICENTERS RECORDED AT SAME LOCATION.)

SOURCES FOR FAULT AND EARTHQUAKE EPICENTER DATA ARE AS FOLLOWS:

1. FAULT DATA FROM JENNINGS, C. W., 1972, GEOLOGIC MAP OF CALIFORNIA, SOUTH HALF. (PRELIMINARY)
2. FOR EARTHQUAKES OF ≥ 4.0 MAGNITUDE OCCURRING DURING THE TIME INTERVAL 1934 THRU JUNE 30, 1971: CALIFORNIA DIVISION OF MINES AND GEOLOGY PROVISIONAL EARTHQUAKE EPICENTER MAP, SCALE 1:1,000,000, 1972
3. FOR EARTHQUAKES OF ≥ 2.0 MAGNITUDE OCCURRING DURING THE TIME INTERVAL 1932 THRU 1971; BUT NOT INCLUDING EARTHQUAKES GIVEN ONLY AN INTENSITY RATING: SEISMOGRAPHIC STATION BERKELEY (UNIVERSITY OF CALIFORNIA, BERKELEY).
4. FOR LARGE EARTHQUAKES OCCURRING DURING THE TIME INTERVAL 1800 THROUGH 1931, TO WHICH ESTIMATED MAGNITUDE RATINGS HAVE BEEN ASSIGNED: CALIFORNIA DIVISION OF MINES AND GEOLOGY, PROVISIONAL EARTHQUAKE EPICENTER MAP. SCALE 1:1,000,000, 1972.
5. FOR EARTHQUAKES OF ≥ 3.0 MAGNITUDE OCCURRING DURING THE TIME INTERVAL JUNE 30 THRU DEC. 31, 1972; SEISMOLOGICAL LABORATORY OF PASADENA. (CALIFORNIA INSTITUTE OF TECHNOLOGY).

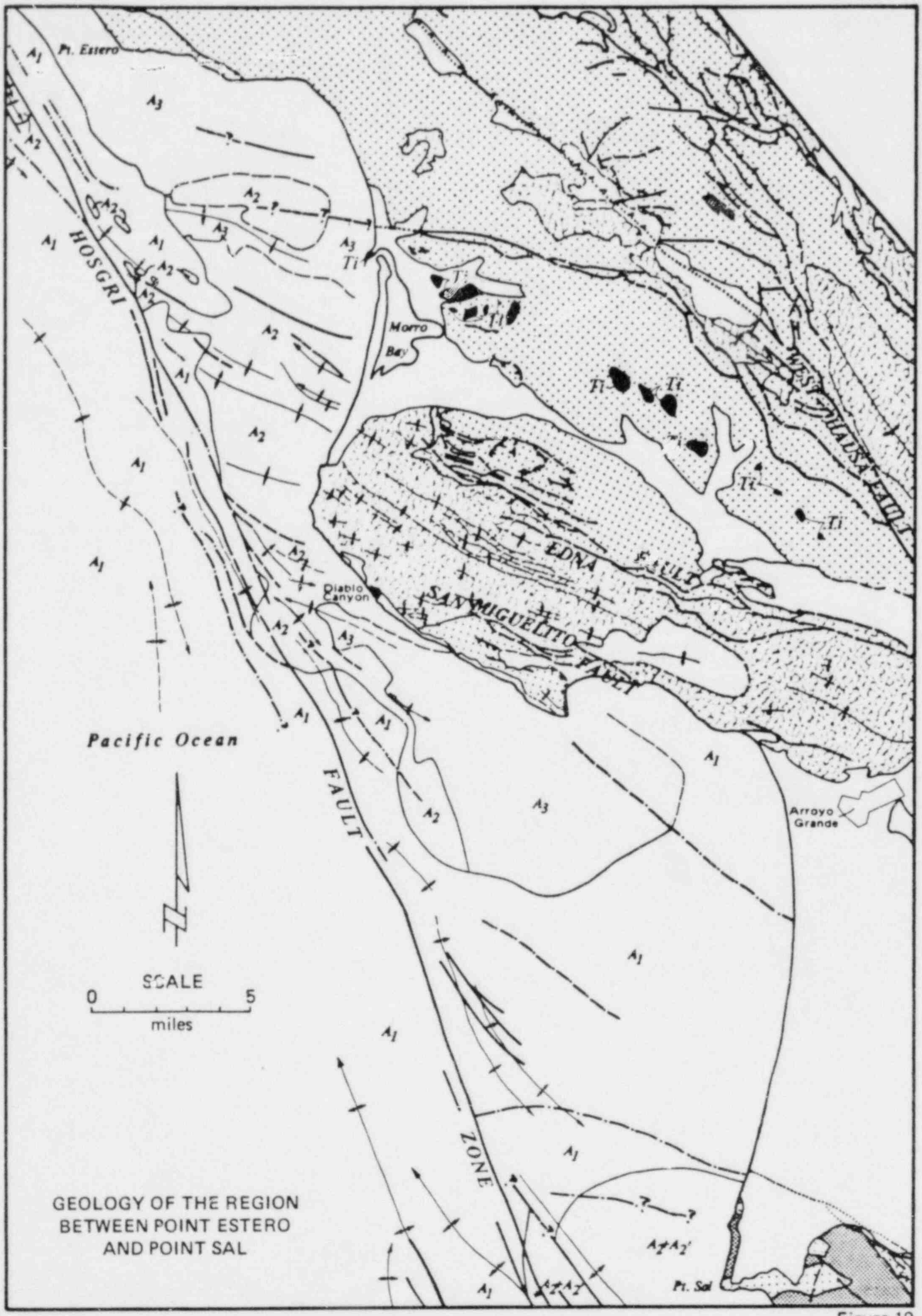
NOTES FOR REVISED FAULT AND EPICENTER DATA

A. FAULT DATA REVISED IN ACCORDANCE WITH NOTE 6, FIGURE 5 (DIABLO FSAR)

B. EPICENTERS OF 19 SELECTED EARTHQUAKES, RECOMPUTED BY S. W. SMITH (1974). EPICENTER - MAGNITUDE SYMBOL OF THESE EVENTS IS INDICATED BY HORIZONTAL DASHES (${}_6$X-, -○$_{26}$) NUMBER SUBSCRIPT INDICATES EVENT NUMBER

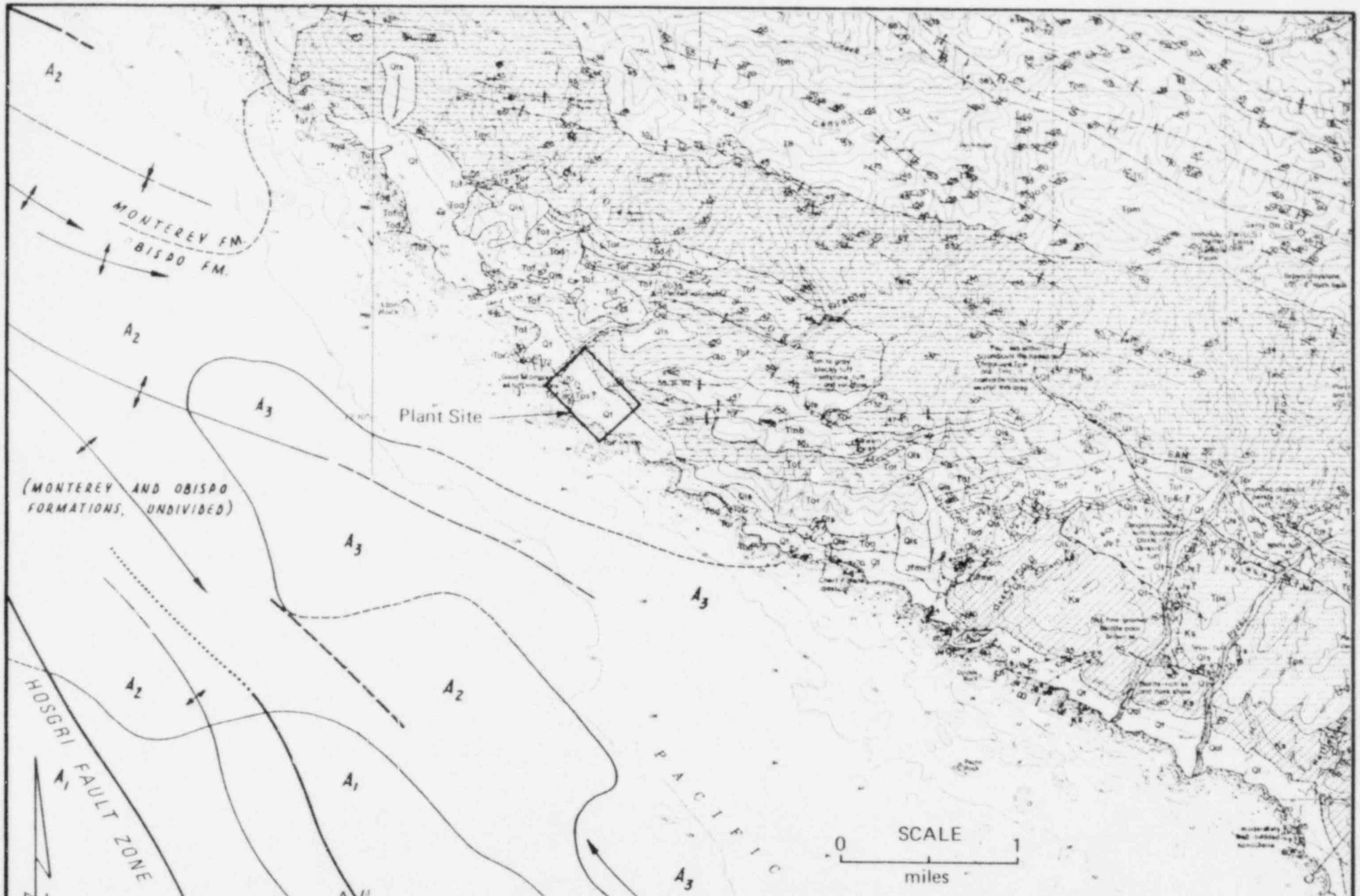
C. •- EPICENTERS (MAGNITUDE 0.4 - 2.0) RECORDED AND LOCATED BY WILLIAM GAWTHROP, (1973). AS DESCRIBED IN "PRELIMARY REPORT ON A SHORT TERM SEISMIC STUDY OF THE SAN LUIS OBISPO REGION IN MAY, 1973."

D. Ⓛ$_{1915}$ APPROXIMATE EPICENTER FOR HISTORICALLY REPORTED EARTHQUAKE OF ≥ MM VII INTENSITY



GEOLOGY OF THE REGION BETWEEN POINT ESTERO AND POINT SAL

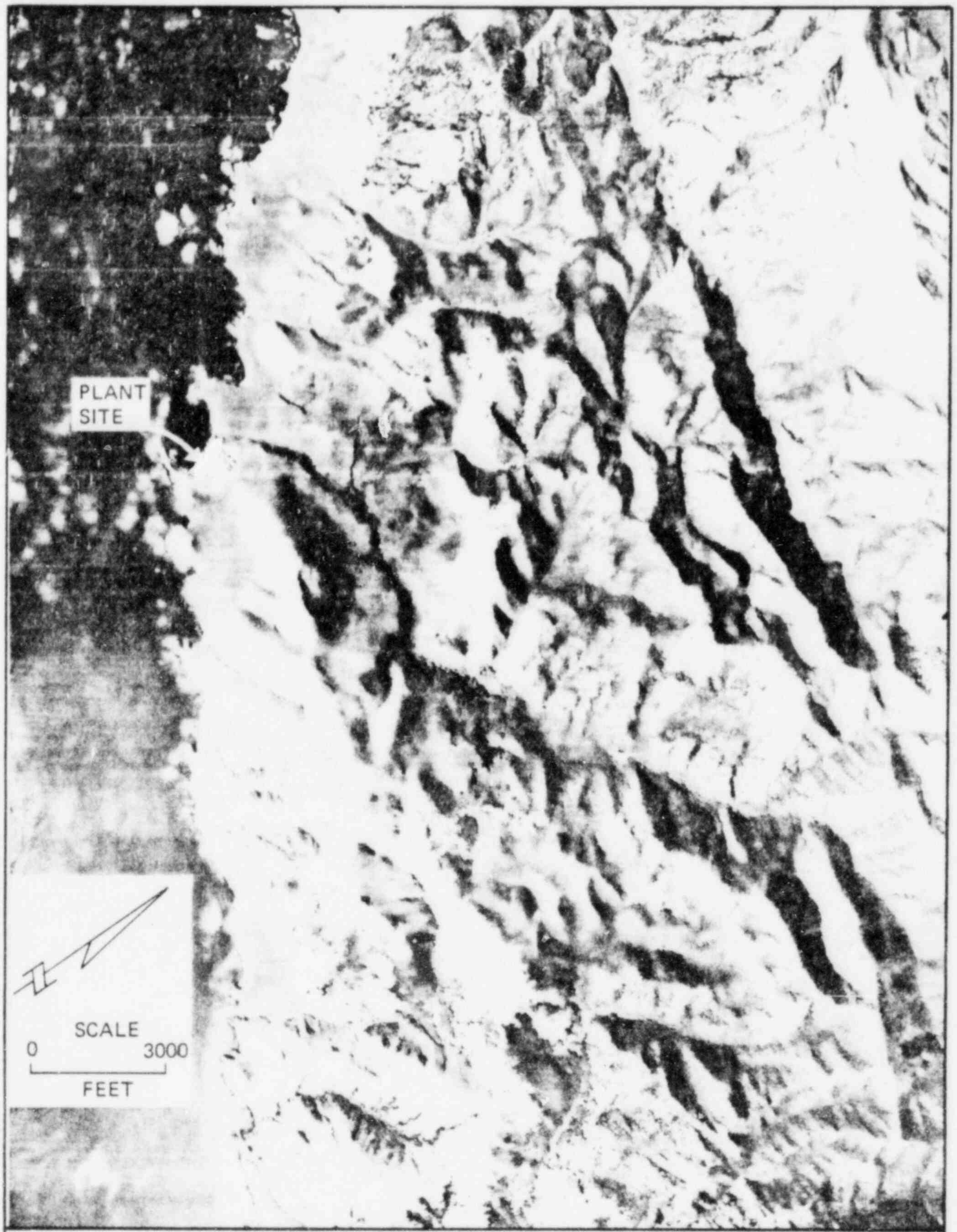
Figure 19



GEOLOGY OF THE SAN LUIS RANGE AND ADJACENT OFFSHORE AREA IN THE VICINITY OF THE DIABLO CANYON SITE

Onshore Geology, C.A. Hall (1973)
Offshore Geology, ESA (1974)

Figure 20

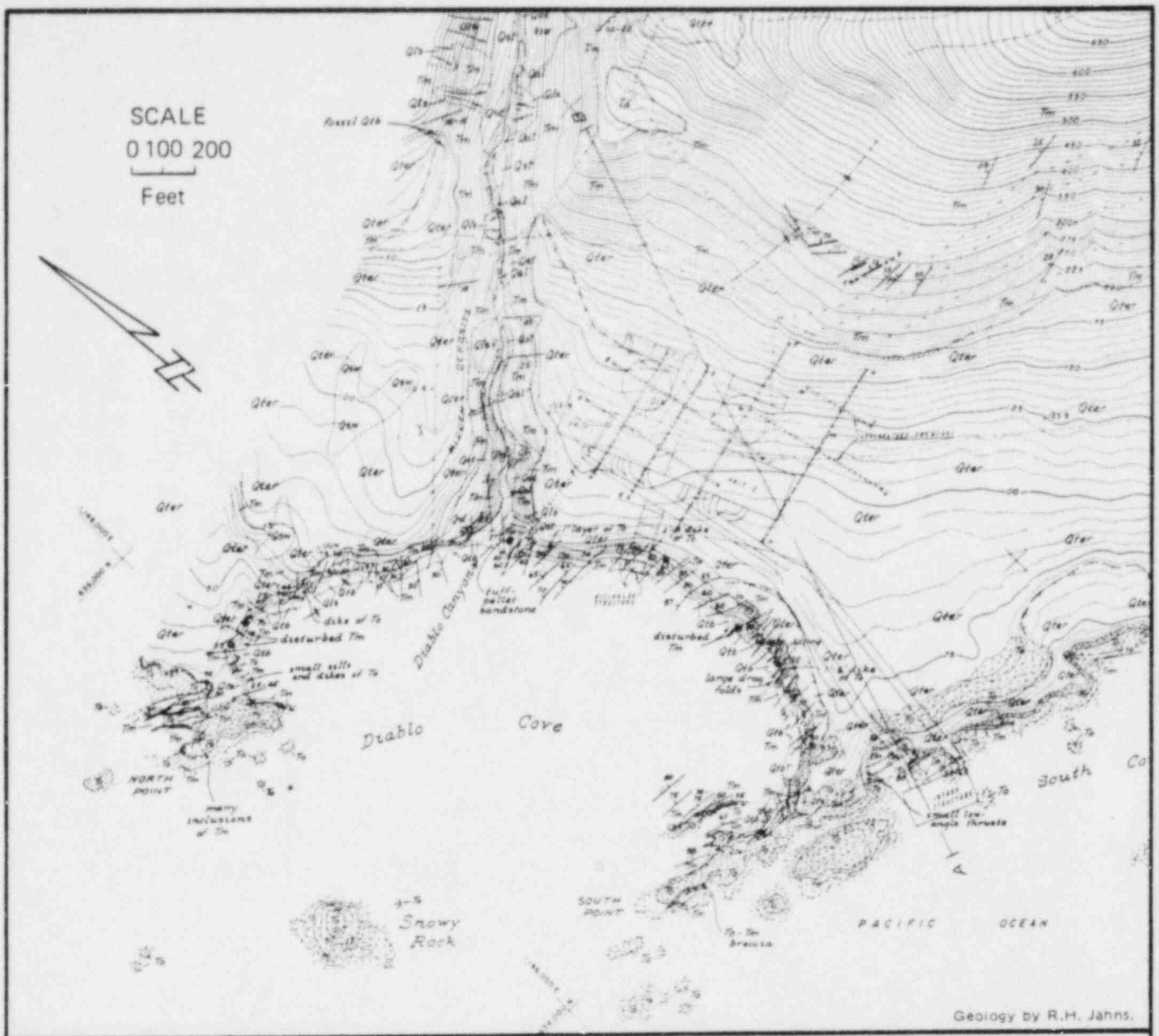


VERTICAL AERIAL PHOTOGRAPH OF THE SAN LUIS RANGE IN THE VICINITY OF THE DIABLO CANYON SITE

Figure 21

Figure 22

OBLIQUE AERIAL PHOTOGRAPH OF DIABLO CANYON SITE, LOOKING NORTHWEST



EXPLANATION

Pleistocene – Recent	Qal	Stream-laid alluvium
	Qtb	Talus and beach deposits
	Qsw	Slump, creep, and slope-wash deposits
	Qls	Landslide deposits
	Qst	Stream-terrace deposits
	Qf	Alluvial-fan deposits
	Qft	Older fan-terrace deposits
	Qter	Deposits on marine wave-cut terraces
	Qlb	Lake-bottom (?) deposits
Miocene	Td	Diabasic intrusive rock
	Tm	Monterey Formation
	To	Obispo tuff

Contact involving surficial deposits

Contact between bedrock units } dashed where approximately located, dotted where concealed by Qter.

Fault, showing dip

Strike and dip of beds

Strike and dip of overturned beds

Highly contorted beds

Axis of syncline

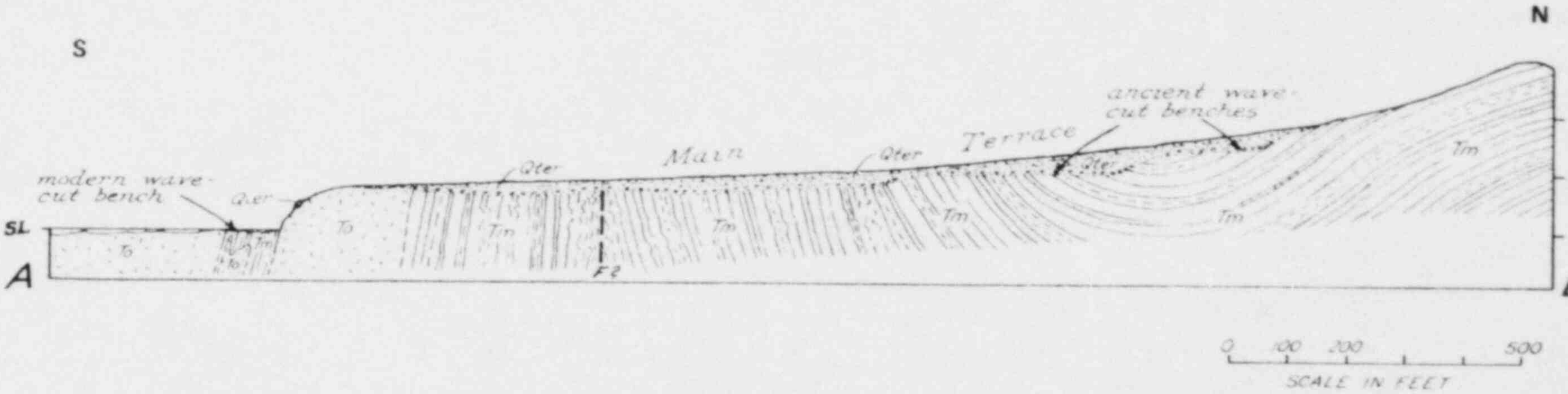
Boundary between different generations of Qter

Trend and range in dip of beds folded or warped as on a small scale

Surface trace of resistant horizon in Tm

SITE GEOLOGY MAP

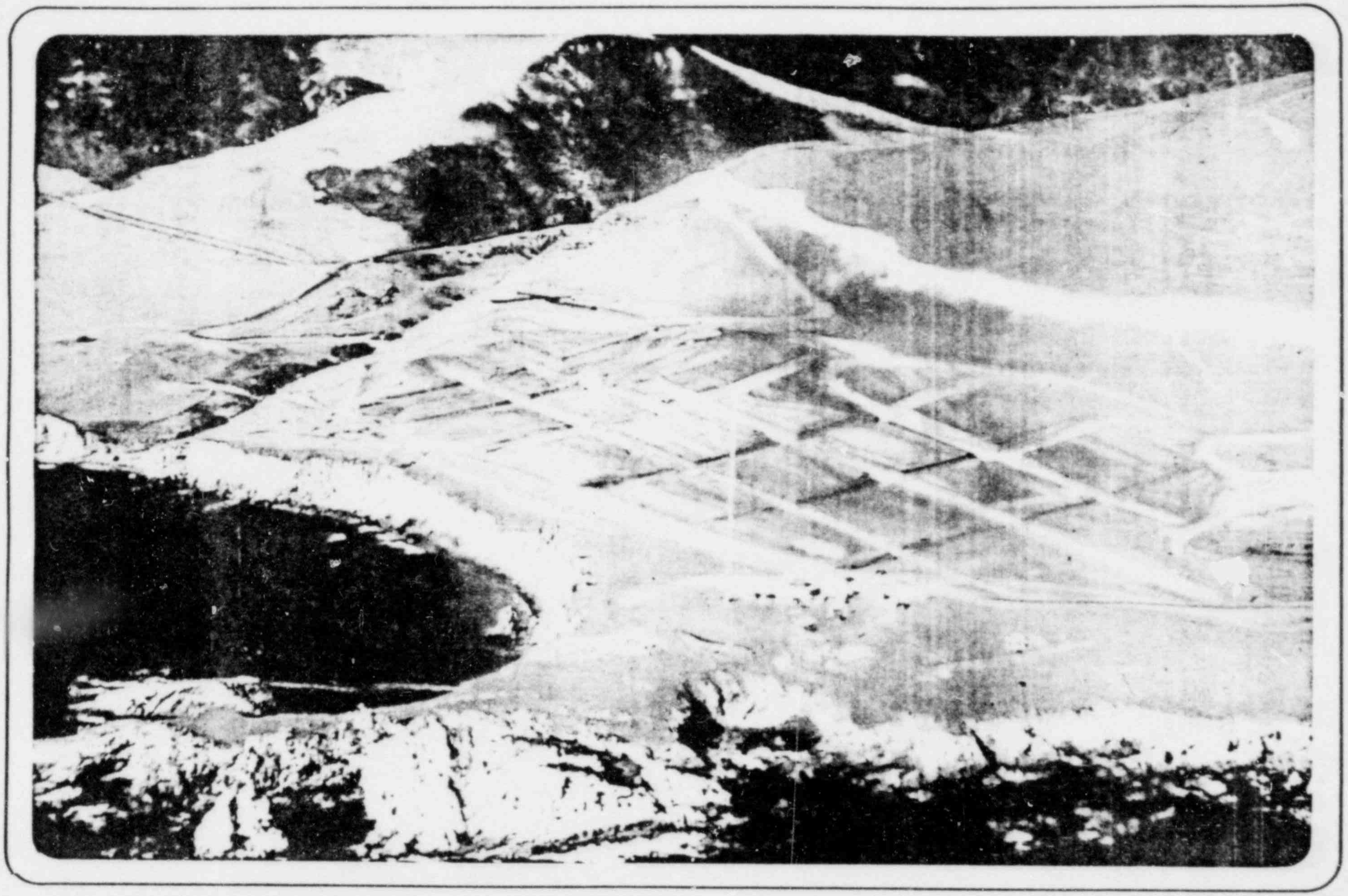
Figure 23



GEOLOGIC SECTION ALONG LINE A-B

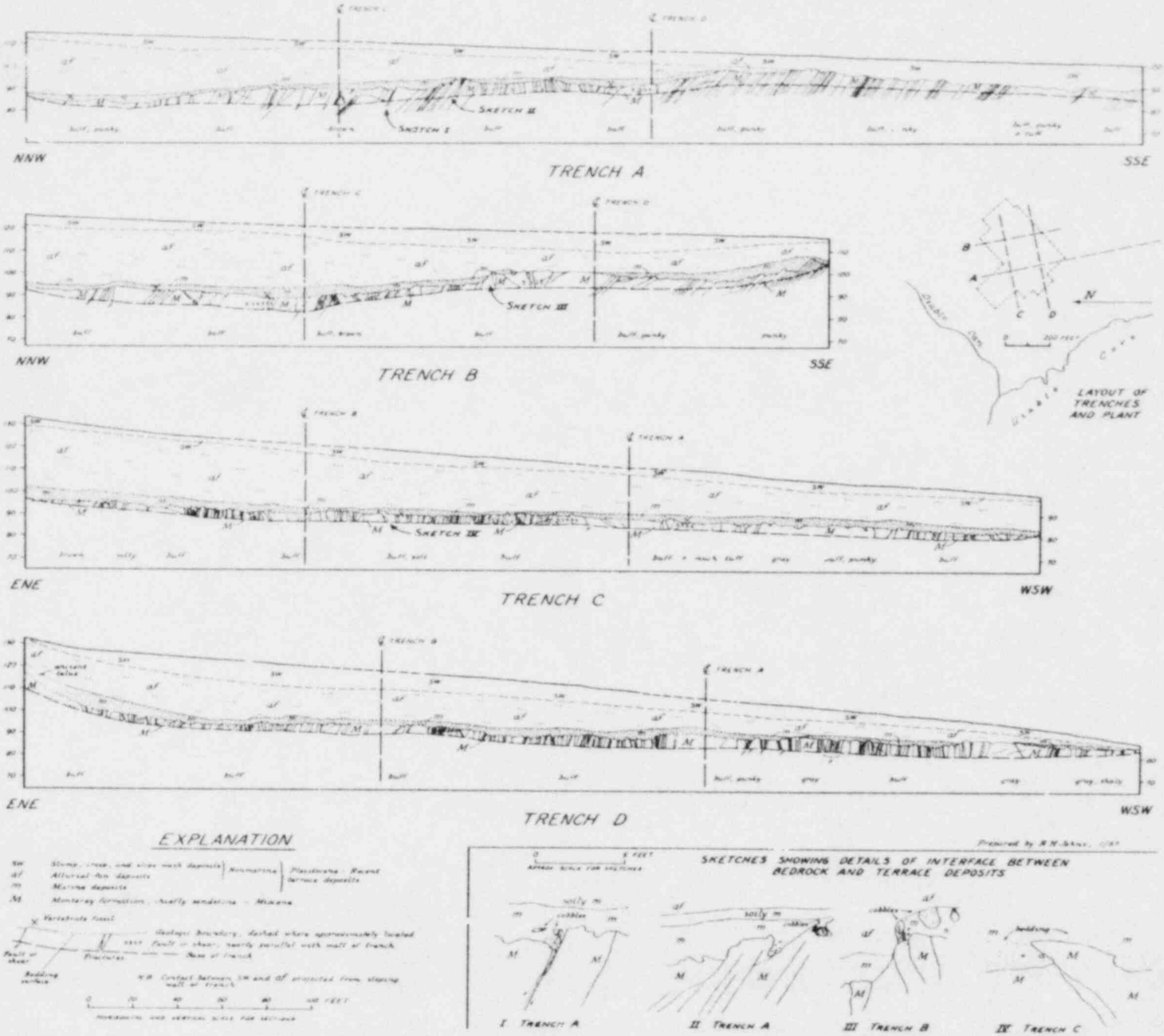
See Figure 23 for location and explanation of symbols

Figure 24



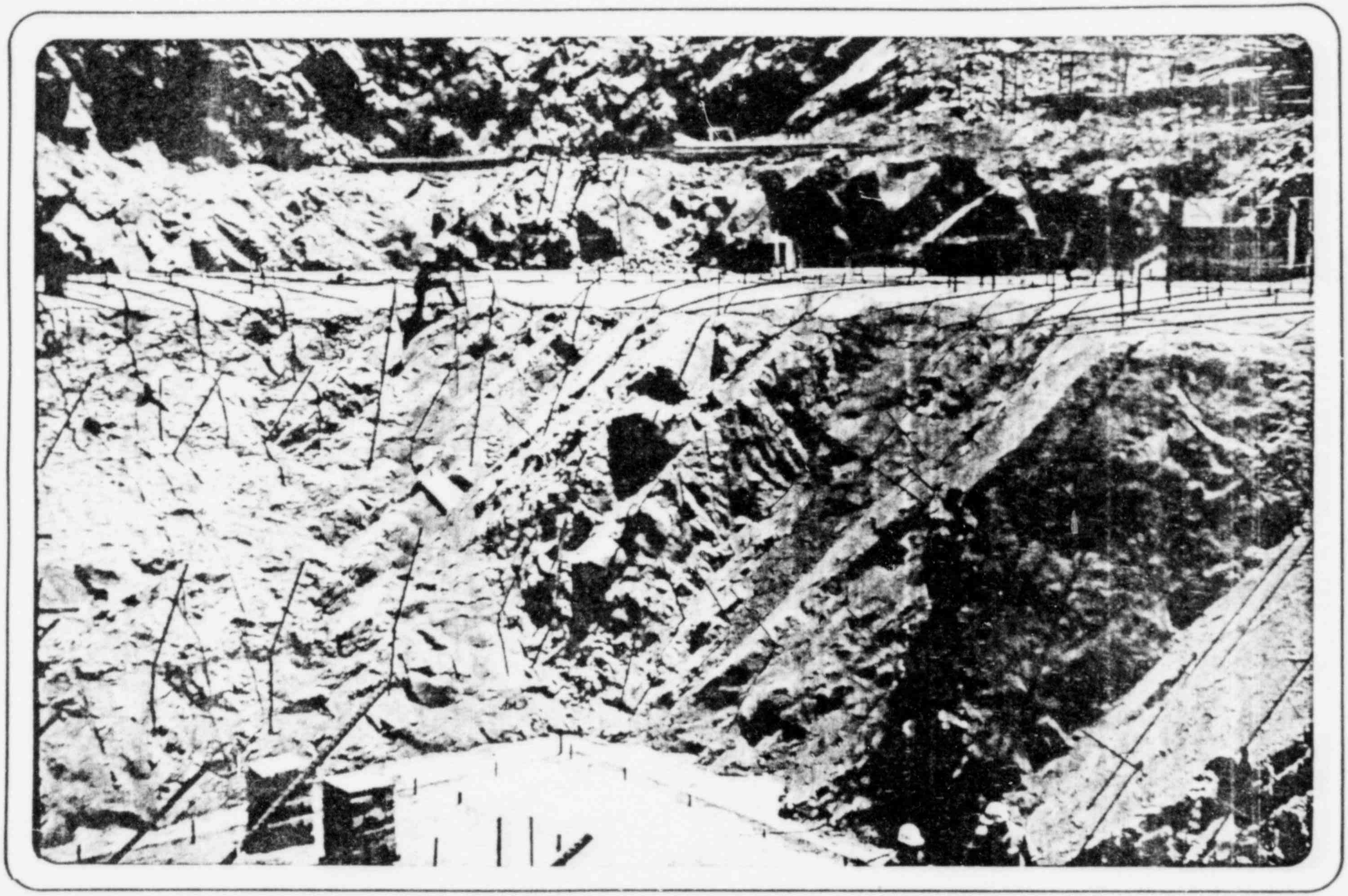
OBLIQUE AERIAL PHOTOGRAPH OF DIABLO CANYON SITE SHOWING EXPLORATORY TRENCHES

Figure 25



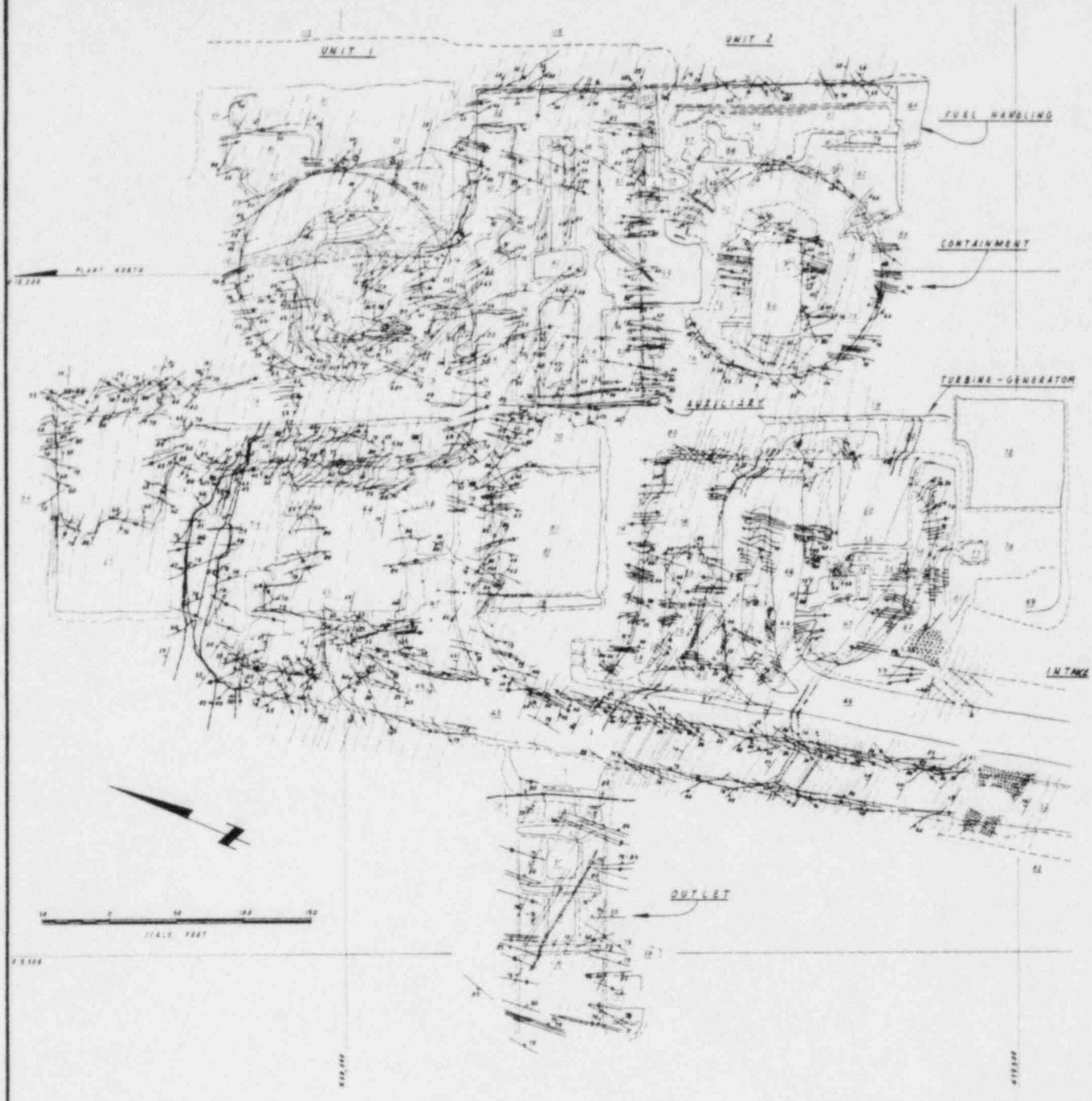
TRENCH LOGS

Figure 26



PHOTOGRAPH SHOWING MASSIVE SANDSTONE EXPOSED IN UNIT 2 CONTAINMENT CONSTRUCTION EXCAVATION

Figure 27



GEOLOGIC MAP OF UNITS 1 AND 2 CONSTRUCTION EXCAVATIONS

Figure 28

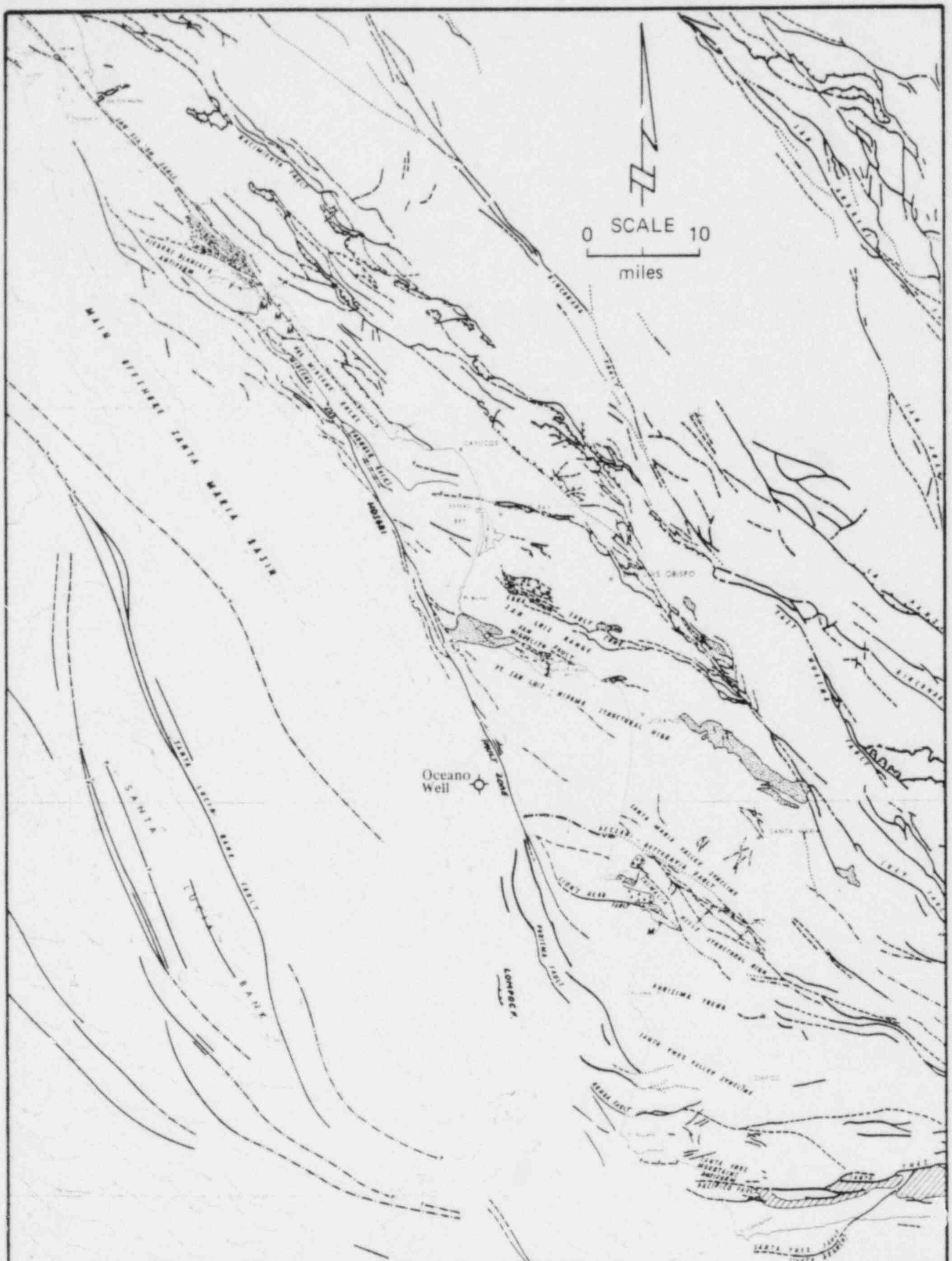
EXPLANATION FOR FIGURE 28
UNITS 1 AND 2 CONSTRUCTION EXCAVATION MAP

ROCK TYPES

▭	*Rocks of the Monterey Formation, undivided: Predominantly thin to thick bedded sandy mudstone and fine-grained sandstone.*
▨	*Claystone and clayey, decomposed tuff, mainly in concordant layers.*
▩	*Tuff and tuff breccia, in intrusive bodies that are at least partly discordant.*
▧	*Breccia with calcite cement*

SYMBOLS

⌒	*Boundary between contrasting rock types; dashed where projected between mapped exposures.*
▨	*Pattern of bedding traces in excavations; dashed where projected between mapped exposures.*
⟋	*Strike and dip of bedding*
⟋	*Strike of vertical bedding*
⟋	*Strike and dip of joint*
⟋	*Strike of vertical joint*
▦	*Zone of blocky fracturing*
⟋	*Strike and dip of fault or shear surface. Number indicates measured stratigraphic separation in feet.*
┌	*Top of cut slope*
┌	*Toe of cut slope*
25	*Approximate elevation of excavated surface*



FAULTS, BATHYMETRY AND LOCATION OF IMPORTANT STRATIGRAPHIC FEATURES – COASTAL REGION BETWEEN POINT CONCEPTION AND CAPE SAN MARTIN

Figure 29

EXPLANATION FOR FIGURE 29

FAULTS, BATHYMETRY AND LOCATION OF IMPORTANT STRATIGRAPHIC FEATURES – COASTAL REGION BETWEEN POINT CONCEPTION AND CAPE SAN MARTIN

	ROCK TYPES
M	*Monterey Formation*
▒	*Obispo Formation*
░	*Lospe Formation of Point Sal and breccia of Point Sierra Nevada*
▨	*Eocene rocks*
▓	*Ophiolite sequence rocks of Point Sal and San Simeon area*

	SYMBOLS
———- - - - -······	*Fault, dashed where approximately located, dotted where concealed*
—·—·—·—·—	*Fault buried beneath Pliocene or older strata*
————————	*Geologic contact*

Hydrocarbon Potential of Northern and Central California Offshore

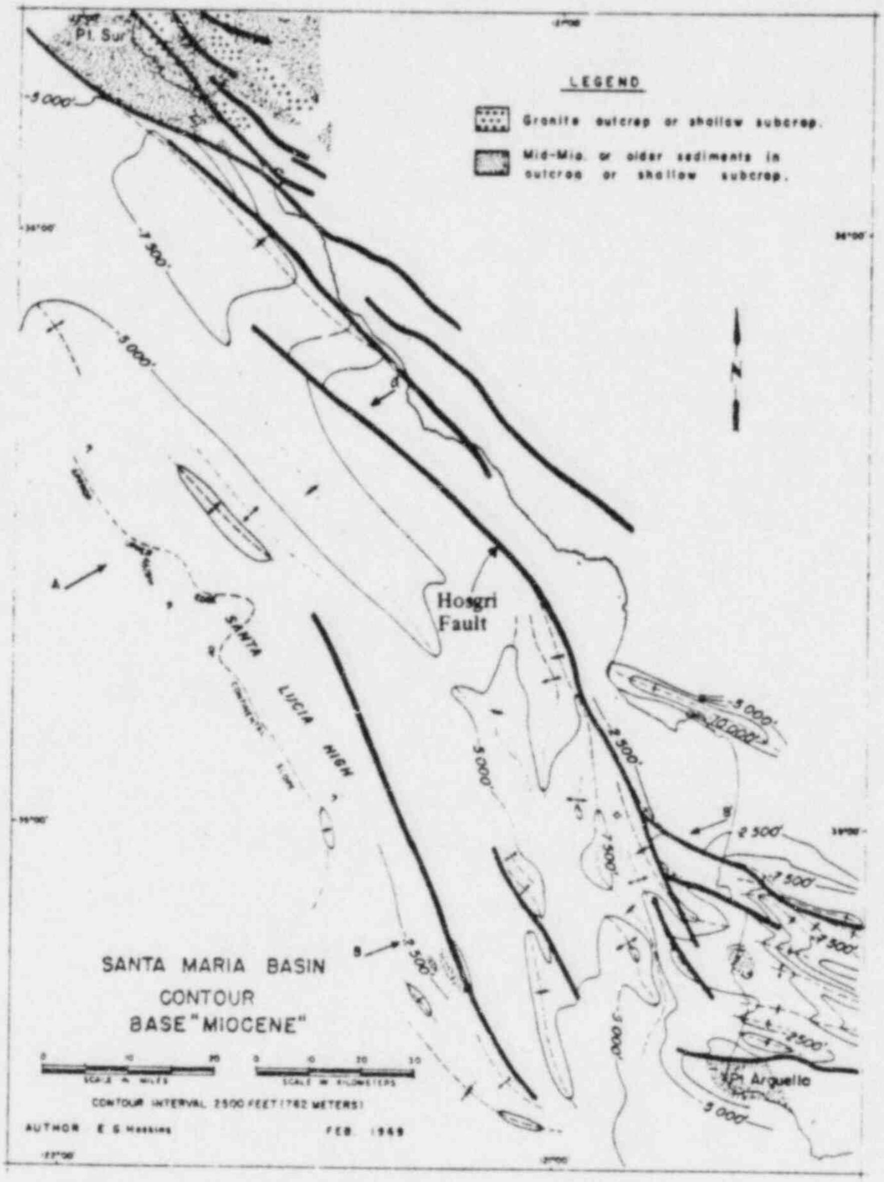
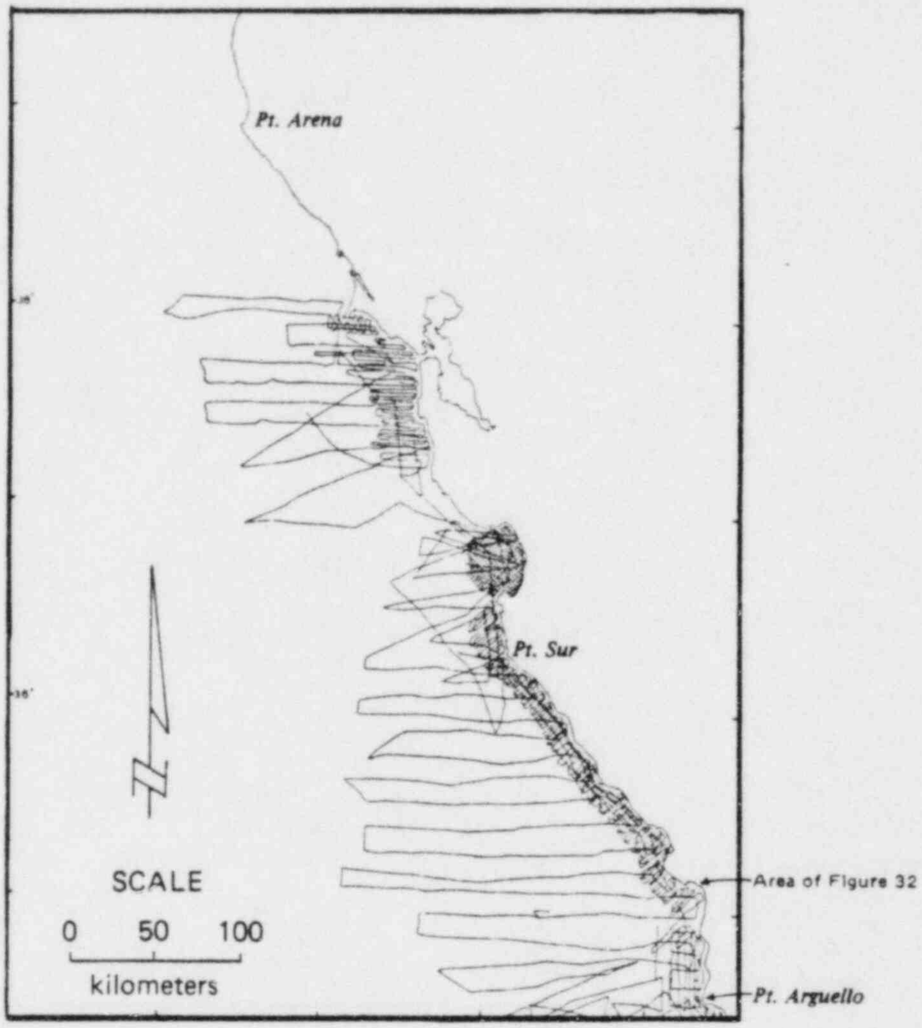


FIG. 2

Map of Santa Maria Basin, from "Hydrocarbon Potential of Northern and Central California Offshore" by E. G. Hoskins and J. R. Griffiths in AAPG Memoir 15, 1971.

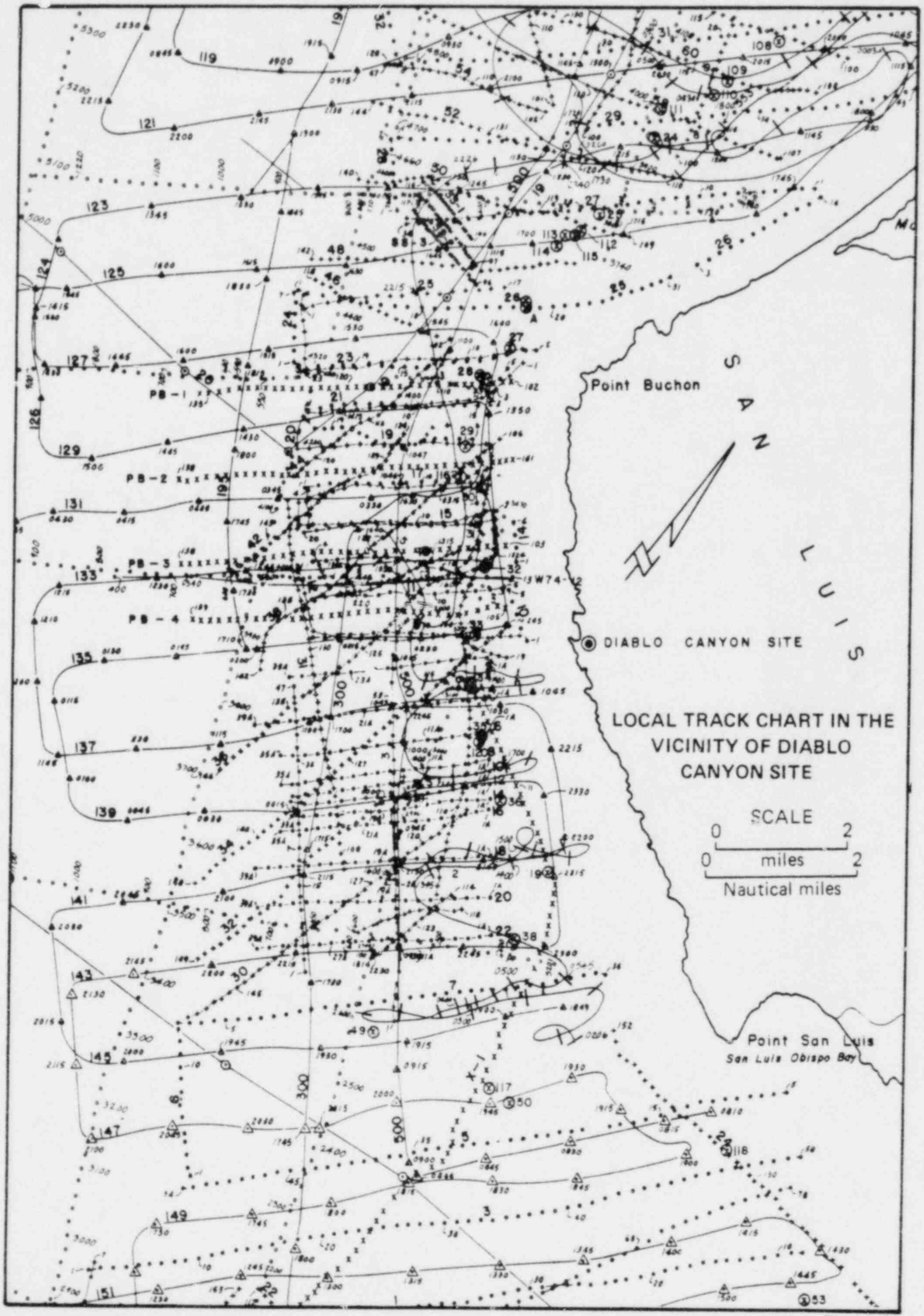
Figure 30



REGIONAL TRACK CHART -- CENTRAL CALIFORNIA COAST

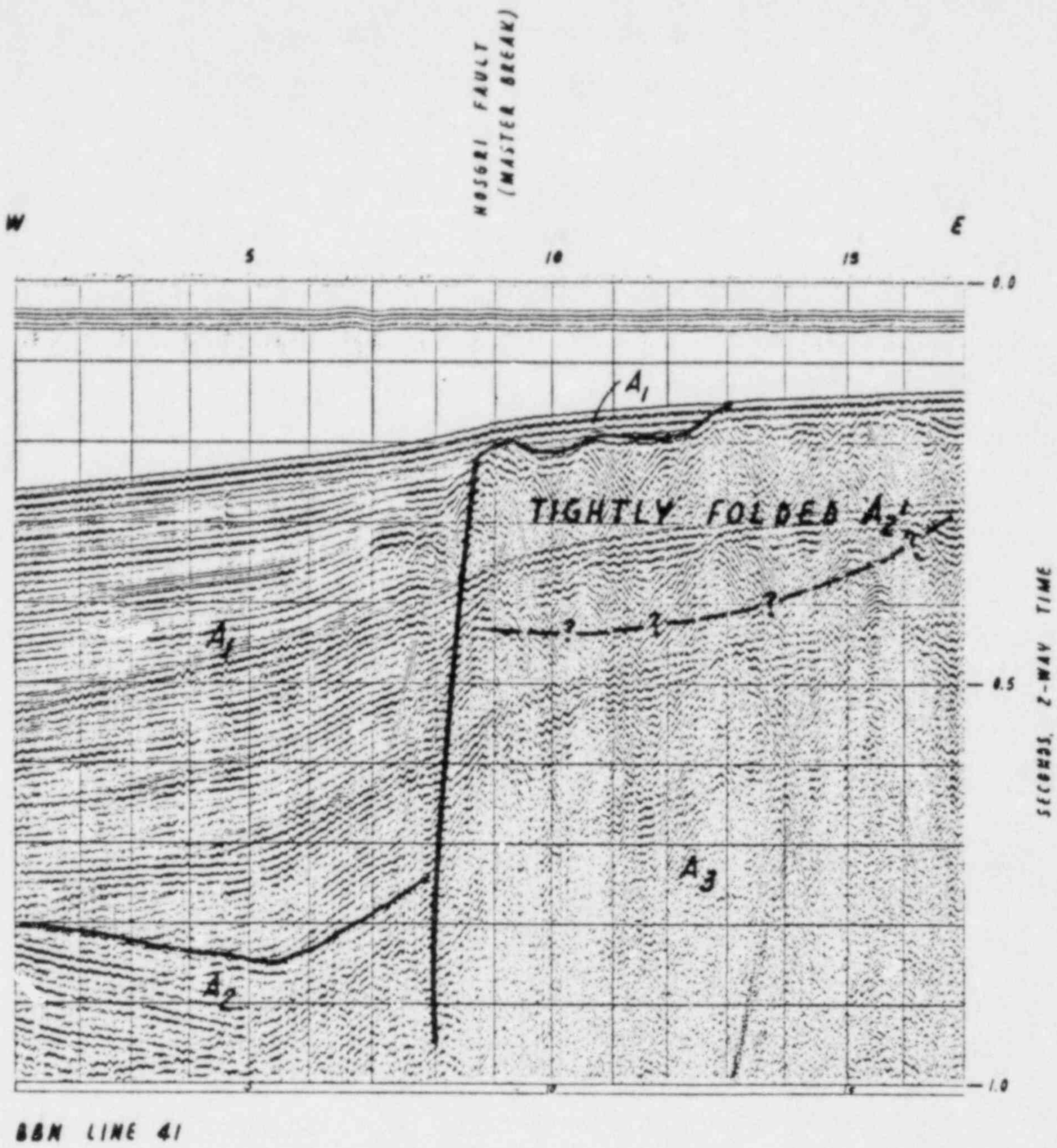
(U.S. GEOLOGICAL SURVEY CRUISES)

Figure 31



LOCAL TRACK CHART IN THE VICINITY OF DIABLO CANYON SITE

Figure 32

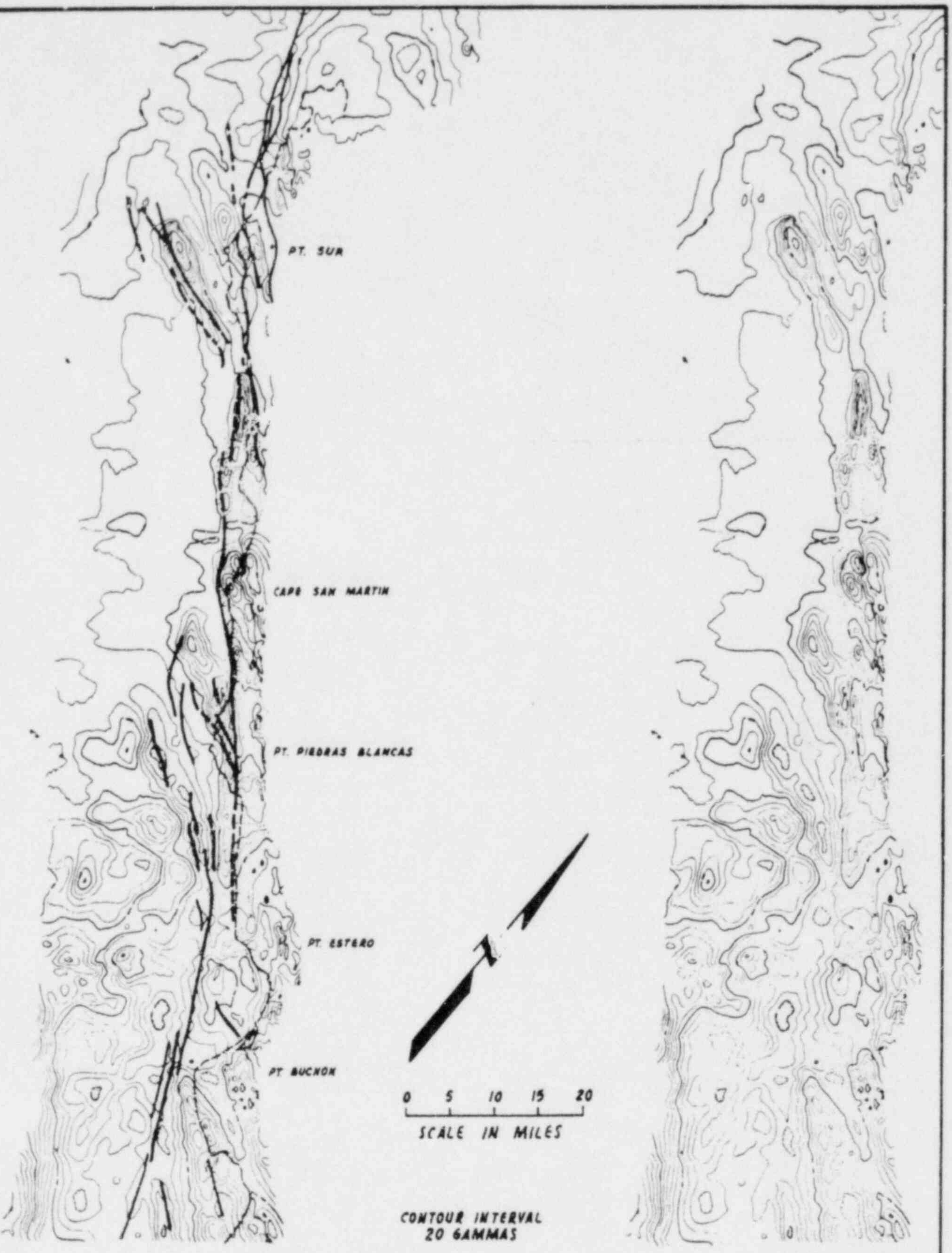


Sparker Seismic Reflection Profile, BBN Line 41

b) This profile is located $\frac{1}{2}$ mile south of the Kelez Line profile (Figure 7(N)a.) It displays a higher resolution sounding of the near surface expression of the Hosgri fault. As is typical of points south of this profile, structural deformation is restricted to the immediate vicinity of the fault.

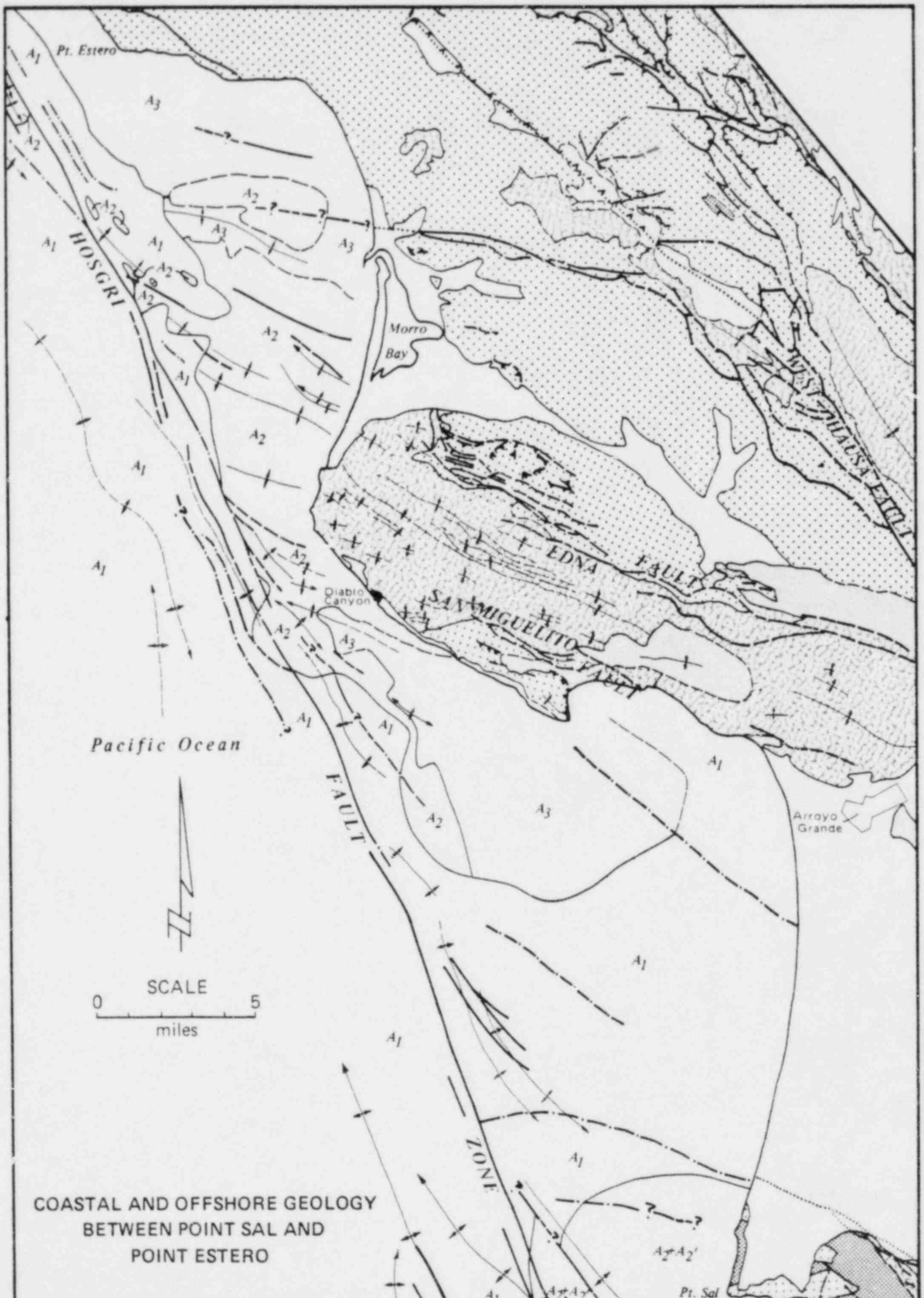
SPARKER SEISMIC REFLECTION RECORD
SHOWING THE HOSGRI FAULT

Figure 33



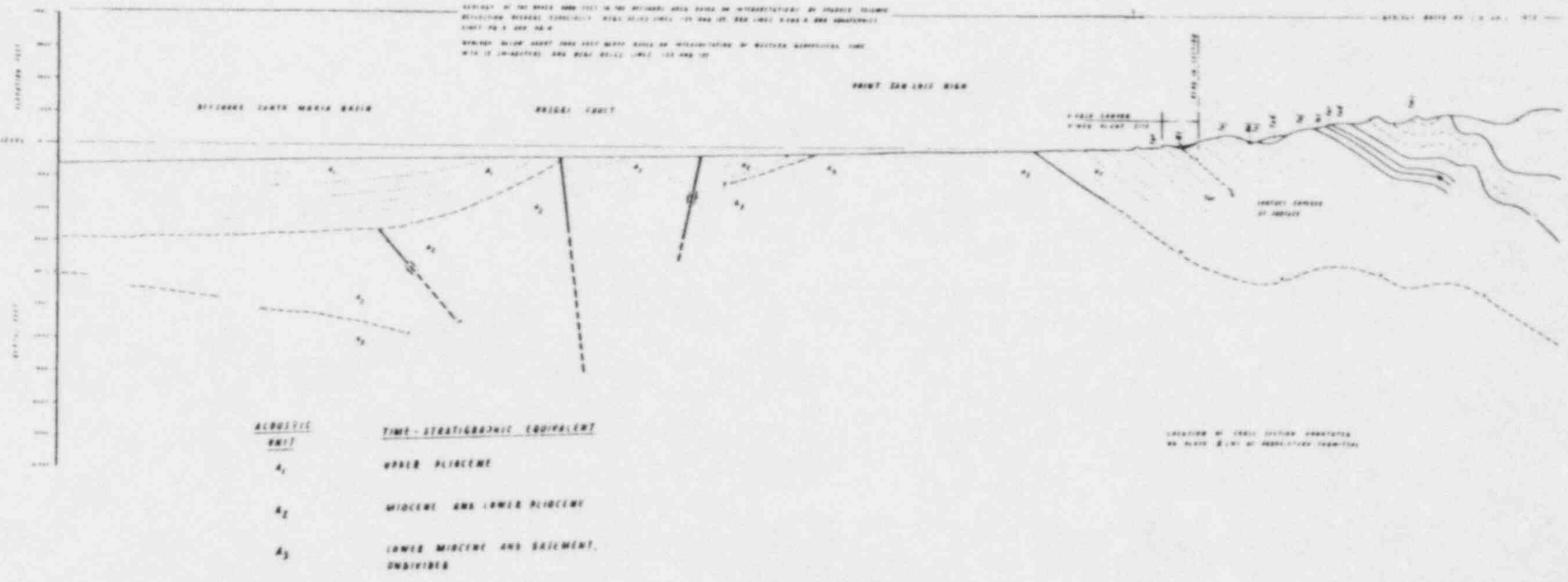
AEROMAGNETIC MAP AND PRINCIPAL COASTAL FAULTS ALONG THE CENTRAL CALIFORNIA COAST

Figure 34



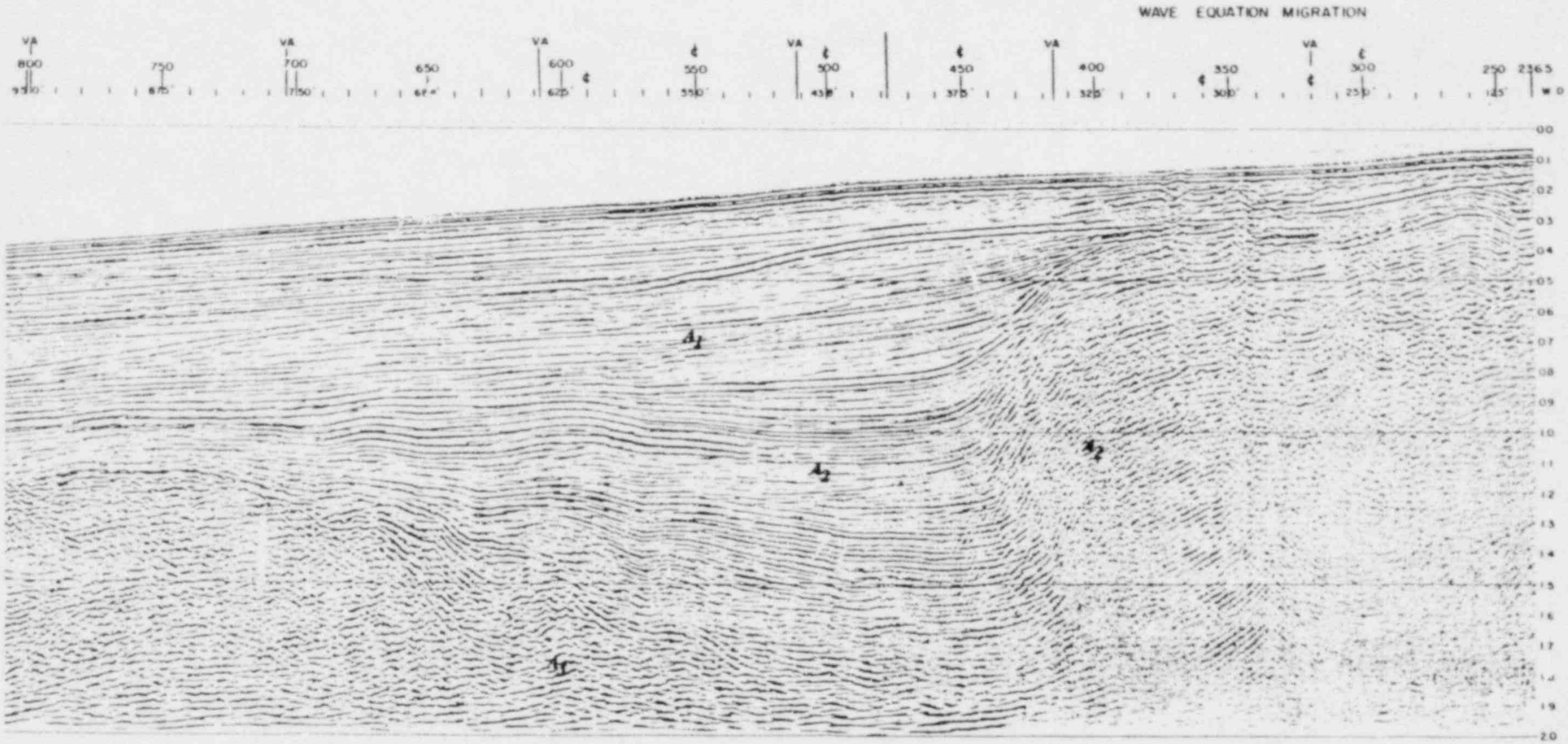
COASTAL AND OFFSHORE GEOLOGY BETWEEN POINT SAL AND POINT ESTERO

Figure 35



GEOLOGIC CROSS SECTION OF THE HOSGRI FAULT ZONE
IN THE VICINITY OF THE DIABLO CANYON SITE

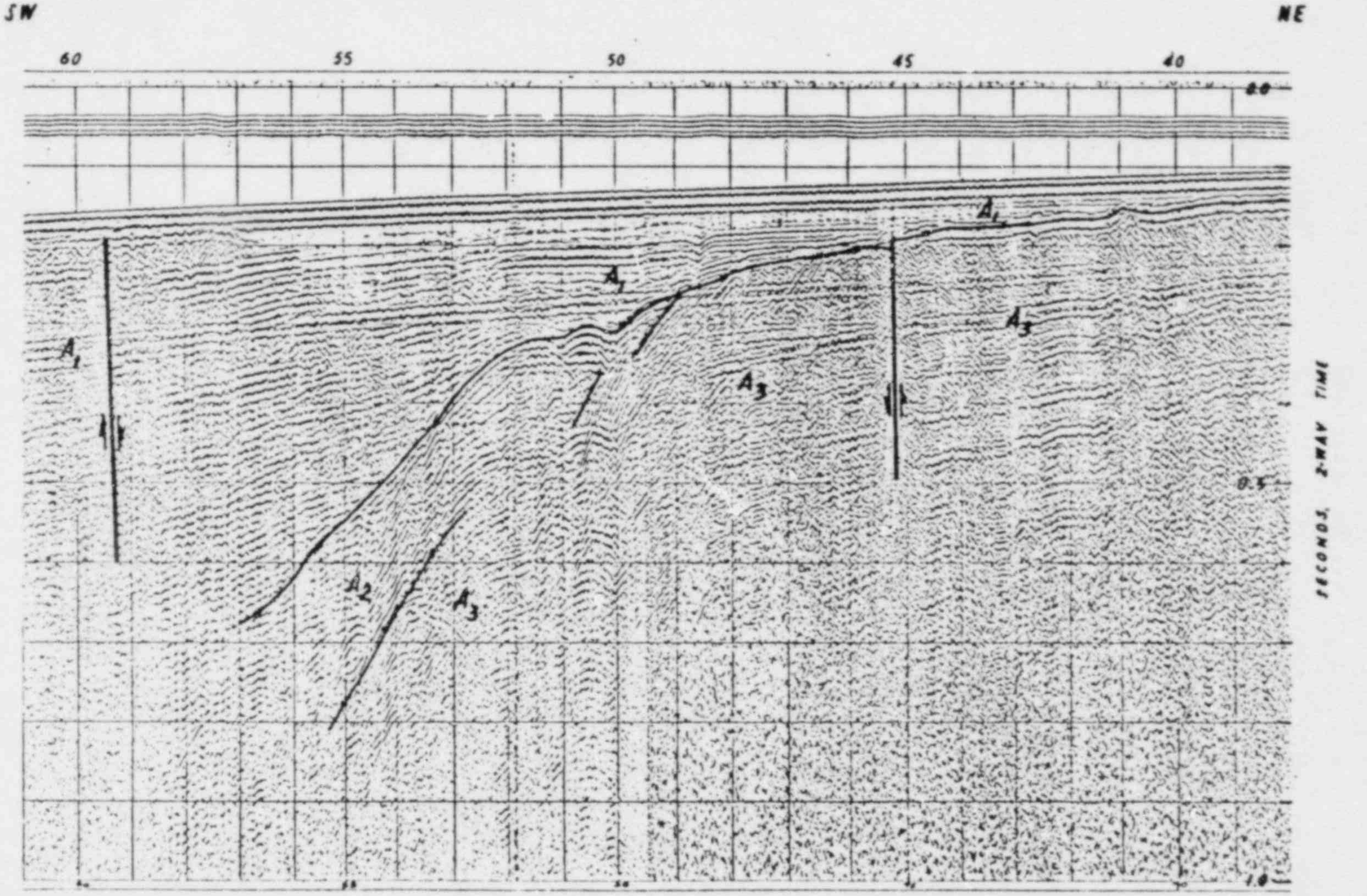
Figure 36



CDP SEISMIC REFLECTION RECORD SHOWING THE HOSGRI FAULT

Note: The left side of the cross section shown on Figure 36 is derived from a record similar to this one.

Figure 37



SPARKER SEISMIC REFLECTION RECORD SHOWING THE HOSGRI FAULT

Figure 38

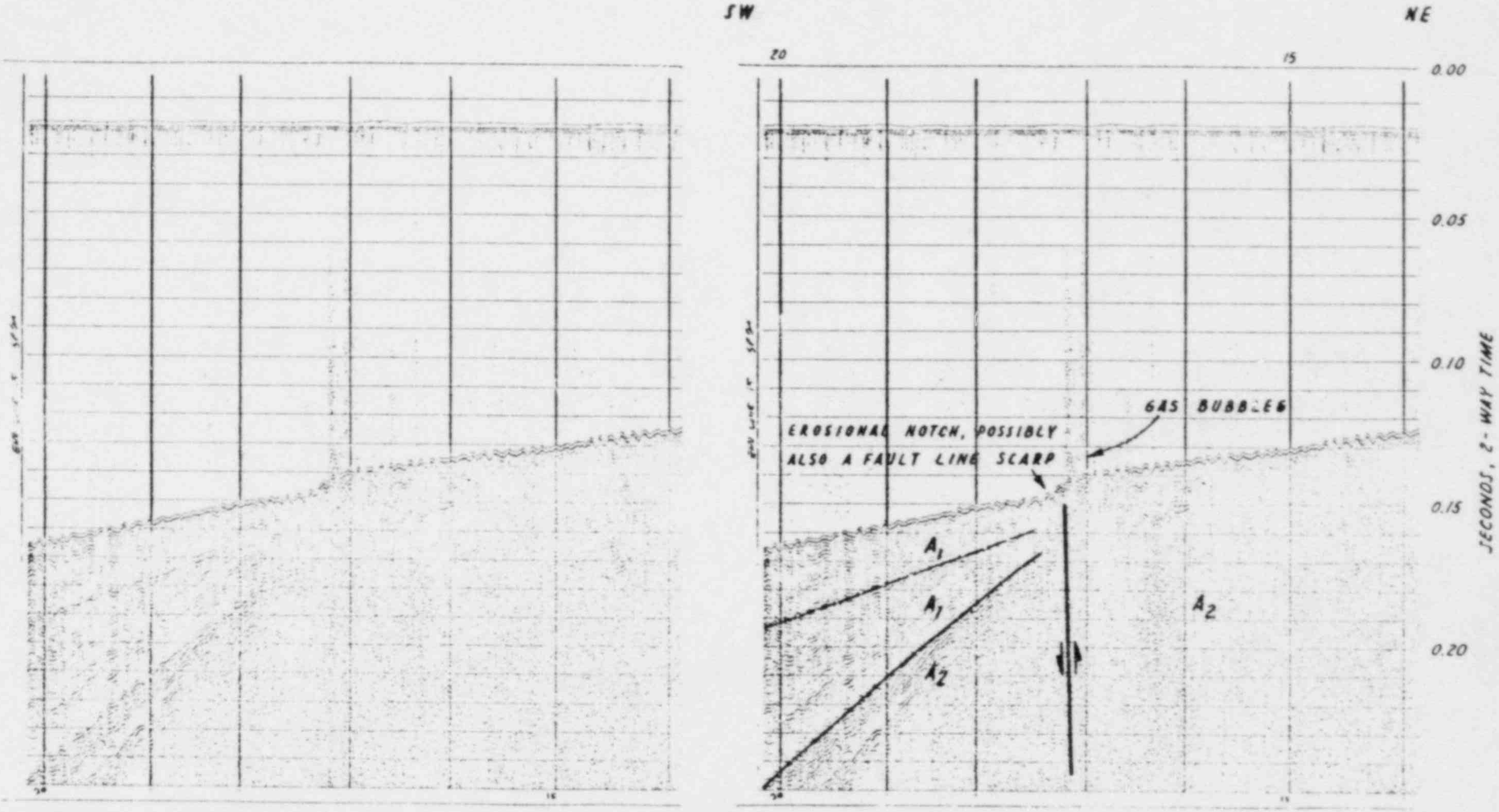
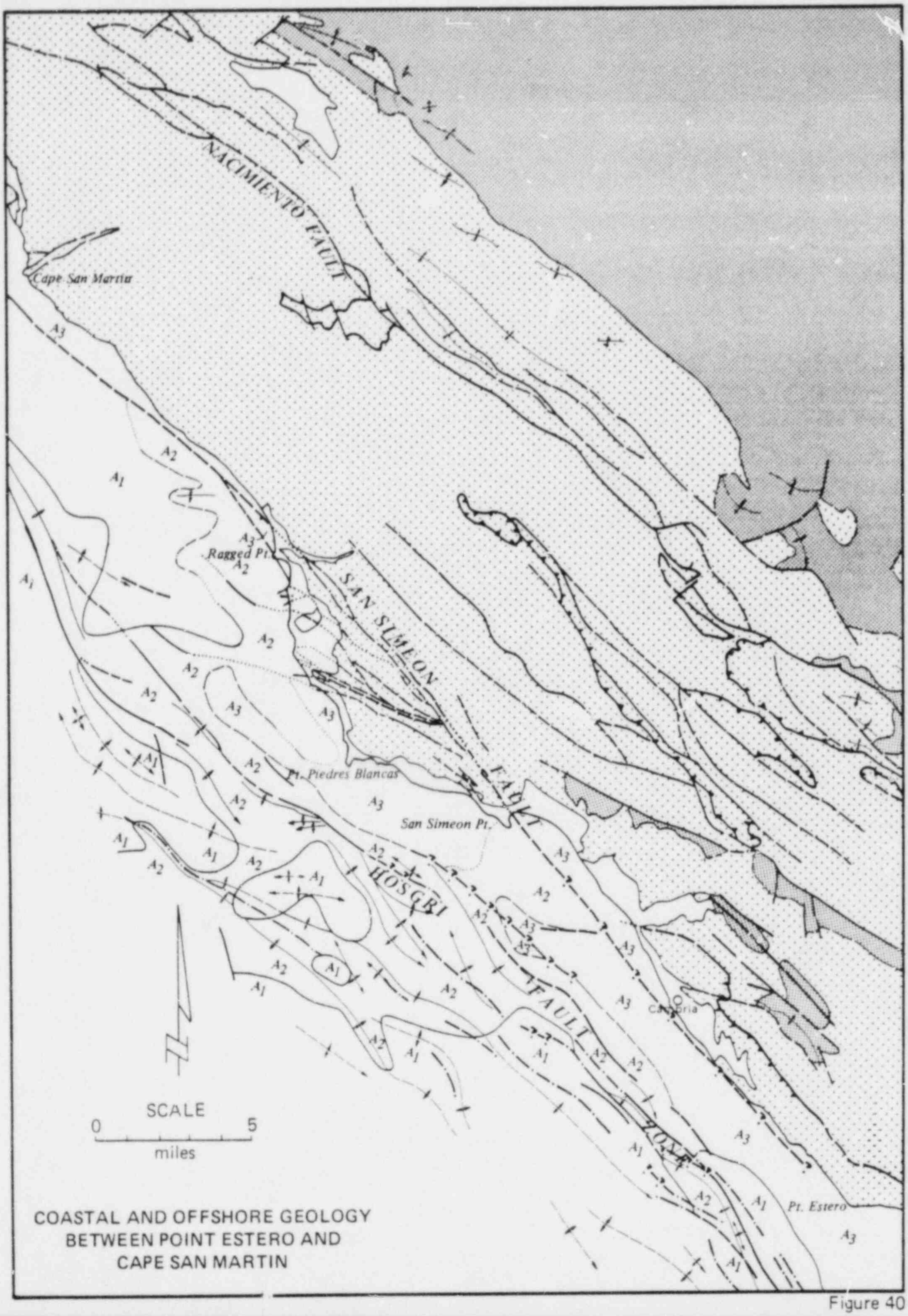


Figure 39

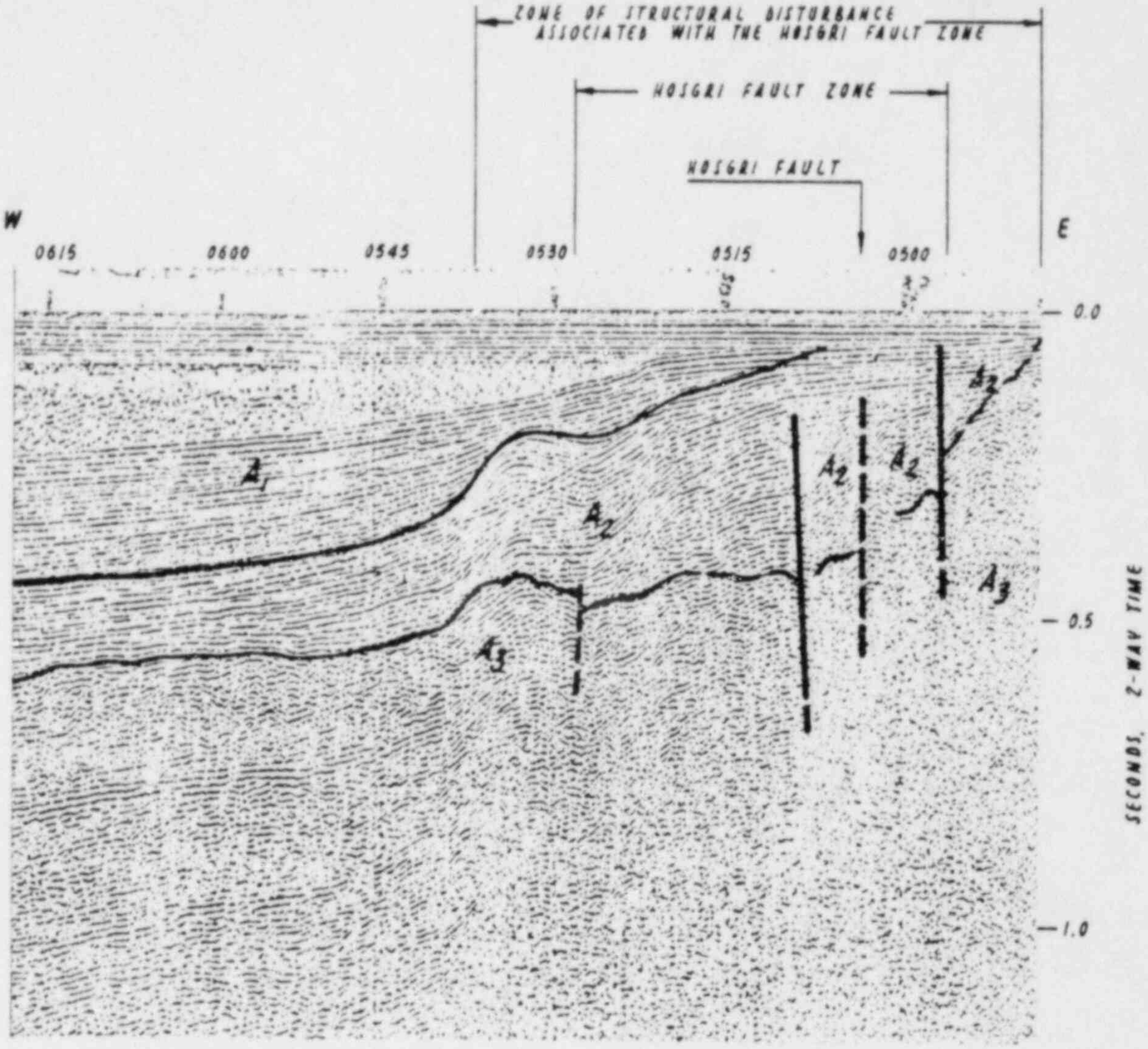
High Resolution Acoustipulse Seismic Reflection Profile, BBN Line Ap 15

This profile shows a bench and scarp feature that is spatially coincident with a west-down fault in the underlying rock section. The notch morphology and geologic relationships of this feature suggest that it is a fault-line scarp that has been modified by strandline wave erosion. The sea floor surface steps down across the notch; however, this could express either fault offset of the sea floor or differential erosion, since the Acoustic Unit A2 rocks in the section northeast of the fault are more resistant than those of the A1 section to the southwest.



COASTAL AND OFFSHORE GEOLOGY BETWEEN POINT ESTERO AND CAPE SAN MARTIN

Figure 40

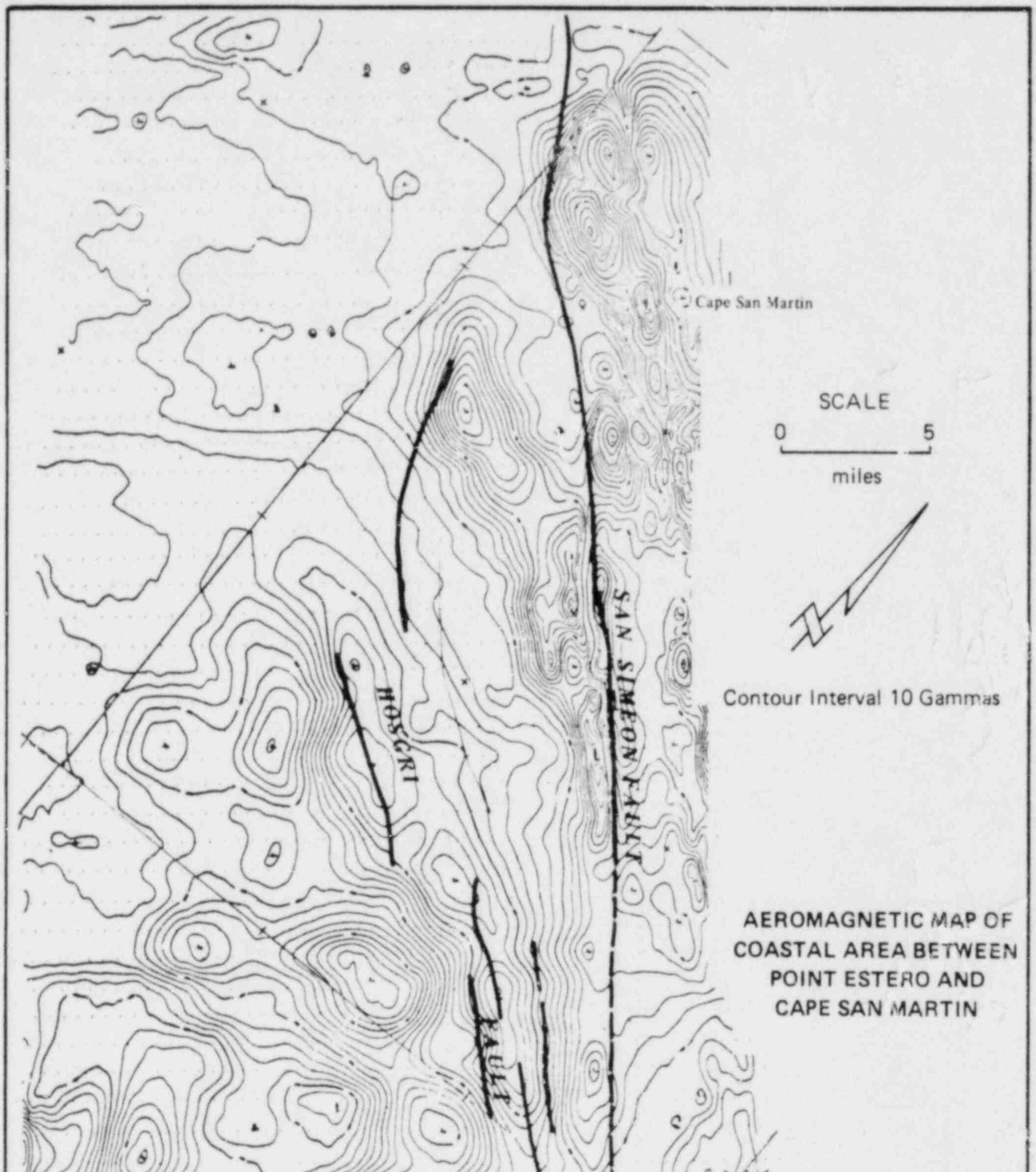


<u>Sparker Seismic Reflection Profile, Kelez Line 87</u>

The style of structural deformation associated with the Hosgri fault zone at the latitude of Kelez Line 87 is similar to that shown in Kelez Line 99, Figure 9(N). In this profile, however, vertical displacements across faults within the zone are smaller and the Hosgri fault master break has diminished to about the same relative size as the other breaks in the zone. The Hosgri fault cannot be identified north of this profile.

SPARKER SEISMIC REFLECTION RECORD SHOWING THE HOSGRI FAULT ZONE

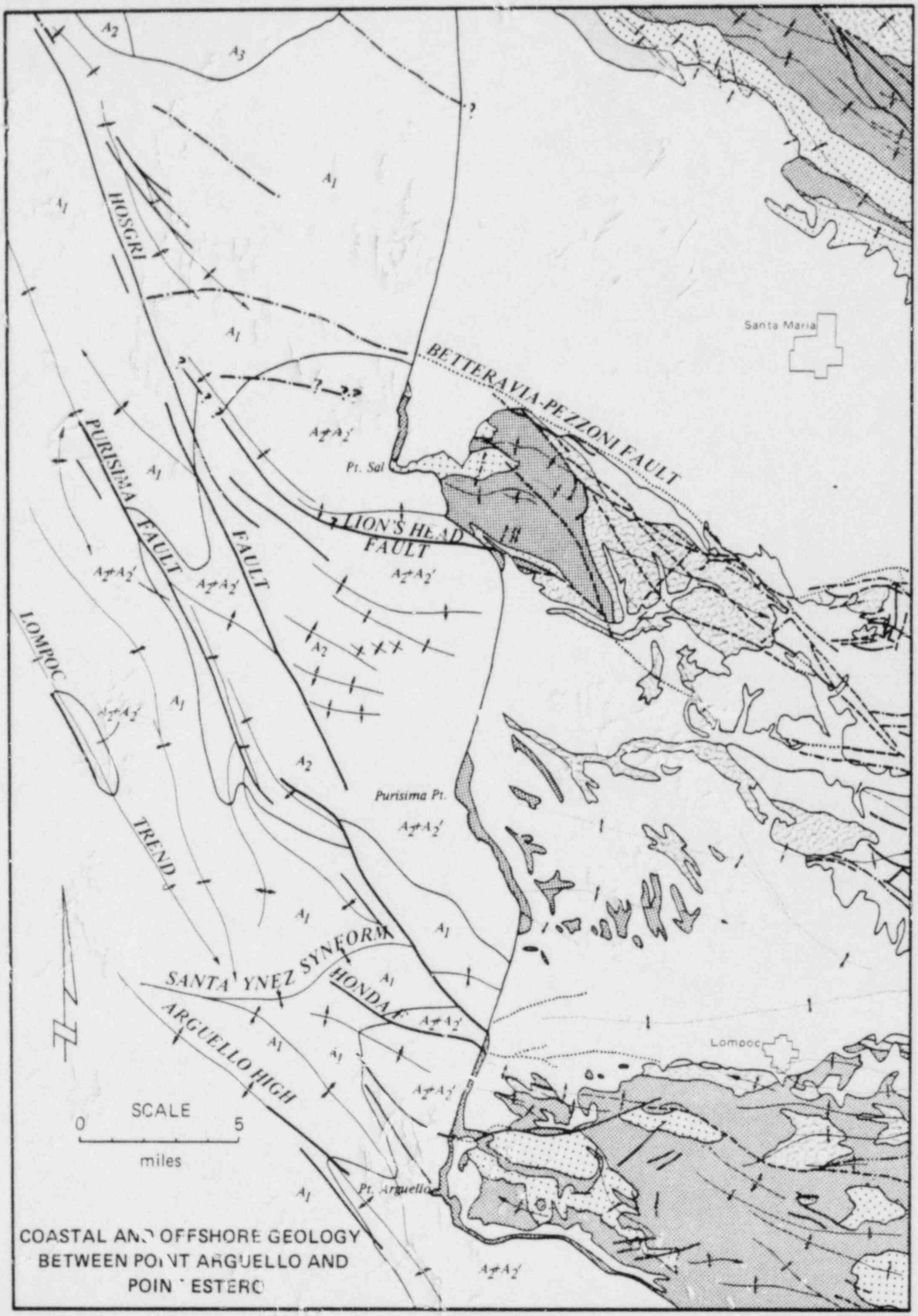
ESA 1310 JULY 11, 1975



AEROMAGNETIC MAP OF COASTAL AREA BETWEEN POINT ESTERO AND CAPE SAN MARTIN

Aeromagnetic data from McCulloch and Chapman, 1977.

Figure 42

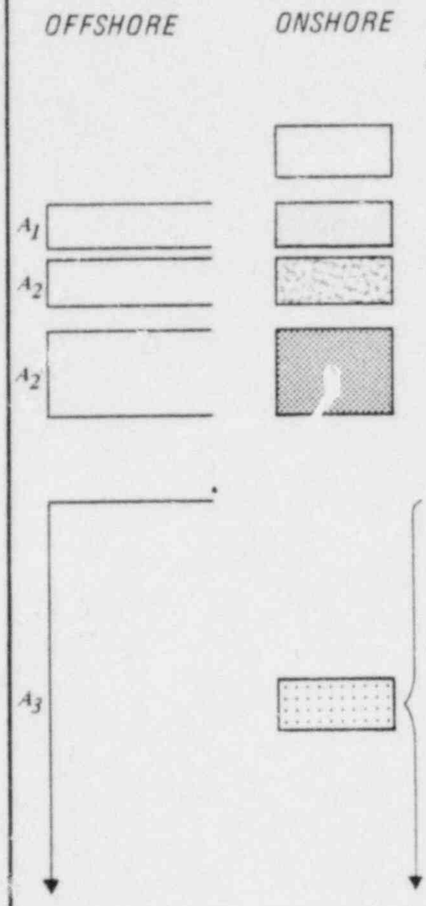


COASTAL AND OFFSHORE GEOLOGY BETWEEN POINT ARGUELLO AND POINT ESTERO

Figure 43

EXPLANATION FOR FIGURES 19, 35, 40 AND 43

GEOLOGIC UNITS



CENOZOIC

SEDIMENTARY DEPOSITS AND ROCKS

Holocene and Pleistocene nonmarine (chiefly alluvial) and marine deposits, undivided. Large land slides where mapped separately.

Plio-Pleistocene and Pliocene nonmarine; Pliocene marine.

Miocene marine and nonmarine, undivided; Upper Miocene marine.

Middle Miocene marine; Lower Miocene marine; Oligocene marine and nonmarine, undivided; Oligocene nonmarine; Eocene marine; Paleocene marine.

VOLCANIC ROCKS

Tertiary volcanic rocks.

Tertiary pyroclastic rocks, (including volcanic mudflow deposits).

Tertiary intrusive rocks. (Ti on Figure 19)

MESOZOIC

SEDIMENTARY AND METAMORPHIC ROCKS

Upper Cretaceous marine rocks.

Lower Cretaceous marine rocks.

Franciscan assemblage (predominantly sedimentary and meta-sedimentary rocks (including Franciscan melange).

Jurassic marine rocks (includes Knoxville Formation).

Metamorphic rocks of Pre-Tertiary Age. Undivided.

METAVOLCANIC ROCKS

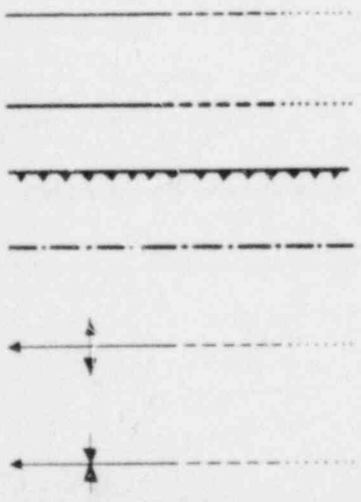
Mesozoic-metavolcanic rocks (including Franciscan volcanic rocks).

PLUTONIC ROCKS

Mesozoic granitic rocks.

Mesozoic ultramafic rocks.

SYMBOLS



Geologic contact, dashed where approximate or where Quaternary deposits are involved.

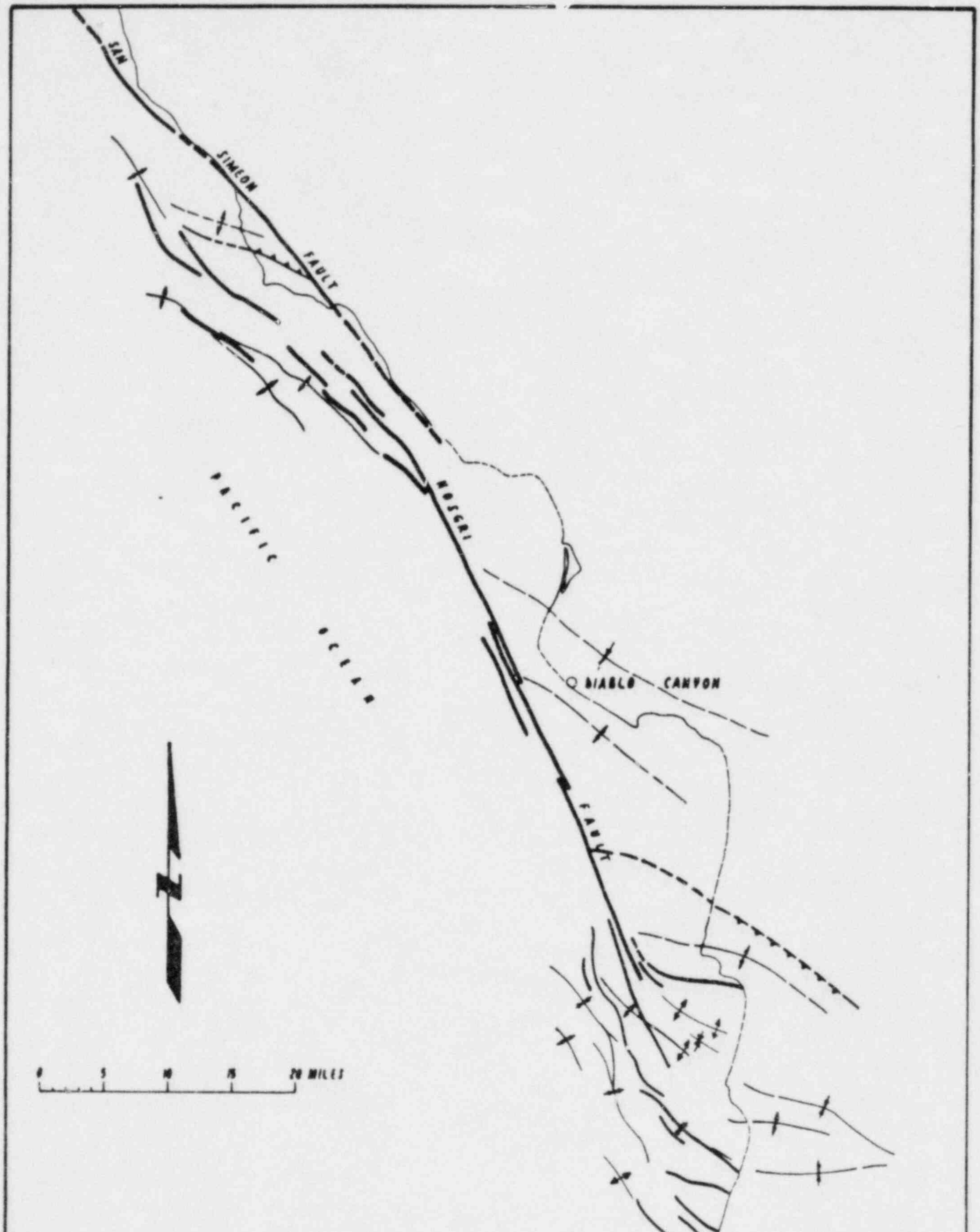
Fault, solid line where location is well defined, dashed line where approximate or inferred, dotted where concealed.

Thrust fault, barbs on up-thrown side.

Buried fault, well controlled from seismic reflection data. (Offshore and subsurface faults onshore.)

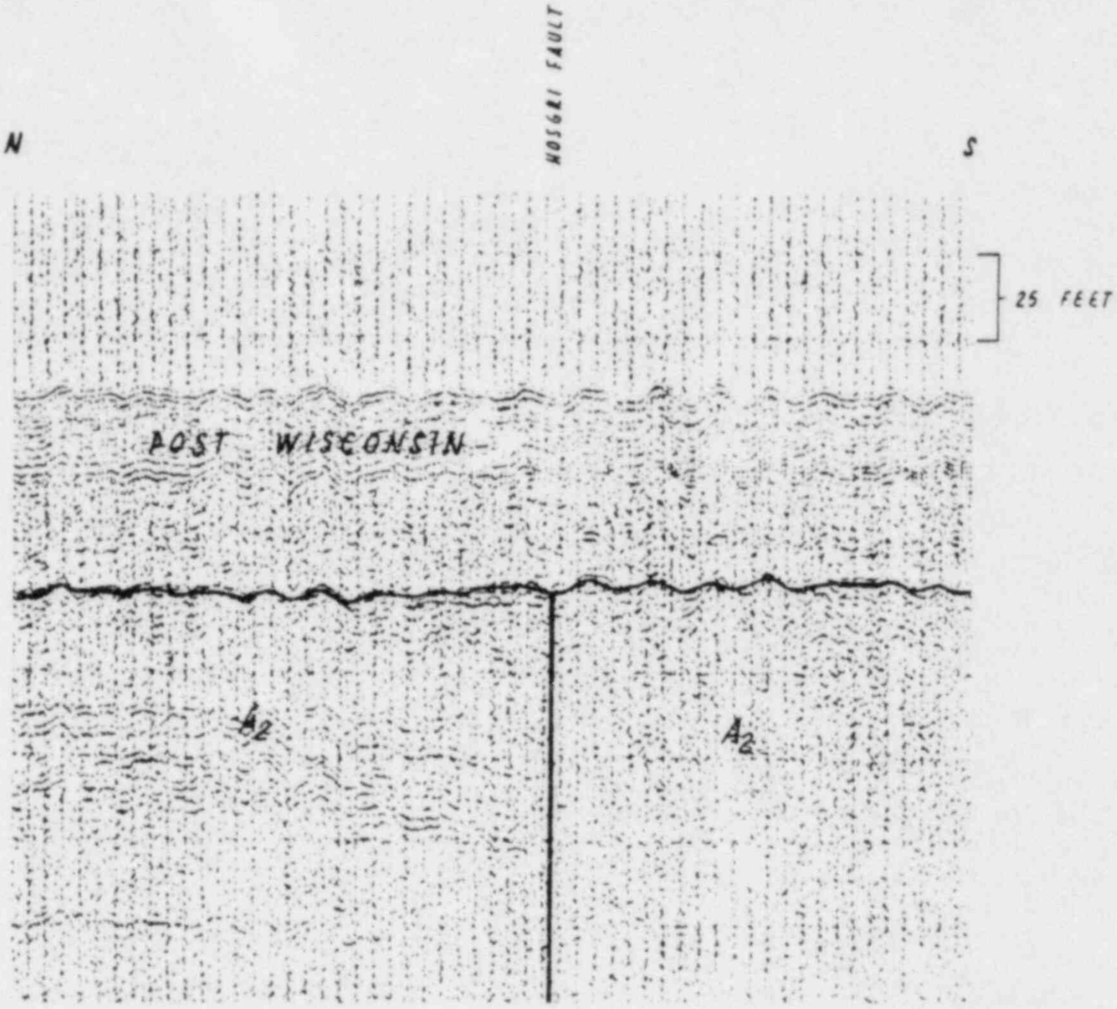
Anticlinal axis -- with plunge indicated. (Solid line where location is well defined, dashed line where approximate or inferred, dotted where concealed.)

Synclinal axis -- with plunge indicated. (Solid line where location is well defined, dashed line where approximate or inferred, dotted where concealed.)



HOSGRI STRAIN SYSTEM

Figure 44



High Resolution Uniboom Seismic Reflection Profile, Polaris Line 1-7

This profile shows the southernmost unambiguous evidence of the Hosgri fault. The fault is represented by the truncation of reflector horizons within the Acoustic Unit A2 rock section. The fault does not disturb the post-Wisconsin unconformity, the overlying post-Wisconsin section, or the sea floor. Undulation in the unconformity and sea floor reflector are caused by surface wave action.

HIGH RESOLUTION RECORD SHOWING THE SEA FLOOR
AND NEAR SURFACE GEOLOGY OVER THE HOSGRI FAULT

Figure 45

TESTIMONY OF
DR. STEWART SMITH
ON BEHALF OF
PACIFIC GAS AND ELECTRIC COMPANY
DECEMBER 4, 1978
DOCKET NOS. 50-275, 50-323

A. Original Seismic Evaluation

The original specification of earthquake hazards at the Diablo Canyon site was made jointly by the late Dr. Hugo Benioff and myself in 1967. We concluded at that time that a conservative estimate of future earthquake activity here should include the following:

1. A great earthquake may occur on the San Andreas fault at a distance from the site of more than 48 miles. It would be likely to produce surface rupture along the San Andreas fault over a distance of 200 miles with a horizontal slip of about 20 feet and a vertical slip of 3 feet. The duration of strong shaking from such an event would be about 40 seconds, and the equivalent magnitude would be 8.5.

2. A large earthquake on the Nacimento fault at a distance from the site of more than 20 miles would be likely to produce a 60 mile surface rupture along the Nacimiento fault, a slip of 6 feet in the horizontal direction, and have a duration of 10 seconds. The equivalent magnitude would be 7.25.

3. Possible large earthquakes occurring on offshore fault systems that may need to be considered for the generation of seismic sea waves are listed below:

Location	Length of Fault Break	Slip	Magni-tude	Distance To Site
Santa Ynez Extension	80 miles	10' horizontal	7.5	50 miles
Cape Mendocino, NW Extension of San Andreas Fault	100 miles	10' horizontal	7.5	420 miles
Gorda Escarpment	40 miles	5' vertical or horizontal	7	420 miles

4. Should a great earthquake occur on the San Andreas fault as described in paragraph 1, above, large aftershocks may occur out to distances of about fifty miles from the San Andreas fault, but those aftershocks which are not located on existing faults would not be expected to produce new surface faulting, and would be restricted to depths of about 6 miles or more and magnitudes of about 6.75 or less. The distance from the site to such aftershocks would thus be more than 6 miles.

B. <u>Present Seismic Evaluation</u>

There have been substantial advances in seismology and a large body of new data on earthquakes and ground motion has been collected in the ensuing 11 years. Were the 1967 report written today, it would reflect new data and improved understanding that now exists. Some of the conservatisms that were insisted on at the earlier date -- due to inadequate data -- could now be relaxed. As in many fields, an improved understanding of a physical process allows more confidence in predicting the operation of that process in the future. As an example, we postulated a magnitude 6.75 earthquake to occur as an aftershock of a great earthquake on the San Andreas fault. This aftershock was considered possible anywhere in the region, including directly beneath the site. In the light of developments during the last decade, it now seems unlikely that an earthquake larger than about magnitude 5 could occur in California without being directly associated with a recogizable fault. Other examples exist where very conservative estimates were utilized in order to reflect the then existent state of knowledge regarding earthquakes. For example the characterization of the Nacimiento fault as being capable of an event similar to the 1952 Tehachapi earthquake should be relaxed in light of present day understanding.

Let us first examine the impact of the discovery of the Hosgri fault. Data presented by Dr. Jahns and Douglas Hamilton in earlier testimony show this fault to be approximately 135 km long with a history of ten to twenty km displacement during the past 10-15 million years. Although Hamilton finds that the Hosgri is not directly connected with the San Simeon or other faults to the north, it would appear to be part of an en echelon system which may include, among others, the San Gregorio fault to the north. As one would expect, the history of seismic activity on all of these various northwest trending faults appears to show an increase the closer they are to the San Andreas fault, which is the boundary between the North American and Pacific plates. The San Gregorio, for example, shows a considerable history of slip and, in fact, has been postulated to join the San Andreas at a point offshore from San Francisco.

The fault information that is relevant to its seismic potential is length, slip rate, style of faulting, and historic seismicity. As indicated above, Hamilton has found the Hosgri to die out to the northwest off San Simeon and to the southeast in the vicinity of Point Sal. The total length of this fault is about 135 km. Since geologic processes can change significantly over periods of millions of years, the most relevant geologic data on fault slip is that from Holocene time, the past 10,000 to 20,000 years. The "low stand" of sea level which occurred some 17,000 years ago is an important geologic time mark for us since fault slip on the Hosgri since that time would have had to have been beneath the sea and thus removed from the rapid erosional processes which might obscure evidence of faulting. This period of time is certainly long enough to characterize the activity of this fault for the purposes of seismic hazard evaluation. Extensive marine seismic profiling establish that vertical offsets of the sea floor on the Hosgri are rather insignificant. Hamilton finds offsets of no more than about a meter over distances of several kilometers. Although pure horizontal slip of flat lying sedimentary layers could escape detection in seismic profiling, it is unlikely that significant horizontal slip could have occurred here during the past 20,000 years without there having been a record of larger and more pervasive vertical slip. Strike slip faults typically produce, at least locally, some vertical offset. In following sections, the relationship between earthquake magnitude and slip history will be examined in detail to demonstrate that earthquakes much larger than about 6.5 cannot have occurred with any regularity here without having produced a more visible record of their occurrence.

While the seismic history of the Hosgri is not as well known as faults such as the San Andreas, primarily because there have been few earthquakes in this part of central California during historic times, relocations of historic seismicity shows that several earthquakes in the range of about magnitude 4 are located close enough that they may well have been associated with the Hosgri. Some general conclusions about seismic behavior of second order faults in California can be made, however, if one takes a large enough region to insure an adequate statistical sample. In a subsequent section, this data is examined and shown to be generally consistent with the geologic picture given here.

In summary, we see that because of the initial conservatism in specifying a magnitude 6.75 earthquake anywhere in the region, (including directly beneath the site), the introduction of new information on the existence of the Hosgri fault does not significantly impact our conclusions about close-in earthquake activity. In particular, it follows that the current assumptions made in reanalysis of the plant in which a magnitude 7.5 earthquake is specified on the Hosgri must be classified as grossly conservative.

C. Tectonic Framework

A glance at the geologic map of California is enough to convince one that a good deal of deformation has taken place here and that the principal trend has been northwesterly shear paralleling the San Andreas fault. Looking at a map of historic earthquakes, it is clear that not all significant earthquakes are confined to the San Andreas fault. The question then becomes, how can one assess the earthquake potential of these thousands of other faults? Even if one focuses on faults with a history of Quaternary displacement, the picture is an extremely complex one. In a later section, the case is made for the inadequacy of using the length of faulting as a measure of future seismic potential. In this section I want to examine the relative importance of fault length, slip, type of faulting, and proximity of plate boundaries.

Faults are discontinuities in the earth across which there has been relative displacement. Although there may be a few special cases where superficial cracks actually open, faults are essentially shear type cracks, and every surface crack has 2 ends. The length of a fault would thus ideally be defined as simply the distance on the earth's surface between its two ends. Both in the laboratory and in the real earth, we know this is not an adequate measure of fault length, because there may be a series of cracks organized in such a manner that they produce shear deformation over larger dimensions than those of just one single crack. <u>En</u> <u>echelon</u> faults are one such example. Numerous examples exist where faults appear to terminate in folds. Sometimes the folding is the mechanism for distributing strain over a larger area, or transferring it to other nearby faults. For those who interpret earthquake potential in terms of fault length, it is necessary to make judgments about how continuous a fault zone must be in order to support a single rupture event. This task is made more difficult because our geologic information is generally restricted to only the near surface region. Examples exist where a single earthquake apparently has produced rupture along several planes, which although they are closely adjacent, are not actually connected, at least at the surface. This effect has been seen over distances of several kilometers. A good deal of geologic effort has gone into tracing faults with emphasis on establishing continuity, in order to determine the total length of the system. I believe that this effort is largely misplaced, if its primary intent is to establish the potential for future earthquakes.

On the other hand, the amount of fault slip that has taken place over recent geologic time appears to be quite a direct measure of the amount of tectonic activity, that is earthquake activity and fault creep, that has occurred. Fundamental consideration of the strength of earth materials can give us limits on how long a rupture must be given the amount of slip. If for example a fault has had kilometers of slip, it must have had a substantial length during the time that slip accumulated. This would be true irrespective of whether or not the geologic data is adequate to show continuity of a single fault trace. Thus the emphasis should clearly be on establishing fault slip rather than in trying to tie together individual strands of, what is in Coastal California, a myriad of intertwined traces.

The next important point to consider is the time frame within which the fault slip has taken place. In geology we deal with time intervals of incredible length. Over times of tens of millions of years, the earth's surface appears very mobile, even fragments of continents can become separated and drift away. Stress conditions that produce these deformations can change significantly over geologic time. The existence of fault slip many millions of years ago may have little or no relevance to the present day seismic potential of that fault. If the earthquake history of the past century or two is inadequate to represent the seismic potential of a fault, and conditions may have changed too much to put reliance on a record that is millions of years old, what is the appropriate time interval we should use to judge a fault? Smith (1976) makes the case that for regions with dimensions on the order of 100 km Holocene time, about the last 20,000 years of history, is an appropriately conservative interval on which to base our assessment of fault activity. It is long enough to assure an adequate sample of earthquakes as revealed in fault slip, and short enough that the assumption can be made that geologic conditions have not changed significantly.

Finally, we should ask what the tectonic framework can tell us about stress conditions on the faults in question. This is important because stress conditions are more likely to control a ground motion parameter, such as peak acceleration, than is earthquake magnitude. Regions undergoing normal faulting, a situation characterized by horizontal tension, typically produce lower stress earthquakes than those associated with thrust, or reverse faulting, in which horizontal compression is dominant. Strike slip faulting is likely to be intermediate between these two extremes. In addition to the local style of faulting, the proximity of the region to major plate boundaries is important in assessing what the stress conditions are likely to be. In the case at hand, the San Andreas is the major boundary between the

Pacific Plate and the North American Plate. Relative motion between these plates has been at an average of between 3 and 6 cm/yr over the past several thousand years. Some of this motion must be taken up on faults parallel to the San Andreas. The actual plate boundary is not razor thin, but rather spread out over a substantial width. Just how wide the zone is can best be seen by looking at the slip history of some of the parallel faults. What results is that faults closest to the main break of the San Andreas appear to have the largest amount of late Quaternary slip. The zone of influence of the San Andreas should diminish over distances of the order of 100 km based on simple models of moving plates. This seems to be born out from the record of slip on subsidiary faults. Those which are close, and may even intersect the San Andreas, such as the Hayward fault or the San Gregorio fault, appear to have the most late Quaternary displacement, while those such as the Nacimiento or the Hosgri have progressively less displacement the further removed they are from the present plate boundary.

Thus we conclude that total mapped fault length is an illusory concept, more like a game of "connect the dots" than a matter of real substance, and that the history of slip, particularly that during the past 10-20 thousand years, is the fault parameter that has the most relevance to earthquake potential. We also conclude that the style of local faulting is important in assessing local stress conditions, and that distance from major plate boundaries is important in determining the level of stress and thus the earthquake potential.

Application of these principles to the Diablo Canyon site yields the following:

1. Slip history of the Hosgri fault during late Quaternary is several meters indicating that during this time it was not operating as part of a long fault system.

2. Focal mechanisms and geologic data show that deformation changes from right lateral shear on the San Andreas to normal faulting in the offshore Santa Maria Basin. The transition appears to be a gradual one with oblique slip on the Nacimiento. The local stress conditions for the Hosgri would thus be expected to be intermediate between normal faulting and strike slip faulting, that is, significantly less than those expected for compressional regimes.

3. The Hosgri is some 80 km from the San Andreas fault, which is the present day boundary between the North America and Pacific plates. Although still influenced to a certain extent by the stress field from this plate boundary, it is much less affected than those faults which are closer to or intersect the San Andreas, and thus the stress levels and earthquake potential are correspondingly less.

D. Earthquake Magnitude

Some confusion exists in the use of the term magnitude. A brief discussion should help to clarify its use herein. Although there are currently about a half dozen different types of earthquake magnitude, only the three most common need be considered. They are local magnitude (M_L), body wave magnitude (m_b) and surface wave magnitude M_S.

M_L, the local magnitude, is based on the peak horizontal ground motion as observed on a Wood Anderson Torsion Seismograph. It is generally considered valid at distances less than about 600 km. Because of the way it is defined, it turns out to be most sensitive to motion in the high frequency range, above several cycles per second. As a result, it is probably the most appropriate measure of earthquake "size" for engineering purposes. In recent years, it has become clear that peak motions in this part of the frequency spectrum probably have a limiting value corresponding to an M_L of near 7. That is, the scale saturates and as the earthquake energy increases, the higher frequencies don't change much. The largest value of M_L ever measured was 7.2 for the 1952 Kern County earthquake.

The body wave magnitude, m_b, is based on the amplitude and period of compressional waves recorded at great distances. It is primarily a measure of relative earthquake energy in the frequency band around 1 Hz. Theoretical considerations indicate that this scale also may well saturate at about magnitude 7. If M_L values are not available, m_b would be the next best choice of magnitude for engineering purposes.

The surface wave magnitude, M_S, is a measure of energy at very low frequency (periods of 20 seconds). It is the only one of the commonly used scales which can be used to measure earthquakes much in excess of magnitude 7. It plays a special role in earthquake statistics because it is most closely related to geologic parameters such as fault rupture length and slip. U.S.G.S. Circular 672 uses both M_L and M_S. Local magnitude is used, up to 6.5-7.0 and then, at greater magnitudes, surface wave magnitudes are used. There is a reasonable degree of consistency between these measurements in the magnitude range of 6 to 7, where both are applicable and, in the late 1960's, it was assumed that this equivalency would continue at higher magnitudes. It has been shown, however, that the M_L scale saturates at 7+ and thus any reference to larger magnitudes is, by definition, an M_S.

In the seismicity discussion that follows, I have used M_L data since it represents the bulk of the data up to magnitude 6, but when I use these statistics to extrapolate to larger magnitudes for the purpose of calculating slip rates, the implicit assumption is that those magnitudes represent M_S values.

E. <u>Seismicity</u>

The Southern Coast Range Province in which Diablo Canyon is located is an area of low to moderate seismicity. Major activity is centered on the San Andreas fault about 70 km to the east, and in the Transverse Range Province about the same distance to the south. Earthquakes are, however, not restricted to these zones, and the Southern Coast Range Province has experienced some modest amounts of seismic activity during historic times. There are several reports of locally felt shocks during the last century which did some damage in San Luis Obispo County. Intensities are estimated at VIII Rossi Forel (VII MM). The largest instrumentally recorded earthquake in the region appears to be the 1952 Bryson shock, with a magnitude of 6.0, and maximum intensity of VII MM. Its location makes the most probable association the Nacimiento fault, although no direct confirmation of this has been possible. The Southern Coast Range Province includes a large number of intertwined northwest trending faults, which have varying degrees of continuity. The Nacimiento fault does not appear greatly distinguished from any of these in terms of length, continuity, or slip rate. Our approach from the beginning has been to assume that all of these faults are seismically capable, and that their potential activity in the future can best be estimated by examining their geologic record of slip in the past.

Examining the geology and the seismicity of central California, it becomes clear that although the San Andreas fault is the principal plate boundary, significant deformation has occurred over a fairly broad zone centered on that boundary. Since the lithosphere, that is the moving tectonic plate, is perhaps 100 km in thickness, a distribution of surface deformation (faulting) over a zone with a width roughly comparable to this thickness is not too surprising. Coastal California is laced with such faults. The geologic record of movement on these faults can give us a direct measure of how the plate motion is distributed over this wide zone. Furthermore, the historic record of earthquakes can be examined to confirm this view.

Although there may sometimes be a temptation to oversimplify the geology of this region by reference to simple plate tectonic models, the distribution and thickness of rock types shows the development of more complex features than predicted for simple rigid plates. Off the coast there are thick sedimentary basins bounded by normal faults. Clearly, the stresses operating in the offshore region have been significantly different from the north-south compression currently operative on the San Andreas system. Tensional stresses must have existed at the time these basins were formed and may in fact exist today as well. The information we have to assess the stress direction comes from the geologic record of movement and from the focal mechanisms of recent earthquakes. Both lines of evidence point toward a gradual transition from the right-lateral shear environment near the San Andreas fault to a tensional environment in the offshore on the Santa Lucia Bank fault. If the offshore region is one of transition to a tensional rather than a compressional regime, this would significantly reduce the potential for high-stress, high-peak - acceleration earthquakes on the Hosgri or other nearby faults.

In our earlier 1967 report, we examined both the seismic and geologic history of this region and concluded that to insure a very conservative estimate of future seismic potential we should place our emphasis on the geologic record. The reasons for this were the uncertainty of whether or not the past several centuries of seismic history, during which time there had been very little activity, were truly representative of what the future might be. Evidence from other parts of the world available at that time indicated that patterns of seismicity could shift on a time scale of centuries. By placing our emphasis on the geologic record of fault slip we could effectively push back the record of earthquake activity for nearly 20,000 years and thus obtain an estimate that we were sure would be both reliable and conservative. Although I still believe that this is the proper emphasis, recent developments in the use of seismic moment make it possible to directly assess the present day seismicity in terms of slip rates and thus test the idea of whether or not the current rate of earthquake activity is consistent with the geologic record of fault slip. Before doing this, some explanatory comments about the concept of seismic moment are needed.

During the past decade, seismic moment has come into common use in seismology as an effective means to characterize the size of an earthquake. Since earthquakes are caused by rupture and sliding along fault surfaces in the earth, the net effects of an earthquake can be measured in terms of the amount of slip and the area over which it took place. This type of dislocation in an elastic medium can be represented mathematically in terms of its equivalent force system - that is the pair of forces that would have to be applied to produce the same elastic displacements throughout the medium. The moment of these forces turns out to be simply the product of the average slip u, the fault area A, and the rigidity μ of the surrounding rocks.

$$\text{Seismic Moment} \quad M_o = \mu \, u \, A$$

Seismic moment can also be related empirically to earthquake magnitude, thus making the link to relate geologically observable quantities to seismological data. Kanamori and Anderson (1975) review the theoretical framework within which this empirical correlation can be made.

Their result is

$$\text{Log } M_o = 1.5 \, M_S + 15.8$$

for average California earthquakes with a stress drop of

30 bars. Although such correlations can be made with other magnitude scales for limited ranges of magnitude, the most generally applicable one is that which utilizes surface wave magnitude as given here. For recent earthquakes which have high quality instrumental data, it is also possible to measure the seismic moment directly from the seismograms by means of spectral analysis.

Considerable data exists for fault lengths, fault slip, and the strength of the crust. The remaining parameter, depth of faulting, is the most difficult to estimate. In California, virtually all the earthquakes on strike slip faults appear to be in the top 10-12 km of the crust. We know that motion must take place beneath this as well but this is the brittle region where sudden slip occurs producing earthquakes. In all the calculations referred to herein, we have assumed fault depths of 10 km and crustal rigidities of 3×10^{11} dynes/cm^2.

The first approach to relating seismic history to fault slip through seismic moment was done by examining the average seismicity during the last half century in the Southern Coast Range Province excluding both the San Andreas activity and the activity in the Transverse Ranges. This result is given in Appendix D-LL11A of Amendment 50 of the FSAR. To briefly summarize, it shows the usual type of size distribution for California earthquakes and yields the relationship

$$\text{Log } N = 3.72 - .92M$$

where N is the number of earthquakes per year that exceed magnitude M in the 54000 square kilometer region sampled. Distributing these earthquakes over the four principal northwest trending fault zones (Hosgri, Rinconada, Nacimiento, and Santa Lucia Bank) allows us to calculate a return period for earthquakes of a specified magnitude on each fault zone. For example, a magnitude 6.5 earthquake should be expected to occur about every 700 years somewhere along each of these four faults, if the statistics presented above are an adequate representation of the long-term average for the region. For this simple model, we can convert the postulated seismic activity into an estimate of fault slip by means of the seismic moment. Each of the four faults would have to be assumed to span the entire region we have sampled, thus making them about 200 km long. A rough calculation shows that one magnitude 6.5 earthquake every 700 years along a 200 km fault will lead to a net slip of about 1.5 meters over the past 17,000 years. Since observations of surface faulting show the slip locally may exceed 2 to 3 times the average slip, one would expect to see, locally at least, slip of several meters from this postulated level of seismic activity. This is in fact what has been observed in the seismic profiles across the Hosgri, leading us to the conclusion that this level of seismicity, up to magnitude about 6.5, is likely to represent the maximum that has occurred here. Similar calculations with a magnitude assumed to be 7.0 lead to a total average slip during the past 17,000 years of about 3 meters. From this one could expect to see slip locally exceeding 2 or 3 times this amount. Since fault slip of this magnitude would have produced a more significant and pervasive record of sea floor disturbance, even if it were primarily horizontal in direction, we conclude that earthquakes of this size cannot have been characteristic of this region during the last 17,000 years.

The above exercise is not viewed as conclusive proof, but rather was undertaken to see if the last half century of earthquake data in the Southern Coast Range Province makes a consistent picture when taken together with the geologic record of slip. We concluded that it did. In an effort to further test these ideas and examine the sensitivity of the result to the size of the region over which seismicity was sampled, the analysis was extended to include the entire plate boundary region from Cape Mendocino to Baja California. The result is described in Appendix D-LL45A of Amendment 50 to the FSAR. The resulting recurrence relationship for the entire 1350 km long plate boundary is:

$$\text{Log } N = 5.04 - .886 M$$

In order to use a statistical relationship like this, we need to apportion seismic activity between the San Andreas and the various secondary faults which parallel it. By way of illustration, if we distribute the earthquakes proportionally to the fault slip rates, we would find about 5% of the San Andreas activity on the Hosgri. This leads to an average return period for a magnitude 6.5 earthquake on the section of the Hosgri adjacent to Diablo Canyon of about 1000 years. The consistency of this result with that discussed earlier simply means that the sample of seismicity during the last half century in the Southern Coast Range Province is at least as representative of that region as is the larger sample representative of the entire plate boundary.

To further check the consistency of this approach, we can apply it directly to the San Andreas fault where a good deal more is known about the history of slip. Sieh (1978) by means of radio carbon dating techniques, reports that about 9 great earthquakes have occurred on the Palmdale section of the San Andreas fault since the 6th century A.D. The recurrence time ranges between 50 and 300 years with an average of 160 years. On the central section of the San Andreas (Carrizo Plain) he reports a recurrence time for great earthquakes of about 250 years. Slip rates inferred from these observations range between 3.7 and 6.0 cm/year. Using the last half century of instrumental data on earthquake occurrences, as in the previous examples, we would predict a magnitude 8-1/4 earthquake about every 185 years somewhere along the plate boundary. On a specific section of the fault, comparable to that which ruptured in the great earthquakes of 1857 or 1906, we could estimate the return period to be about 600 years. The slip rate corresponding to this estimate is only 2 cm per year. Thus, the sample of seismicity during the last 45 years appears to underestimate the plate boundary motion by a factor of about 2. This type of agreement is considered satisfactory considering that a significant part of the plate motion may take place as creep, or that the period of time sampled was not as seismically active as the average. In either case, the inference drawn regarding the Hosgri would err on the side of conservatism.

F. The 1927 Lompoc Earthquake

It is the understanding of Applicant and others that the U.S.G.S. conclusion that the Hosgri is capable of a 7.5 M earthquake depends to a large extent on their assumption that the 1927 earthquake could have occurred on the Hosgri. This possibility in turn depends on the Open file report by W. Gawthrop which located the 1927 earthquake on the Hosgri based on worldwide seismographic data. His result has not yet been published in the open scientific literature and has been the subject of considerable criticism. In my judgment the 1927 earthquake did not occur on the Hosgri fault.

On November 4, 1927, a magnitude 7.3 earthquake occurred off the coast of Point Arguello. The distribution of damage from this shock is shown in Figure 1, taken from Byerely (1930). Because of the poor quality of seismological data available in the late nineteen twenties, this pattern of actual earthquake effects probably represents our best information on where the event was located. Several different locations have been suggested, however, based on various types of analyses. They are summarized in Figure 2 which is taken from Hanks (1977) and illustrate the wide divergence of opinion regarding this earthquake. Before going further, it may be useful to list the most severe effects of this earthquake so as to maintain some perspective regarding its potential impact on the structure at Diablo Canyon:

<u>Honda</u> Several hundred thousand cubic feet of sand were shaken down from the cliff to the beach below.

<u>Roberds Ranch</u> Man thrown from feet; house shifted on foundations; chimmney thrown down, earthquake fountains; earth lurched; cracks in ground.

<u>White Hills</u> Poorly built block walls collapsed.

Clearly, if this earthquake had been on the Hosgri as assumed by Gawthrop (1975), its repetition even further north and adjacent to Diablo Canyon would pose no ground motion problem more severe than those originally considered in the design of the plant.

The evidence that can be brought to bear on the location of this earthquake is as follows:

1. Arrival times of seismic waves at distant seismograph stations in North America, Europe, Japan, and Australia. This data suffers from large errors in timing. My experience leads me to believe that of the various techniques for locating older earthquakes, this is the most unreliable. It is, however, the primary basis of Gawthrops conclusion and thus of the U.S.G.S. assumption regarding a magnitude 7.5 on the Hosgri fault.
2. Interval times between shear and compressional waves for aftershocks. This aftershock data was first exploited by Hanks, Hileman, and Thatcher (1975) making use of the fact that the S-P interval is a direct measure of distance from the recording station and thus can be used in a simple triangulation scheme. Their critical assumption was that the main shock would be located within the main body of the aftershock distribution. This data is more reliable than the direct arrival times mentioned above because it does not depend on the absolute accuracy of time keeping at a seismograph station but only on the difference in arrival time between two different seismic waves at the same station. As an example, the closest seismograph station, and thus potentially the most important one, was in the museum in Santa Barbara, but its arrival

time could not be used in a direct solution because the clock correction was completely unknown. The S-P times for hundreds of aftershocks, however, could be accurately measured from these records.

3. Intensity data. The pattern of isoseismals, or lines of roughly equivalent earthquake damage effects shown in Figure 1, gives us a general idea of the north south location of the shock, but not much about its distance off shore. This pattern would put the earthquake directly offshore from Point Arguello.
4. Sea floor topography. An earthquake of this site would be expected to produce surface displacement. A careful examination of high resolution seismic profiling reveals no sea floor offsets along the Hosgri that appear as if they could have been associated with this earthquake. A recently active structure, the Lompoc faulted anticline, however, shows sea floor disturbances of approximately the right magnitude to account for this earthquake.

Although taken separately, none of these lines of reasoning leads to a definite conclusion regarding the location of the earthquake; when taken together, they point convincingly toward the Lompoc structure as the source. This is perhaps best illustrated by Figure 3 in which the possible locations and their associated error bounds are shown to overlap in the region of the Lompoc structure.

G. Peak Instrumental Acceleration At The Site

There has been a steady increase in the amount of ground motion data available in the decade since our original report was written. Because the sample now includes a fairly large body of earthquakes, recorded in a wide variety of circumstances, we have started to see occasional accelerations in excess of 1 g. The number of these observations is small, and fits well within the extreme bounds that one would expect due to statistical scatters. The variation in recorded accelerations is due to combined effects of local geological and soil conditions, topography, and rupture propagation (focussing) phenomena. As an example, the Pacoima record of the San Fernando earthquake which showed accelerations up to 1.15 g was most likely a result of both focussing of energy due to rupture propagation and amplification due to the location of the instrument on a ridge. These physical explanations do not in any way detract from the validity of this measurement but they point out that there is a difference between recorded ground motion and ground motion used as input to a design analysis. In this particular instance, the strong motion station location high on the ridge above the Pacoima Dam makes it very obvious that this instrumentally recorded motion is inappropriate for design. In other earthquakes, the effects of special circumstances may not be so obvious, and furthermore, they may contribute to either decreasing or increasing the "free field" or undisturbed ground motion that should be used for design purposes. It is for this reason that the body of strong ground motion be viewed from a statistical standpoint. Of the thousands of earthquake records that now exist, three have shown accelerations in excess of 1 g. They are

Pacoima, Calif.,	1971	1.15g	Magnitude 6.4 M_L	Intensity (MM) X
Naghan, Iran,	1977	1.08g	5.5	VII +
Karakyr, U.S.S.R.,	1976	1.30g	6.6	IX

The circumstances that produced these accelerations are very complex, and we cannot at the present time expect to understand them in all details. We do understand enough of the conditions regarding the Hosgri fault, however, to make some assessment about the gross effects of topography, rupture propagation, and geologic conditions there and thus assess the relevance of these high acceleration records to the case at hand. Topography amplification or soil amplification can be ruled out immediately based on the known properties of the site. Rupture focussing effects can be estimated and shown to be significantly less than those for Pacoima which is the best understood of the three examples based on the strike and dip of the Hosgri fault and its distance and geometrical relation to the site.

Hanks and Johnson (1976) have examined all available near field data and concluded there is no magnitude dependence of peak acceleration above magnitude 4.5. The recent data from Iran and the Soviet Union do not change this result. The average of all peak accelerations from earthquakes above magnitude 5.5 recorded in the near field is now .49g with a standard deviation of .40g. Thus from either a deterministic approach where we try to assess the physical processes that have produced existing strong motion records and extrapolate to the Hosgri fault, or from a statistical approach where raw peak accelerations are simply averaged, the conclusion is that a peak ground acceleration of 1.15 g at Diablo Canyon for a large earthquake on the Hosgri is a very conservative estimate. The term "large earthquake" is used because of the fact that peak motion in the near field is essentially independent of magnitude.

H. Conclusion

Based on my evaluation of the Diablo Canyon site and related surrounding geologic and seismic data, I can conclude within a reasonable degree of seismological certainty the following:

1. The original seismic evaluation of 1967 provided many conservatisms which could be relaxed in light of present day knowledge and data.

2. The current assumptions made in the Hosgri reanalysis of Diablo Canyon in whch a magnitude 7.5 earthquake

is specified on the Hosgri must be classified as grossly conservative.

3. There have not beeen recurrent earthquakes above about a 6.5 magnitude on the Hosgri in the past 17,000 years.

4. It is highly unlikely that the 1927 Lompoc earthquake occurred on the Hosgri.

5. A peak ground acceleration of 1.15g at Diablo Canyon for the maximum earthquake on the Hosgri is a very conservative estimate.

REFERENCES

Ambraseys, M.N. -- Preliminary Analysis of European Strong-Motion Data 1965-1978 Part II Report by E.A.E.E. Work Group on Strong Motion Studies, 1978.

Boone, David M., A. Olivier, R. Page, and W. Joyner -- Estimation of Ground Motion Parameter, U.S. Geol. Survey Open File Report 78-509, 1978.

Brune, James N. -- Seismic Moment, Seismicity, and Rate of Slip Along Major Fault Zones, J. Geophys. Research 73 pp. 777-784, 1968.

Byerly, Perry -- The California Earthquake of Nov. 4, 1927 Bull. Seism. Soc. Am. 20 pp. 53-66, 1930.

Davies, Geoffrey F. and J. Brune -- Regional and Global Fault Slip Rates from Seismicity, Native Phys. Science 229 pp. 101-107, 1971.

Flemmons, David B. -- State-of-the-art for Assessing Earthquake Hazards in the United States, Report No. 6. Faults and Earthquake Magnitude U.S. Army Engineers, Wash. D.C., 1977.

Gawthrop, W. -- Seismicity of the Central California Coastal Region, U.S. Geol. Survey Open File Report pp. 75-134.

Hanks, Thomas C. and D. Johnson -- Geophysical Assessment of Peak Accelerations, Bull. Seism. Soc. Am. 66 pp. 959-968, 1976.

Hanks, Thomas C. -- The Lompoc, California, Earthquake (Nov. 4, 1927; M = 7.3) and its Aftershocks Submitted for publication by the Bulletin Seismic Society of America, 1978.

Hanks, T.C., J.A. Hileman, and W. Thatcher -- Seismic Moments of the Larger Earthquakes of the Southern California Region, Geol. Soc. Am. Bull. 86 pp. 1131-1139, 1975.

Kanamori, H and D. Anderson -- Theoretical Basis of Some Empirical Relations In Seismology, Bull. Seism. Soc. Am. 65 pp. 1073-1095, 1975.

Lee, W.H.K., C.E. Johnson, T.L. Henyey, and R.F. Yerkes --A Preliminary Study of the Santa Barbara Earthquake of Aug. 13, 1978 and its Major Aftershocks, Unpublished Report of the U.S. Geol. Survey, Menlo Park, Calif. 1978.

Page, Robert A., D. Borre, W. Hayner and H. Coulter, Ground Motions Valves For Use In Seismic Design Of The Trans-Alaska Pipeline System USGS Circular 673, Washington, D.C., 1972.

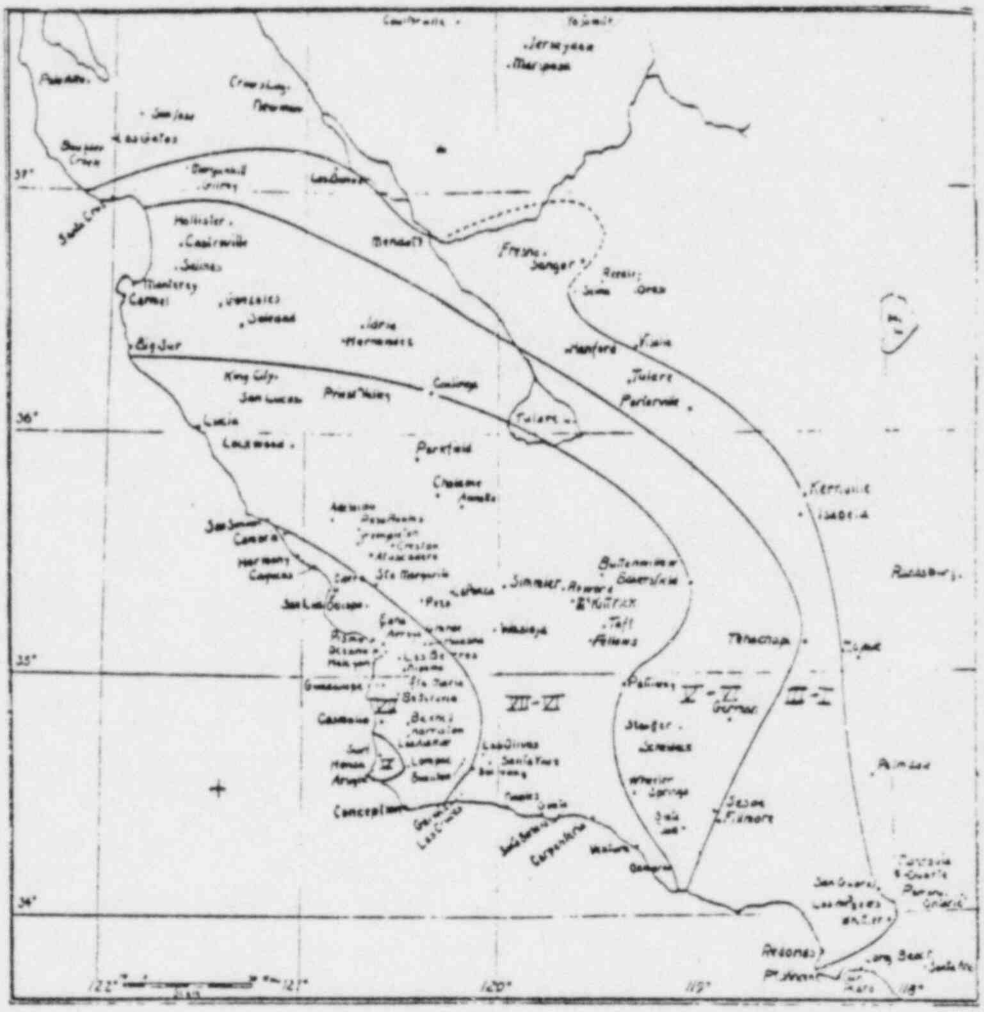
Person, Waverly J. -- Seismological Notes May-June 1976, Bull. Seism. Soc. Am. 68 pp. 255-264, 1978.

Savage, J.C., and W. H. Prescott, Geodetic Control and the Lompoc, California, Earthquake, Submitted for publication by the Bulletin Seismic Society of America, 1978.

Sieh, Carry E. -- Prehistoric Earthquake Produced by Slip on San Andreas Fault at Pallet Creek, California, J. Geophys. Research 83 pp. 3907 and 3939, 1978.

Smith, Stewart W. -- Determination of Maximum Earthquake Magnitude Geophys. Research Letters, 3 pp. 351-354, 1976.

Wyss, Max and J. Brune -- Seismic Moment, Stress, and Source Dimensions for Earthquakes in the California-Nevada Region, J. Geophys. Research 73 pp. 4681-6494, 1968.

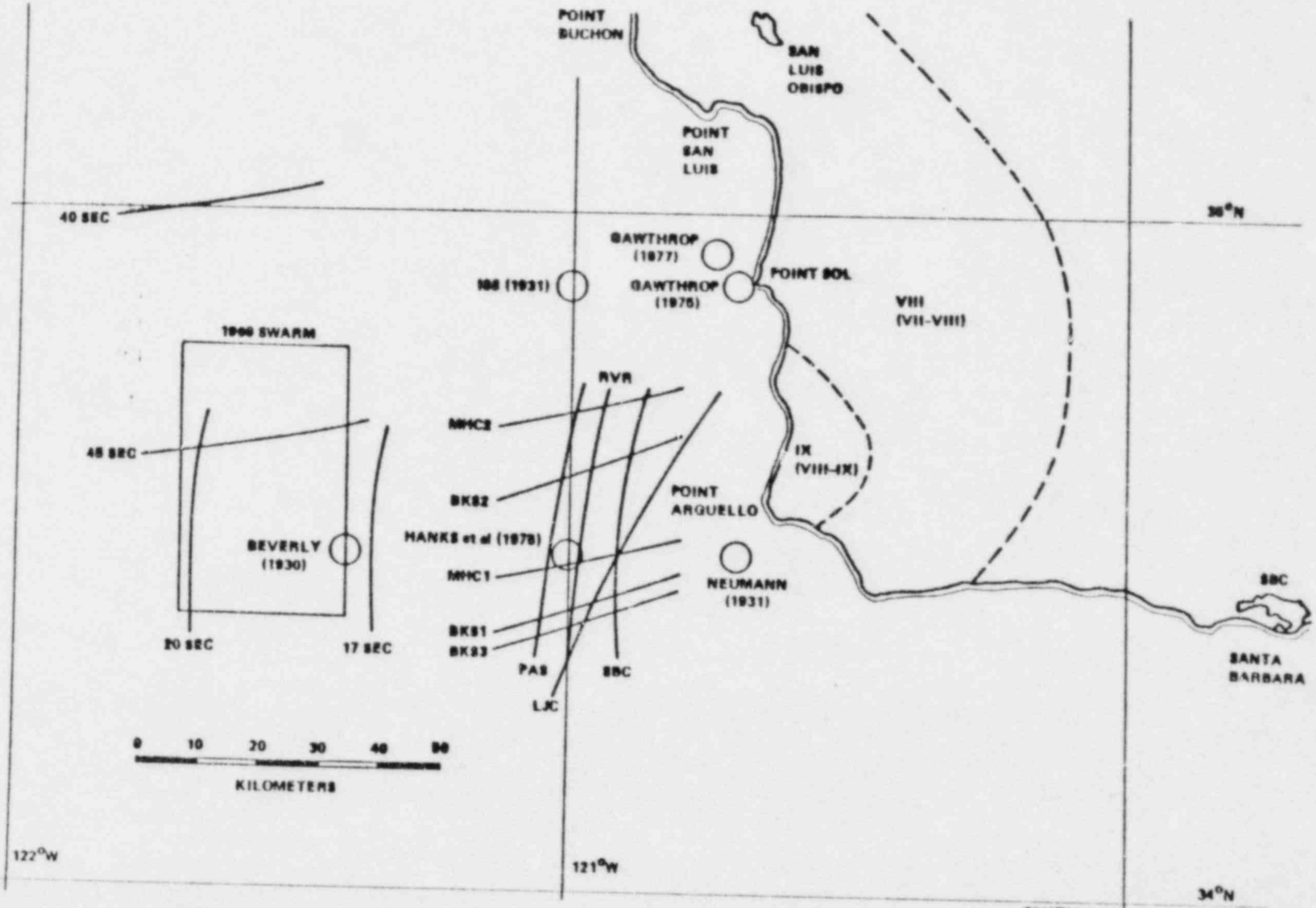


ISOSEISMALS FOR 1927 EARTHQUAKE

FIGURE 1

SMITH

FIGURE 2



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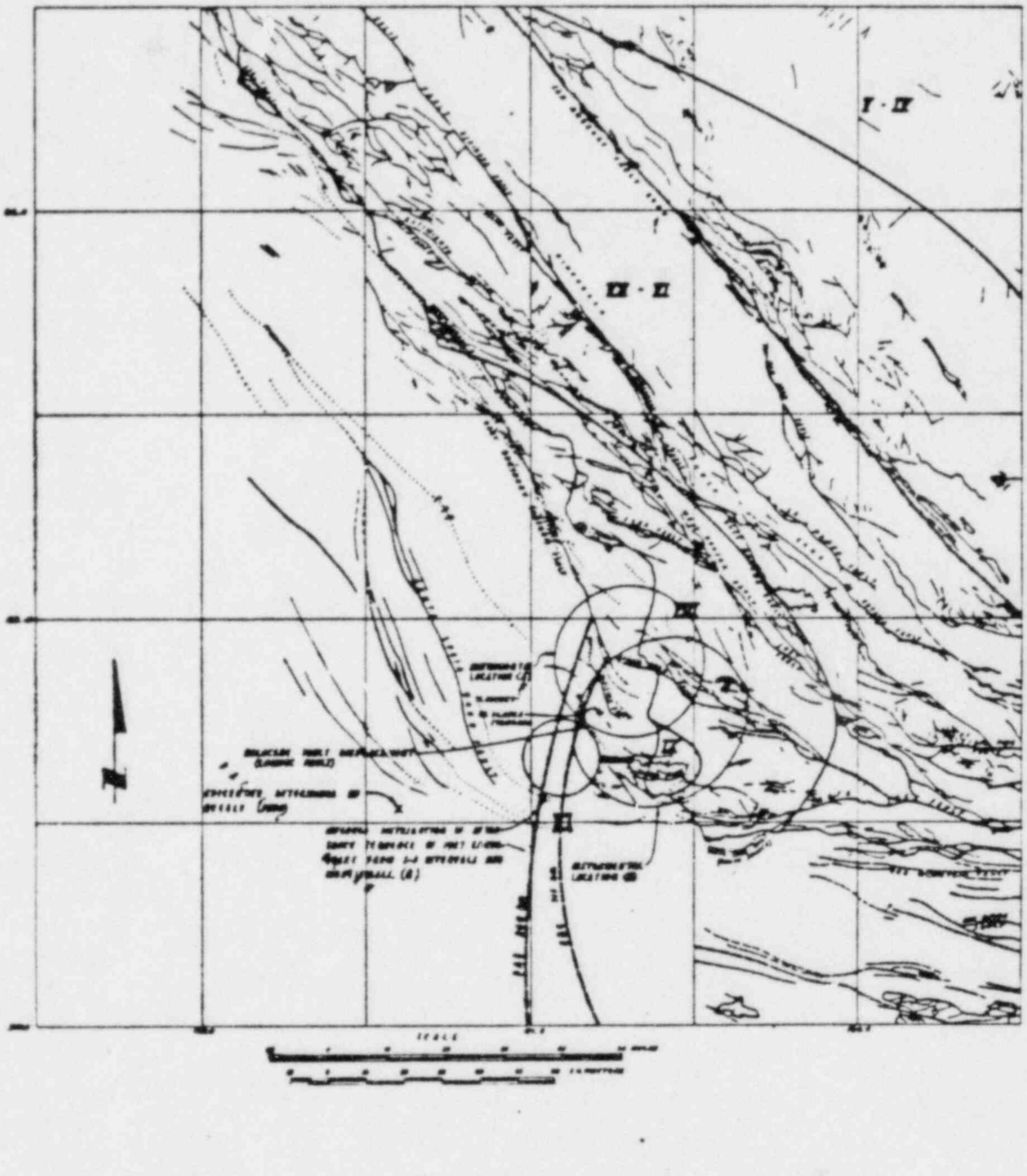

FIGURE 3