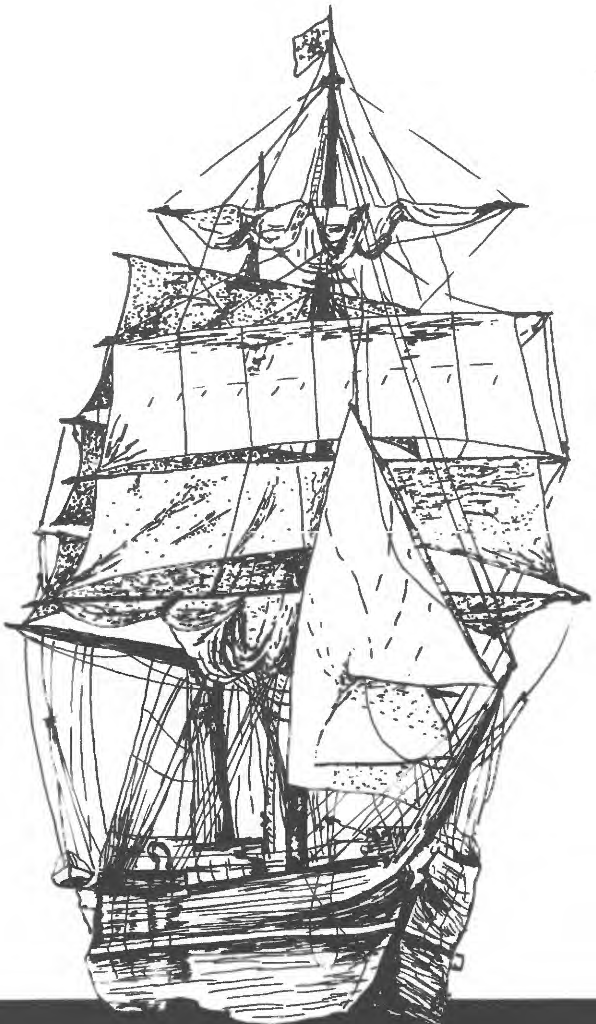
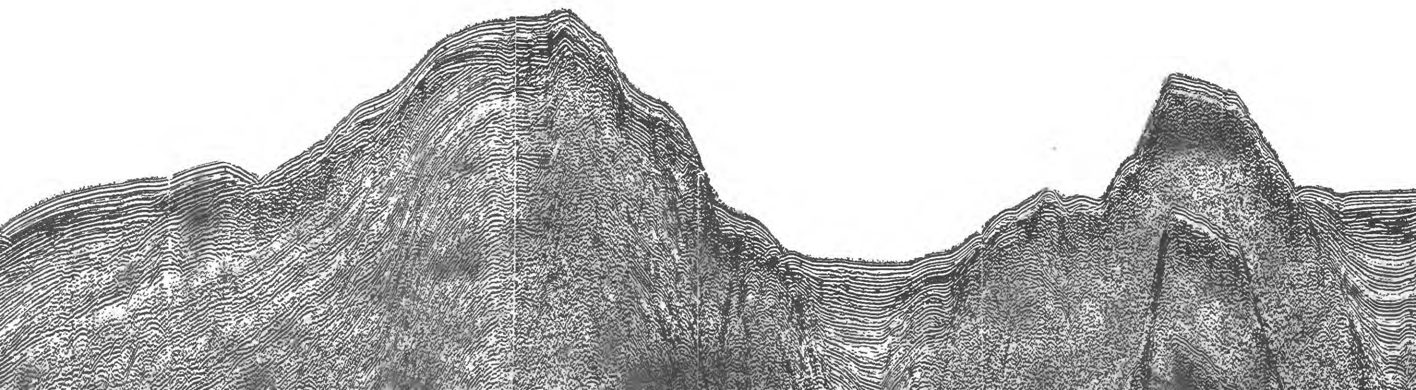


General Geology, Petroleum Appraisal, and Nature of Environmental Hazards Eastern Pacific Shelf Latitude 28° to 38° North

GEOLOGICAL SURVEY CIRCULAR 786



General Geology, Petroleum Appraisal, and Nature of Environmental Hazards Eastern Pacific Shelf Latitude 28° to 38° North

By D. G. Howell, D. S. McCulloch, and J. G. Vedder

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ILLUSTRATIONS

General Geology, Petroleum Appraisal, and Nature of Environmental Hazards, Eastern Pacific Shelf Latitude 28° to 38° North

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INTRODUCTION

SETTING

Additional petroleum exploration is anticipated within the Federal waters of the California offshore region. To assist in evaluating the impact of petroleum exploration and development, the geology and environmental setting of the Outer Continental Shelf (OCS) are reviewed for the region from the latitude of San Francisco Bay (38° N.) to the approximate latitude of Cedros Island (28° N.), Baja California, Mexico.

This area is nearly 2,000 kilometers long; within it, the shelf width varies from as little as 10 km south of Point Sur to as much as 280 km off San Diego (fig. 1). All or part of three physiographic provinces lie within the area. From north to south, these provinces are the central California shelf, the western Transverse Ranges, and the California Continental Borderland (fig. 2). The geologic history, tectonics, stratigraphy, and petroleum potential of each of these provinces are different. In addition, the origin of the anomalous west-trending Transverse Ranges is poorly understood. Consequently, the provinces are treated separately; and the general geology,[1] petroleum potential, and environmental hazards are outlined for each.

PLATE TECTONIC PROCESSES

Plate tectonic processes have largely governed the geologic development of the three provinces. The west margin of California appears to have been a zone of oblique plate convergence throughout most of the late Mesozoic and early Cenozoic Eras. Atwater and Molnar (1973) conclude that subduction occurred along the entire western U.S. continental margin before 29 m.y. ago, after which an increasing segment of the margin was subjected to right-lateral translational shear; thus, in Oligocene time the tectonic setting for this area underwent a profound transition from a convergent to a sliding margin. At present, more than 90 percent of the known petroleum accumulations west of the San Andreas fault in California occur in strata deposited in areally restricted Neogene basins that formed during this major tectonic reorganization of western California (fig. 3). Figure 4 shows most of the major late Quaternary faults that are believed to be a tectonic expression of the Pacific-North American plate motions.

ENVIRONMENTAL HAZARDS

Much of the study area is a zone of strong ground shaking due to earthquakes (fig. 5). The areas where the highest ground accelerations would be expected are in California along the San Andreas fault and in the Owens Valley east of the Sierra Nevada. Maximum values within these areas represent accelerations of about 0.8 *g*. Although acceleration does not describe all characteristics of ground motion, it is frequently used in establishing design criteria for earthquake-resistant structures.

Instability of the seafloor, whether resulting from seismic activity or sedimentary processes, is the principal hazard to emplacement of platforms and pipelines offshore. Hazards related directly to seismic activity include ground shaking, fault rupture, generation of tsunamis, and earthquake-induced failures such as liquefaction and slumping. Faults showing displacement either of the seafloor or of young (< 11,000 years) sediment and faults associated with historical earthquakes are considered active and therefore potentially hazardous to development. Instability of the seafloor also can result from dynamic forces, such as wave surge, and static forces, such as gravity acting independently of seismic activity. Some areas of the seafloor are prone to mass movement (slumps, slides) or other forms of sediment transport (flows, creep, or current scour). Oil and gas seeps, though not inherently hazardous, may indicate the presence of fractured reservoir and cap rocks and shallow overpressured gas pockets that can pose danger to drilling operations.

Tsunamis (seismic sea waves) are large oceanic waves generated by earthquakes, submarine volcanic eruptions, and large submarine landslides. The waves are formed in groups and have great wave length and a long period. In deep water, wave heights (crest to trough) may be a few meters or less, wave lengths a hundred kilometers or more, and velocities greater than 750 km/hour. As a tsunami enters shallow water, wave velocity diminishes and height increases. At places, such waves are known to have crested at heights of more than 30 m and to have struck with devastating force.

[1] The stratigraphic nomenclature used in this report is from many sources and may not entirely conform to U.S. Geological Survey usage.

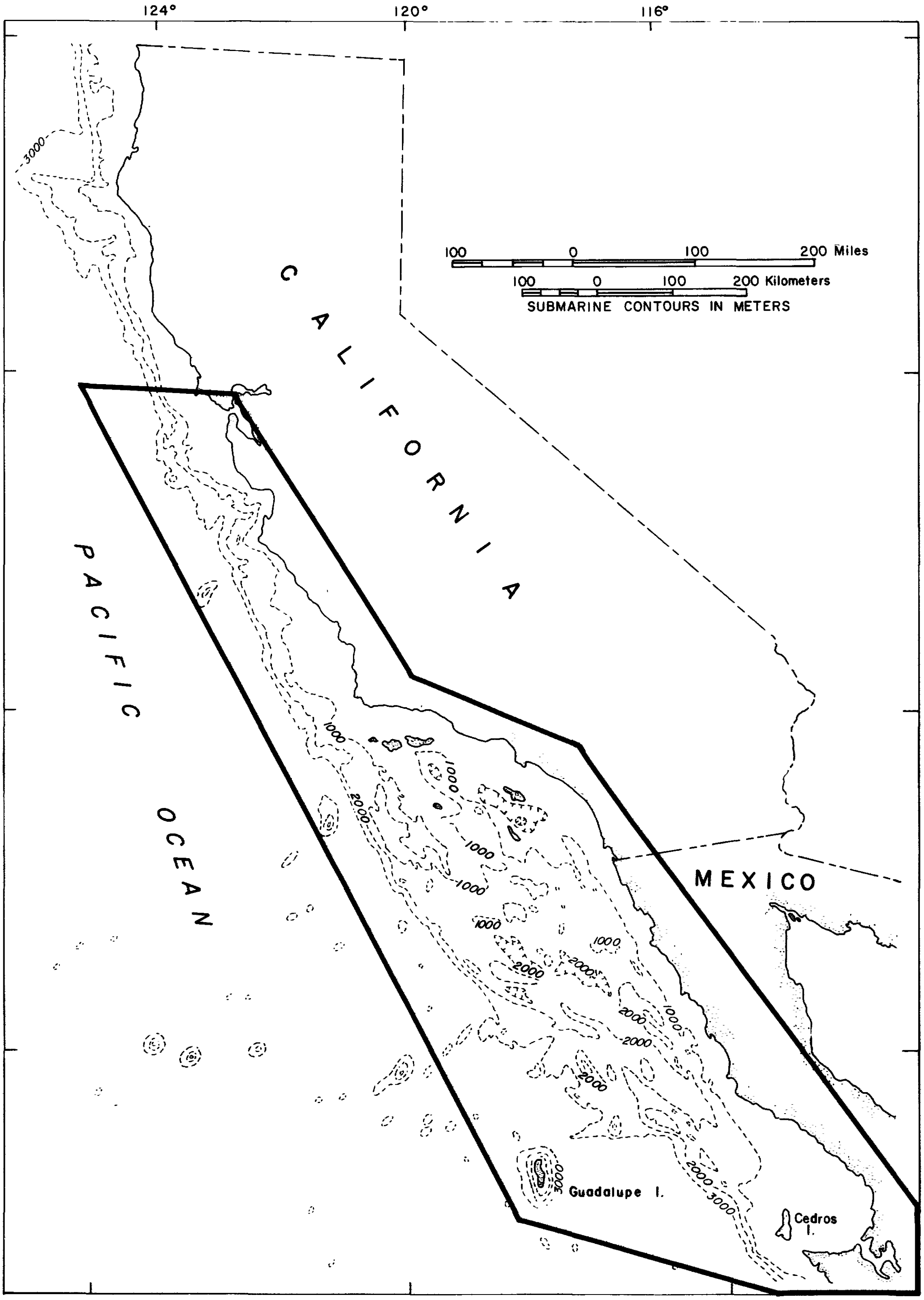


Figure 1. Physiographic index map for region discussed in text.

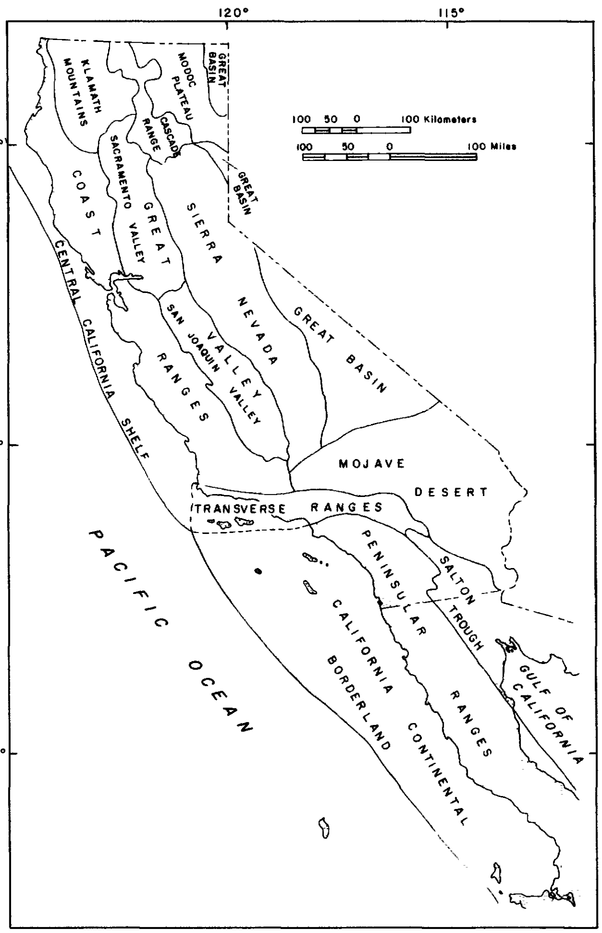


Figure 2. Physiographic provinces of California and Baja California, Mexico.

CENTRAL CALIFORNIA COAST

GEOGRAPHY

Offshore from central California south of lat 38° N. is a 500-km-long shelf, 100 km wide at the south end, west of Point Arguello, that narrows northward to 30 km wide west of Santa Cruz. Underlying the gentle relief of this shelf are three major structural highs, the Farallon-Pigeon Point high, the Outer Santa Cruz high, and the Santa Lucia high (fig. 6). Cutting across Monterey Bay is a major east-west trending submarine canyon. On the shelf south of San Francisco there are two sediment-filled troughs, the Outer Santa Cruz and the Santa Maria basins (figs. 3, 6a, and b).

GEOLOGY

Beneath the seafloor, major structural highs and basin axes trend generally northwest (fig. 6a, b). At most places the basins are bounded on the east by major nearshore faults with a shoreward side up sense of vertical displacement. Between these faults and the shore, the structures generally have a more westerly trend. The basement terrane of the shelf and the adjoining Coast Ranges province is composed of allochthonous blocks with spatial relations that reflect the complex kinematics of a dynamic plate margin (fig. 7). Sedimentary rock units of Late Jurassic to Holocene age are present in the Coast Ranges province, but discussion of rocks in the offshore region is limited to the strata of the Cenozoic basins where petroleum exploration may be expected.

Outer Santa Cruz basin.--This relatively shallow late Tertiary basin, which is approximately 25 km by 100 km in extent, trends northwest across the shelf, and extends onto the adjacent continental slope. It is bounded on the west by the Outer Cruz high and on the northeast by the Pigeon Point high. Hoskins and Griffiths (1971) have suggested that this basin is underlain by granitic rocks, based on unstated geophysical evidence and on the proximity of granitic rocks to the east. Alternatively, McCulloch and others (1977) have suggested that the Pigeon Point high composes the western edge of the Salinian block, and that the Outer Santa Cruz basin may be underlain by the Franciscan assemblage.

Two exploratory wells in the basin bottomed in Upper Cretaceous strata, primarily sandstone; however, the distribution of the Cretaceous and early Tertiary (Oligocene?) rocks is not known (Hoskins and Griffiths, 1971) (figs. 8 and 9). Deformation and erosion followed both the Cretaceous and Oligocene(?) episodes of deposition. Fine-grained clastic rocks and volcanic strata are interbedded in the early Neogene strata. Overlying these rocks is a sequence of strata composed chiefly of cherty shale of middle Miocene age. Uplift of the structural highs by late Miocene time resulted in basin-filling deposition of terrigenous detritus.

The structural axis of the basin and the Outer Santa Cruz high plunge to the northwest, beyond the edge of the continental shelf. The sediment thickens downslope, but appears to be blocked along the base of the slope by a discontinuous volcanic ridge along which the Mulberry, Guide, and Pioneer Seamounts form prominent topographic highs. Beneath an early late Miocene unconformity, the rocks are gently folded; and the faults are generally high-angle reverse with a vergence to the west. The southwestern basin margin does not appear to be fault controlled, for the early Tertiary sediment is upturned along the flank of the Outer Santa Cruz high. The northeastern margin is controlled by down-to-basin faulting that displaces rocks at least as old as the late Miocene unconformity.

Santa Maria basin offshore.--This basin measures approximately 40 km by 230 km and is elongate parallel to the coast. The northwest end of the offshore Santa Maria basin continues onto the continental slope. It is bounded on the northeast by Franciscan basement rocks that have been elevated along major coastal faults,

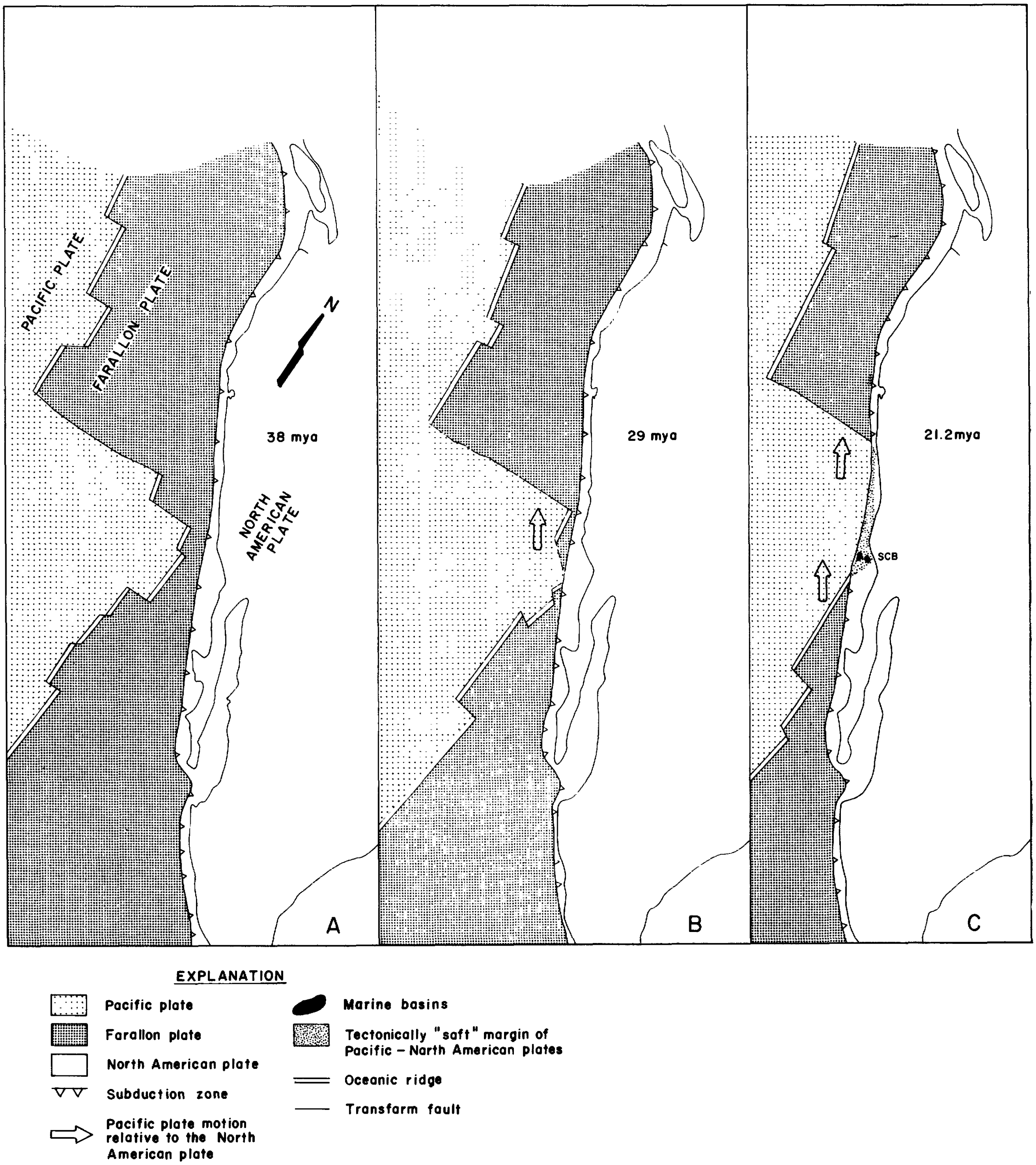
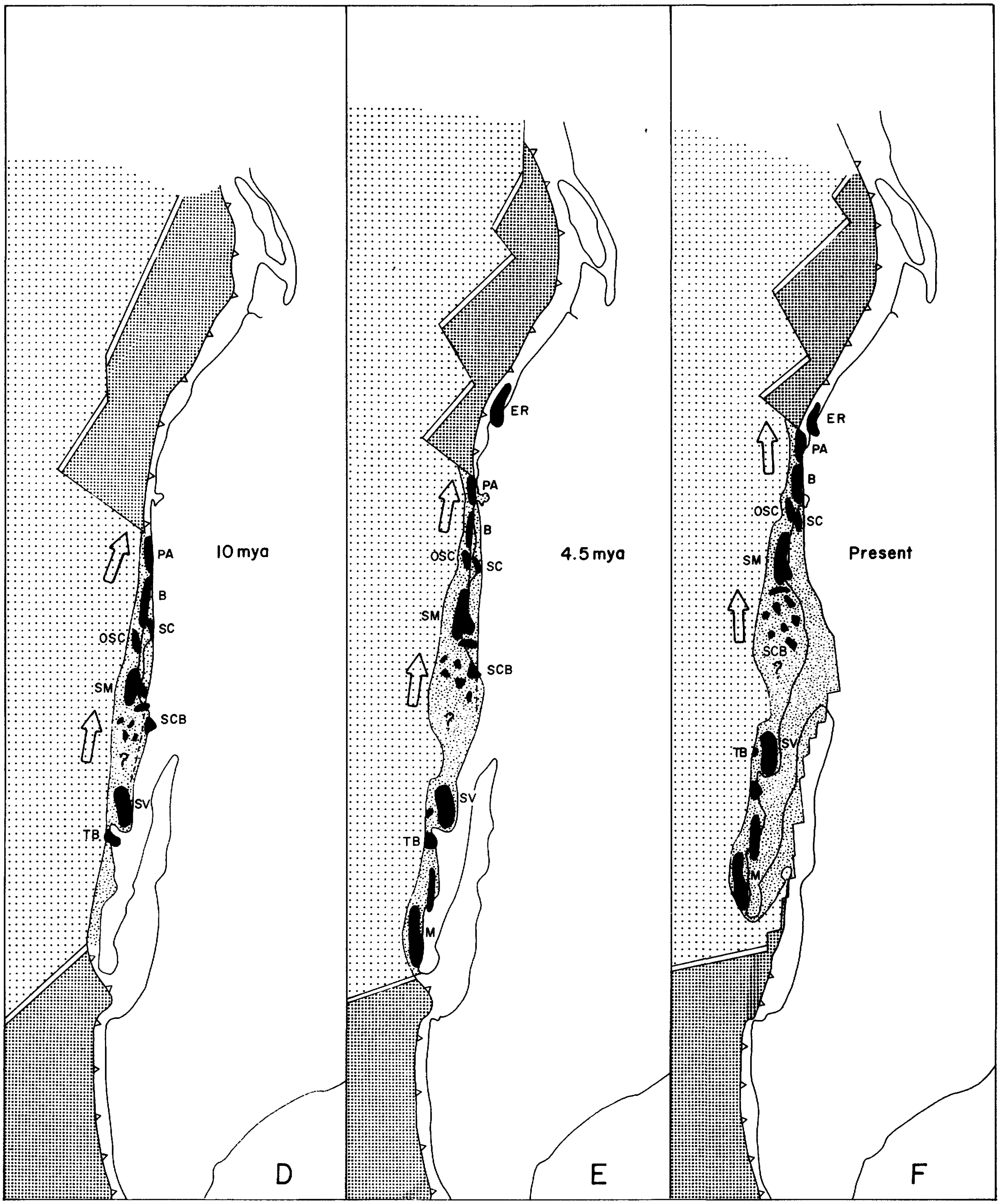


Figure 3. Schematic model of the interaction of Pacific-Farallon and North American plates for six Neogene time intervals, showing the time of initial development, location, and general shape of Neogene basins that formed in the tectonically "soft" or pliant zone between the Pacific and North American plates. The develop-



ment of basins in the Gulf of California is not shown. ER = Eel River basin, PA = Point Arena basin, B = Bodega basin, SC = Santa Cruz basin, OSC = Outer Santa Cruz basin, SM = Santa Maria basin, SCB = Southern California basin, SV = Sebastian Vizcaino basin, TB = Tortugas basin, and M = Magdalena borderland. (Blake and others, 1978).

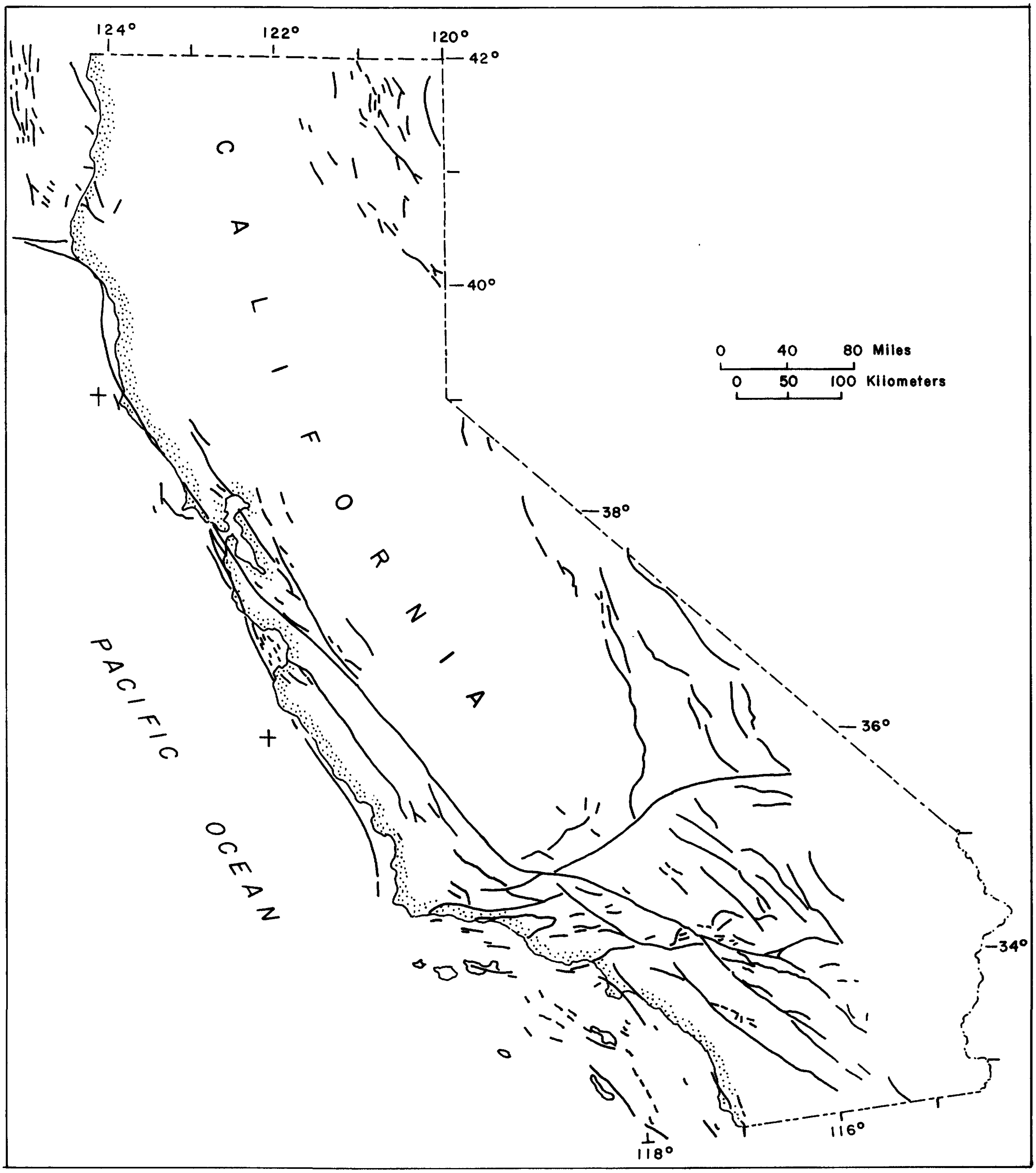


Figure 4. Major Quaternary faults of California (modified from Jennings and others, 1975).

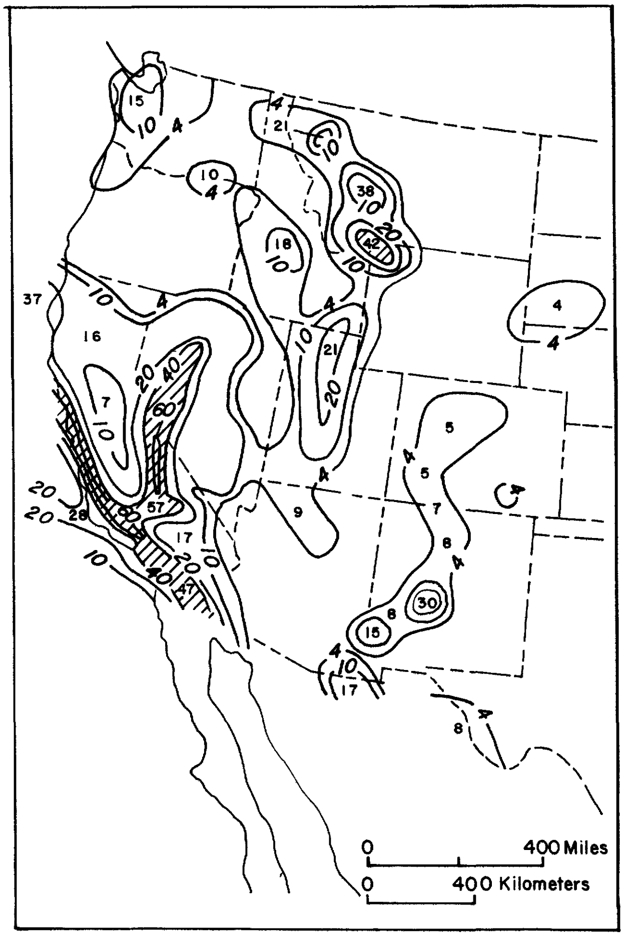


Figure 5. Contours showing estimated seismically generated bedrock accelerations for which there is a constant 90 percent probability that the acceleration will not be exceeded in 50 years. Numbers indicate horizontal acceleration in hard rock expressed as a percentage of g, the Earth's gravity. The numbers within each contour are the maximum expected acclera- tion within the 60-percent contour along the San Andreas and Garlock faults in California is 80 per- cent of g (from Algermissen and Perkins, 1977).

and on the southwest by the Santa Lucia high, an elevated basement block (fig. 6b). A 1972 expedition of the USNS Bartlett recovered from dredge hauls over this bank a variety of rock types that included metasediments, altered mafic igneous rocks, and a large number of granitic fragments (R. E. von Huene, oral commun., 1978). Hoskins and Griffiths (1971) suggested the base- ment of the Santa Lucia high may be granitic because of the structural style of the high and adjoining basin as well as the presence of coarse arkosic sandstone of possible Late Cretaceous and Eocene age. If the basement is granitic, it would necessitate considerable revision of exist- ing tectonic reconstructions of this area which now limit granitic basement to the Salinian block. It is more likely that the basement for the entire offshore area of Santa Maria consists of the Franciscan assemblage and strata equivalent to the Great Valley sequence. Both groups of rock are exposed along the adjoining mainland coast, and included in the Franciscan assemblage are indurated massive arkosic sandstone beds of possible Late Cretaceous age. Where similar rocks crop out near Cambria and Point San Luis, they typically are folded isoclinally and lie above melange (Howell and others, 1977).

Available information concerning the char- acter and distribution of post-Cretaceous rocks in the basin consists of one borehole and in- ferred seismic correlations of acoustic units with onshore lithologies. Based on these limited data a generalized stratigraphic column for the entire basin and a cross section of the basin have been constructed (figs. 10 and 11).

Paleogene rocks (marine mudstone, silty shale, sandstone) are present on the Santa Lucia high. These strata are truncated by an early Tertiary unconformity, and their distri- bution in the basin is thought to be limited to erosional remnants. The lowest Neogene rocks may be volcaniclastic and may contain a few thin igneous flow units. The overlying, acous- tically thin-bedded, wedge-shaped unit (Tmx) may correlate with tuff in the Humble Oceano No. 1 test well, an equivalent to the onshore Obispo Formation, which is early and middle Miocene in age (Crawford, 1971). This unit is verlain by a bedded unit (seafloor samples from the Santa Lucia high indicate that this unit is a foraminiferal siliceous shale of middle Miocene age. The thin-bedded, highly reflective acoustic character of this unit, together with the presence of chert in dredge hauls and dart cores from seafloor exposures suggest that it is in part equivalent to the Monterey Formation. The uppermost unit, principally of Pliocene and Pleistocene de- posits, rests with local unconformity on the thin-bedded unit. The upper unit probably includes a minor amount of upper Miocene strata in the lower part.

PETROLEUM APPRAISAL

The area offshore from central California has been explored by the petroleum industry and geophysical companies during at least the last two decades. For example, Hoskins and Griffiths (1971) indicate that the Shell Oil Company completed an extensive network of shallow and deep penetration seismic reflection profiles over the entire shelf and collected seafloor samples by dart core and shallow borings. Some industry exploration was done in anticipation of and following the May 14, 1963, lease sale that included the offshore Santa Maria and Outer Santa Cruz basins; and ultimately, three exploratory wells were drilled. Most targets appear to have been structural rather than stratigraphic traps in these two basins.

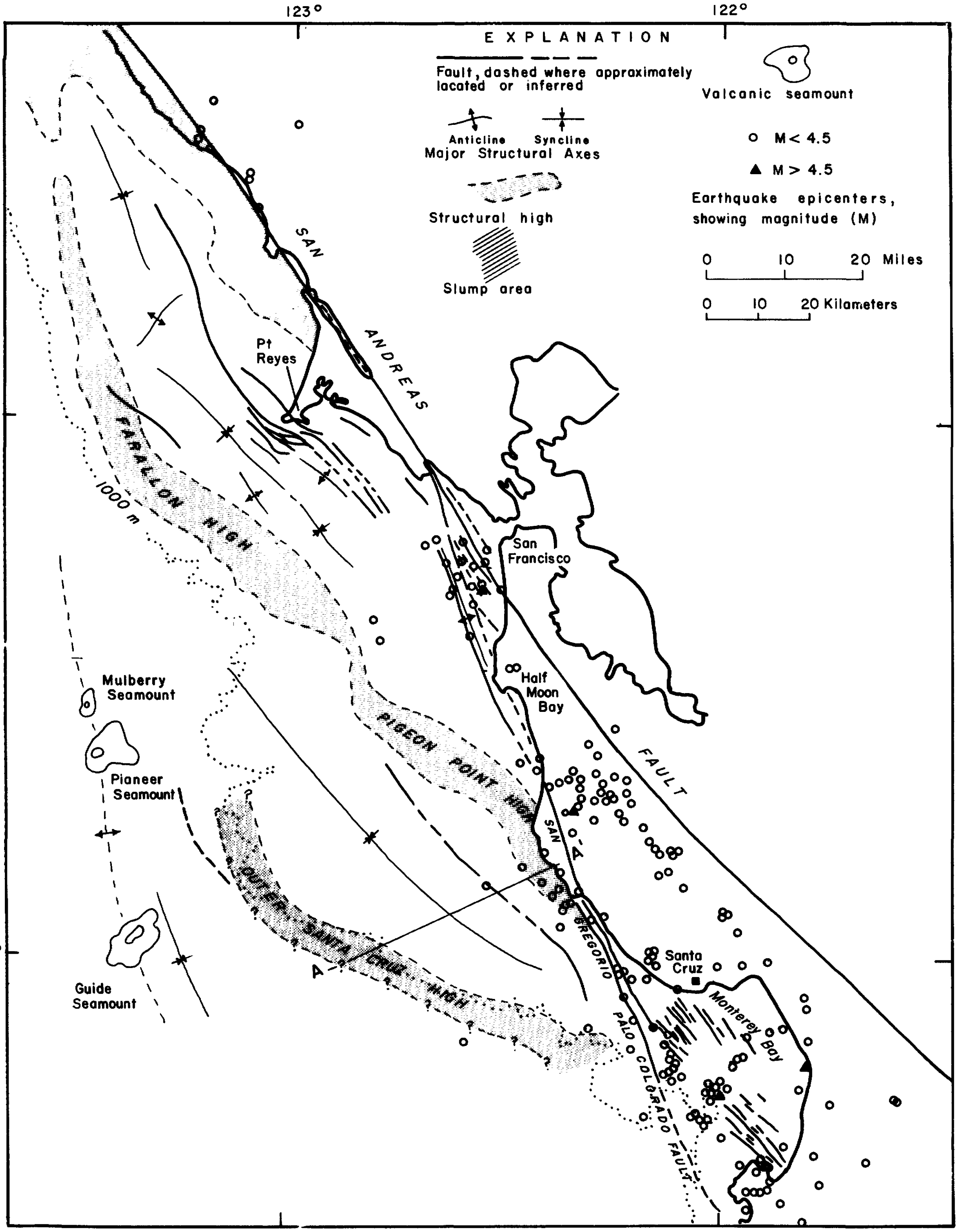
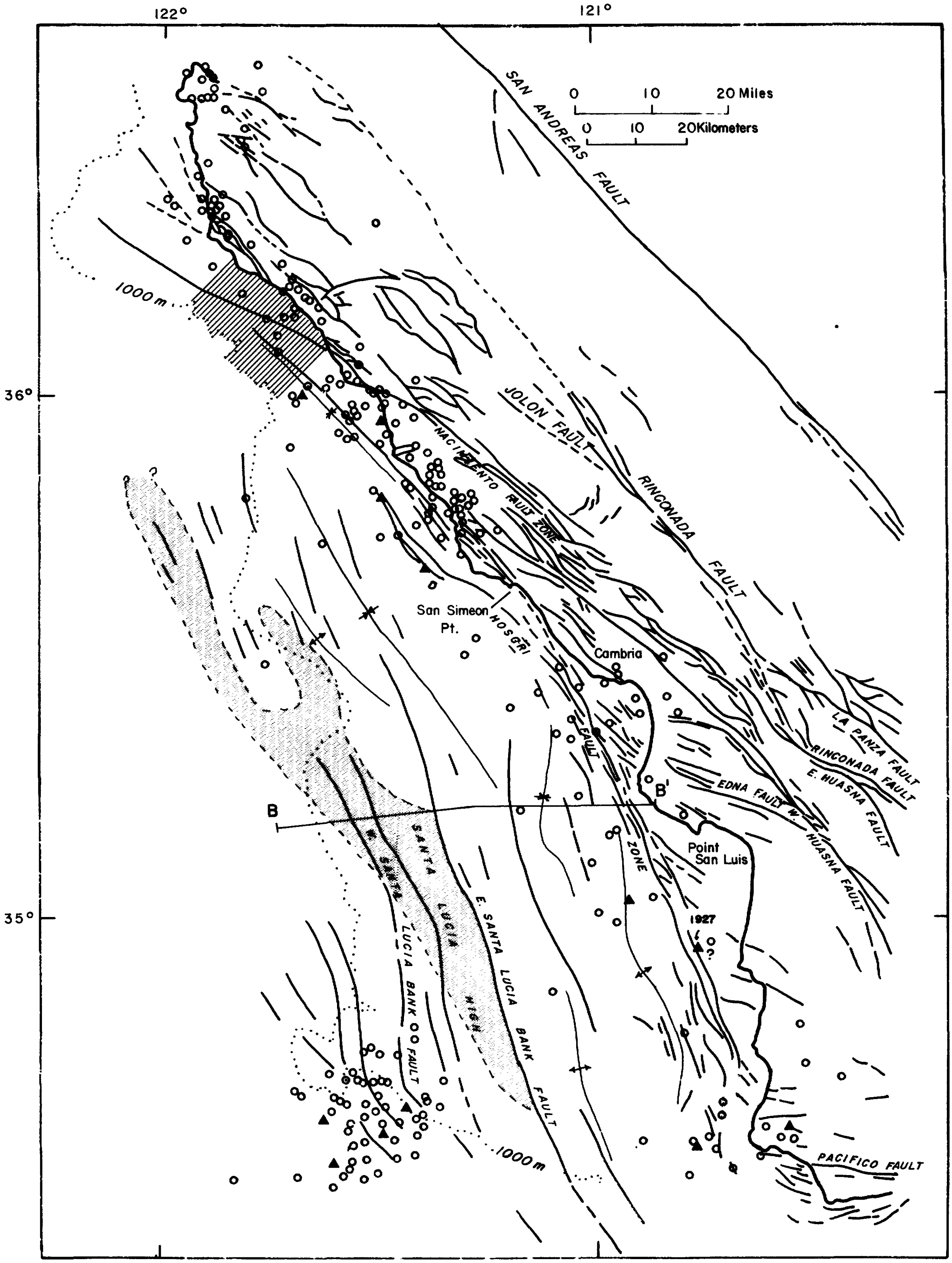


Figure 6. Generalized geologic structures, Point Conception to Point Reyes. Sources include: Hoskins and Griffiths (1971), Greene and others (1971), Earth Science Associates (1974), Jennings (1975), and unpublished



data from H. C. Wagner, E. A. Silver, D. S. McCulloch, and H. G. Greene. Epicenter locations from 1812 to 1976 from Gawthrop (1975, and written commun., 1977).

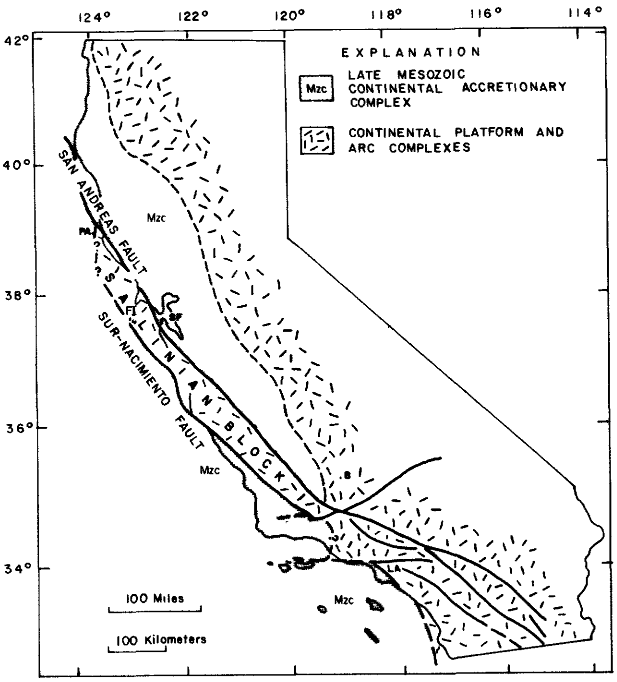


Figure 7. Basement relations along Sur-Nacimiento and San Andreas fault zones (partly based on Figure 95 of King, 1959). Localities: B = Bakersfield; FI = Farallon Islands; LA - Los Angeles; PA = Point Arena; SF = San Francisco. (Modified from Page, 1970).

Production from fields in the onshore Salinian block adjacent to the Outer Santa Cruz basin has been low. The principal onshore fields (La Honda, Half Moon Bay, Oil Creek) had produced a cumulative total of only 1.3 million barrels of oil, and 300 million cubic feet of gas by December 1975. Most production is from Miocene and Pliocene strata. The nearest significant production is from San Ardo field, nearly 200 km southeast of Santa Cruz, where oil and gas are recovered from coarse sandstone zones at the base and in the middle of the Miocene Monterey Formation. Cumulative production from San Ardo through December 1975 was 0.29 billion barrels of oil and 71 billion cubic feet of gas (California Division of Oil and Gas, 1960, 1975). Probable source beds in the Outer Santa Cruz basin are tar-impregnated middle Miocene cherty shale that occurs throughout the basin. Pre-Miocene reservoir beds have not been drilled, but Hoskins and Griffiths (1971) state that the data are insufficient to conclude that such reservoir rocks are absent. Cretaceous rocks below the lower Miocene erosional unconformity are highly deformed, dense, and indurated. Minor oil shows are present in upper Miocene and Pliocene rocks, but these rocks generally are fine grained and of poor reservoir quality.

Nearly 75 percent of the oil (0.5 billion bbls) in the Santa Maria basin onshore is produced from reservoirs of middle Miocene frac-

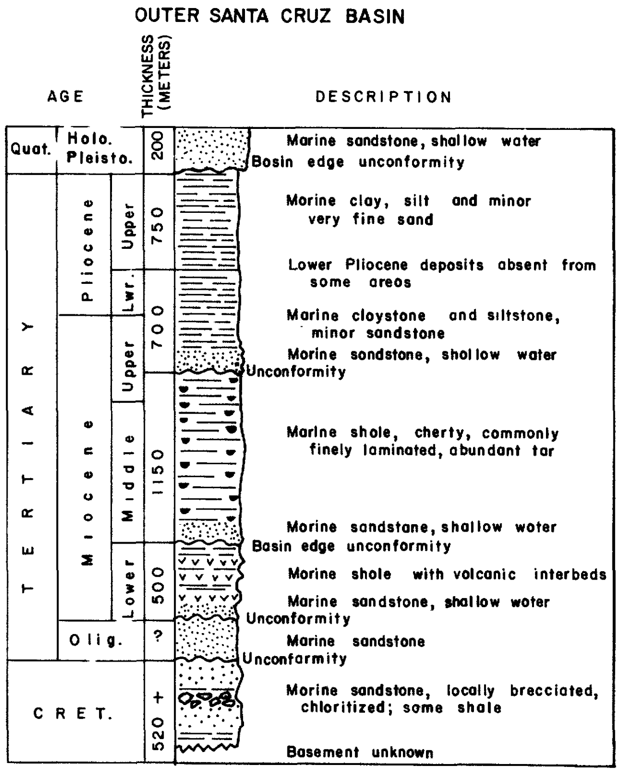


Figure 8. Generalized stratigraphic column for the Outer Santa Cruz basin. The stratigraphic nomenclature, modified from Hoskins and Griffiths (1971), does not necessarily follow the usage of the U.S. Geological Survey.

tured shale and Pliocene sandstone. Recoveries per well in the Santa Maria fields vary greatly. Average recoveries range from about 10,000 to 50,000 barrels per acre but have been achieved only by dense well spacing and a long production history. Many fields in this basin have reservoir characteristics that pose difficult economic and technical problems; if similar reservoirs are found offshore, they may prove too uneconomic to exploit.

Reservoir beds are not known to be present offshore, but it is anticipated that fractured shale in the Miocene Monterey Formation is a potential objective. This presupposes that the rock types and diagenetic history of the Monterey Formation onshore and offshore are similar. Pliocene sandstone reservoirs onshore are limited to the northeast part of the basin and are not expected to extend far offshore.

Miocene source rocks similar to those onshore should be present within the offshore Santa Maria basin. However, seismic reflection data indicate that the offshore upper Tertiary section is thin. The total volume of Miocene or younger rocks in the basin is approximately 7,500 km^3. There are only two relatively small areas where burial is as great as 3,000 m, a depth believed necessary for a thermal regime sufficiently high to generate hydrocarbons from these source rocks. However, a higher than

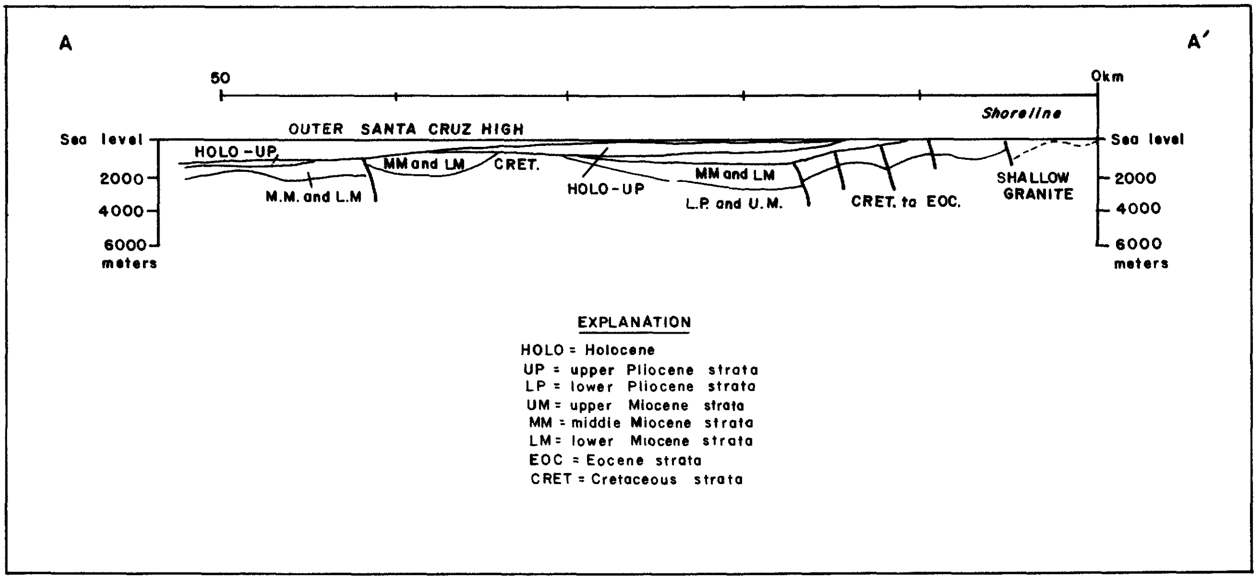


Figure 9. Geologic cross section through Outer Santa Cruz basin (from Hoskins and Griffiths, 1971). Location of section indicated on figure 6a.

normal geothermal gradient exists onshore and may be present offshore as well, perhaps providing a thermal regime adequate for petroleum generation at depths less than 3,000 m. In addition, Claypool (in Taylor, 1976) has presented evidence that petroleum generation can occur at lower than normal temperatures in rocks similar to those in this Miocene section.

Estimates of the undiscovered recoverable oil and gas resources for the two offshore basins are calculated by E. W. Scott (McCulloch and others, 1977):

	95 percent probability	5 percent probability	Statistical mean
OIL			
(billion of barrels)			
Outer Santa Cruz---------	0	0.98	0.34
Santa Maria--------------	0	.92	.44
GAS			
(trillions of cubic feet)			
Outer Santa Cruz---------	0	.98	.34
Santa Maria--------------	0	.92	.44

These estimates include both Federal and State acreage at water depths ranging from 0 to 2,500 m. The development of these estimates is described in Miller and others (1975).

ENVIRONMENTAL HAZARDS OUTER SANTA CRUZ BASIN

Seismicity and faulting.--Seismically active faults displace Holocene deposits on the seafloor in Monterey Bay, at the south end of the Outer Santa Cruz basin (Greene and others, 1973). These faults strike obliquely northwest toward, and terminate against, the seismically active San Gregorio-Palo Colorado fault. First motions indicate that the Monterey Bay faults and the San Gregorio-Palo Colorado fault are moving with right-lateral displacement. Faults also displace Holocene deposits on the seafloor in the Gulf of the Farallones west of San Francisco. Several earthquake epicenters have been located farther offshore along the margins of the Outer Santa Cruz and Farallon-Pigeon Point highs, but their relation to mapped faults is not known.

Active faults have been mapped in offshore Santa Maria basin and on the adjoining mainland (Jennings, 1975; Wagner, 1974; Earth Science Associates, 1974; McCulloch and others, 1977). The principal offshore faults (West Santa Lucia Bank, East Santa Lucia Bank, and Hosgri faults) all appear to be associated with seismic activity or to have segments along which Holocene deposits are offset (fig. 6). The East Santa Lucia Bank fault forms a major shoreward-facing seafloor escarpment that locally exhibits as much as 40 m of relief. The Hosgri fault forms a zone 3 to 5 km wide along the northeast edge of the area, between San Simeon Point and Point Sal. A branch of the Hosgri fault may connect with the onshore San Simeon fault zone which shows evidence of Quaternary movement (Hall, 1975). Seismic profiles indicate that the Hosgri fault shows evidence of Quaternary movement and that a zone of thrust faults in the south end of the basin may be active. This zone lies along the basin axis, and is approximately 20 km wide and 50 km long. Sediment at least as young as Pliocene has been displaced by thrusting; and first-motion studies of seismic events in this zone indicate north-striking thrusts with a vergence to the west (Gawthrop, 1975).

Studies of plate motion in the eastern Pacific indicate that horizontal displacement between the North American and Pacific plates

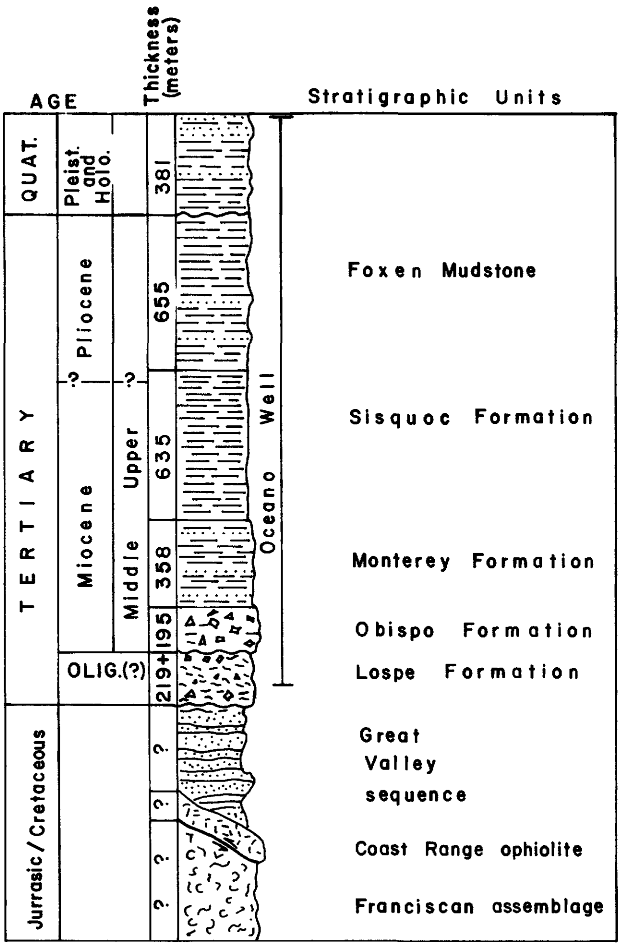


Figure 10. Stratigraphic column, Santa Maria basin. Inferred from seismic data, IES log (Standard Oil Company of California OCEANO No. 1 well), and nearby land exposures (modified from Woodring and Bramlette, 1950, and Hoskins and Griffiths, 1971). Stratigraphic nomenclature does not necessarily follow the usage of the U.S. Geological Survey.

is about 5.5 cm/yr (Atwater, 1970). Displacement on the San Andreas fault amounts to only about 2.5 cm/yr; the balance of this plate motion possibly is accommodated by faulting and folding to the east and west of the San Andreas fault, including the area which encompasses the offshore Santa Maria basin. Epicenters of about 550 instrumentally recorded earthquakes for the periods 1934-69 and 1969-74 were catalogued and, where necessary, relocated on maps by Gawthrop (1975). About 100 of these earthquakes are in the offshore area, and of these approximately 10 percent have magnitudes greater than 4.5 (fig. 6).

Seafloor instability.--There are insufficient data from the Outer Santa Cruz basin to establish the presence or absence of slumps or slides. Seismic profiles suggest slumps and slides in the northern part of the offshore Santa Maria basin, where large discrete blocks of Neogene rocks are recorded as relatively coherent reflectors that are both bounded laterally and underlain by contorted zones. Shallow slumps superimposed on these blocks have not been dissected by erosion, and depressions in the surface of the slumps do not contain ponded sediment, implying that these features are very young. The shallow failures are caused by seaward thrusting associated with high-angle reverse faults along the northeast edge of the basin. Similar deep-seated and shallow failures may be present in the area of active thrusting in the southern part of the basin.

Tsunamis.--From the first observation of a tsunami in San Francisco in 1812 to 1967, the greatest reported change in water elevation was 4.6 m at Half Moon Bay on October 18, 1859 (Iida and others, 1967). A magnitude 7.4 earthquake (April 11, 1946) in the eastern Aleutian Islands produced tsunamis of 3.5 m at Santa Cruz and in Half Moon Bay, but the amplitudes were considerably smaller where measured along adjacent parts of the coast. The Alaska earthquake of March 1964 (M 8.5) generated a highly destructive tsunami at Crescent City but had a minor effect farther south, producing only a 1.3 m rise in water at San Francisco (Iida and others, 1967; Wiegel, 1970).

TRANSVERSE RANGES PROVINCE

GEOGRAPHY

The Transverse Ranges province of southern California encompasses a diverse geologic terrane having a predominantly east-west structural grain. The western part of the province (fig. 12) includes the Santa Barbara Channel, the Santa Ynez Mountains, and the northern group of the Channel Islands (San Miguel, Santa Rosa, Santa Cruz, and Anacapa). The Ventura structural basin is an emergent, former eastward continuation of the channel. The western part of the Santa Barbara Channel is constructed by the large Pescado submarine fan (fig. 12) that merges westward with the Arguello Plateau.

GEOLOGY

Strata in the Santa Barbara Channel region range in age from Late Jurassic to Holocene. The upper Mesozoic section is at least 7,000 m thick and the thickness of the Cenozoic section may reach 10,000 m in the northeast part of the channel (fig. 13).

Although the basement rock beneath the Santa Barbara Channel is not known, several contrasting basement terranes locally are exposed along its margins (fig. 14). Rocks of the Franciscan assemblage crop out within and north of the Santa Ynez fault zone, and Catalina Schist occurs southeast and south of the Malibu Coast fault. Beneath the northeast part of Santa Cruz Island, Franciscan(?) pillow basalt with low-grade zeolite contiguous to lawsonite-bearing rock was cored below a Tertiary section

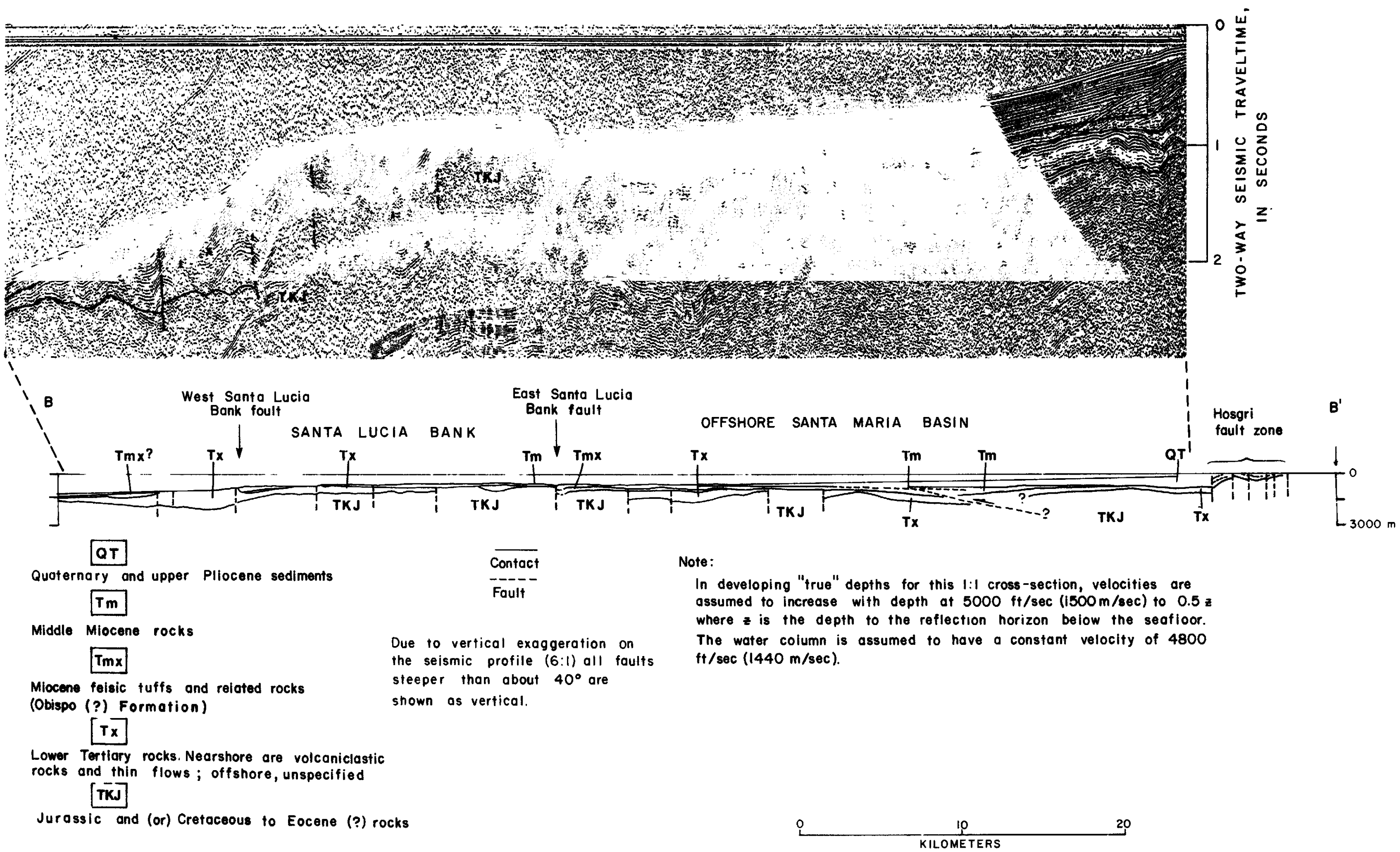


Figure 11. Geologic cross section through Santa Maria basin (McCulloch and H. C. Wagner, from unpublished U.S. Geological Survey data). Location of section indicated on figure 6b.

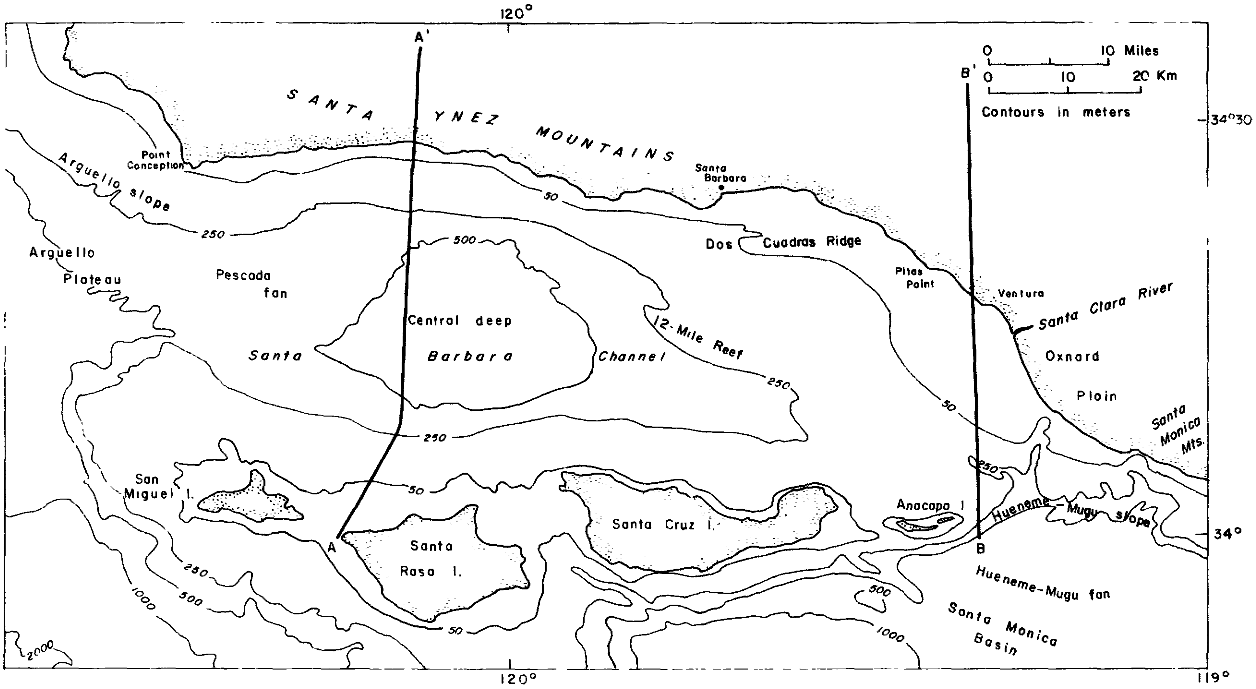


Figure 12. Selected physiographic features of the Santa Barbara Channel region.

in Union Oil Co. Gherini No. 1 well (Howell, McLean, and Vedder, 1976). Catalina Schist forms part of a small ridge just south of Santa Rosa Island. The basement complex exposed on the south side of Santa Cruz Island is inferred to be part of a dismembered ophiolite (Hill, 1976). The basement of the Santa Monica Mountains is composed of acidic plutonic rocks and a pre-intrusive metamorphic complex comprising argillite, lithic wacke, and metavolcanic rocks equivalent to the Mariposa Formation of the Sierran Foothills region (Jones and Irwin, 1975).

Cretaceous and early Tertiary strata are principally thick sub-sea fan sandstone and siltstone beds. A regional marine regression occurred during late Eocene and Oligocene time, during which nonmarine clastic deposition advanced westward and marine deposition persisted only in the westernmost parts of the channel. In early Miocene time, the channel again deepened, and feldspathic sand and mud accumulated in thickest portions at the site of the present northern shoreline. Middle Miocene volcanic centers lay along the margins both northwest and south of the present channel area (Tranquillon Volcanics of Dibblee, 1950, and Santa Cruz Island Volcanics of Nolf and Nolf, 1969, respectively). Post-middle Miocene sedimentation is represented principally by organic-rich mudstone and local accumulations of subsea sandstone turbidites.

Holocene deposits cover the seafloor throughout most of the deeper parts of the Santa Barbara Channel but are absent locally from Mugu and Hueneme Submarine Canyons and are absent from or very thin on large parts of the shallow shelf adjoining the northern Channel Islands and the mainland. Bottom sediments in the central deep are predominantly hemipelagic silt and clay. Rates of sediment erosion and deposition vary greatly from place to place within the channel. Sediment discharged by the Santa Clara River during major floods has formed sediment layers more than 15 cm thick on the inner part of the Oxnard Shelf; this sediment is eroded by wave and current action and redeposited over wide areas of the shelf and basin. The average rate of deposition in the deep central basin of the Santa Barbara Channel is about 2 mm per year (Fleischer, 1972; Hulsemann and Emery, 1961).

The major structures in the Santa Barbara Channel region are east-west oriented folds and left-slip faults, for example, the Santa Ynez fault, Santa Ynez Mountains, Rincon trend, and Montalvo trend. This structural grain may be superimposed on a northwestward trend in older, buried structures. The total structural relief on basement rocks in the channel region may be as much as 18,500 m.

The structural evolution of the Santa Barbara Channel region is complex and difficult to reconstruct, partly because of the lack of knowledge concerning the distribution of the basement rocks. Recent episodes of deformation can be related to (1) regional extension (normal faulting) during late middle Miocene to late Pliocene time between the uplifted blocks that now form the north and south boundaries of the western Transverse Ranges; (2) left-lateral slip at the southern boundary of the province; (3)

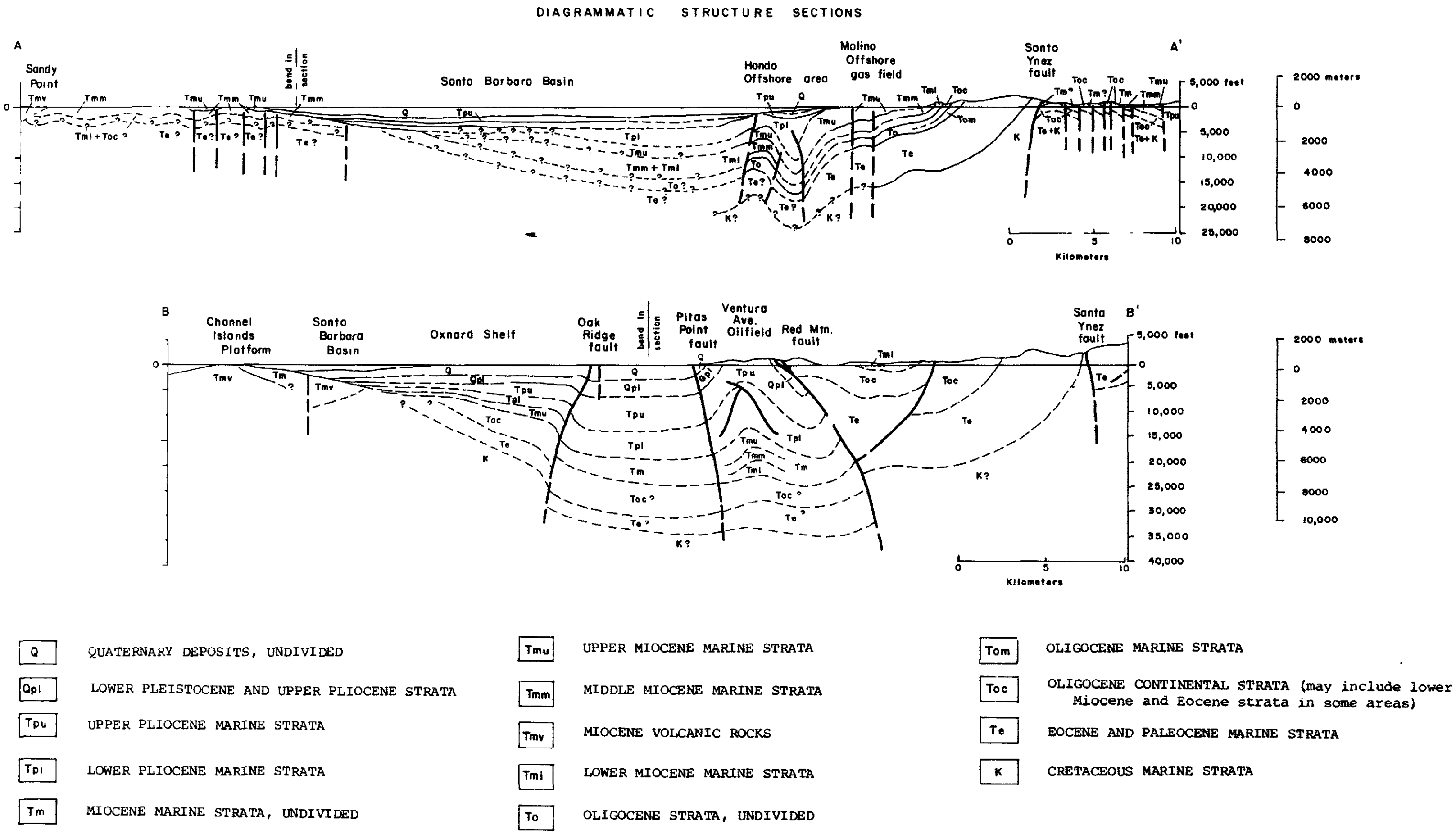


Figure 13. Geologic cross section through the Santa Barbara Channel and vicinity. Location of sections indicated on figure 12. (Modified from draft Environmental Impact Statement: Oil and gas development in the Santa Barbara Channel outer continental shelf off California DES 75-35, 1975.)

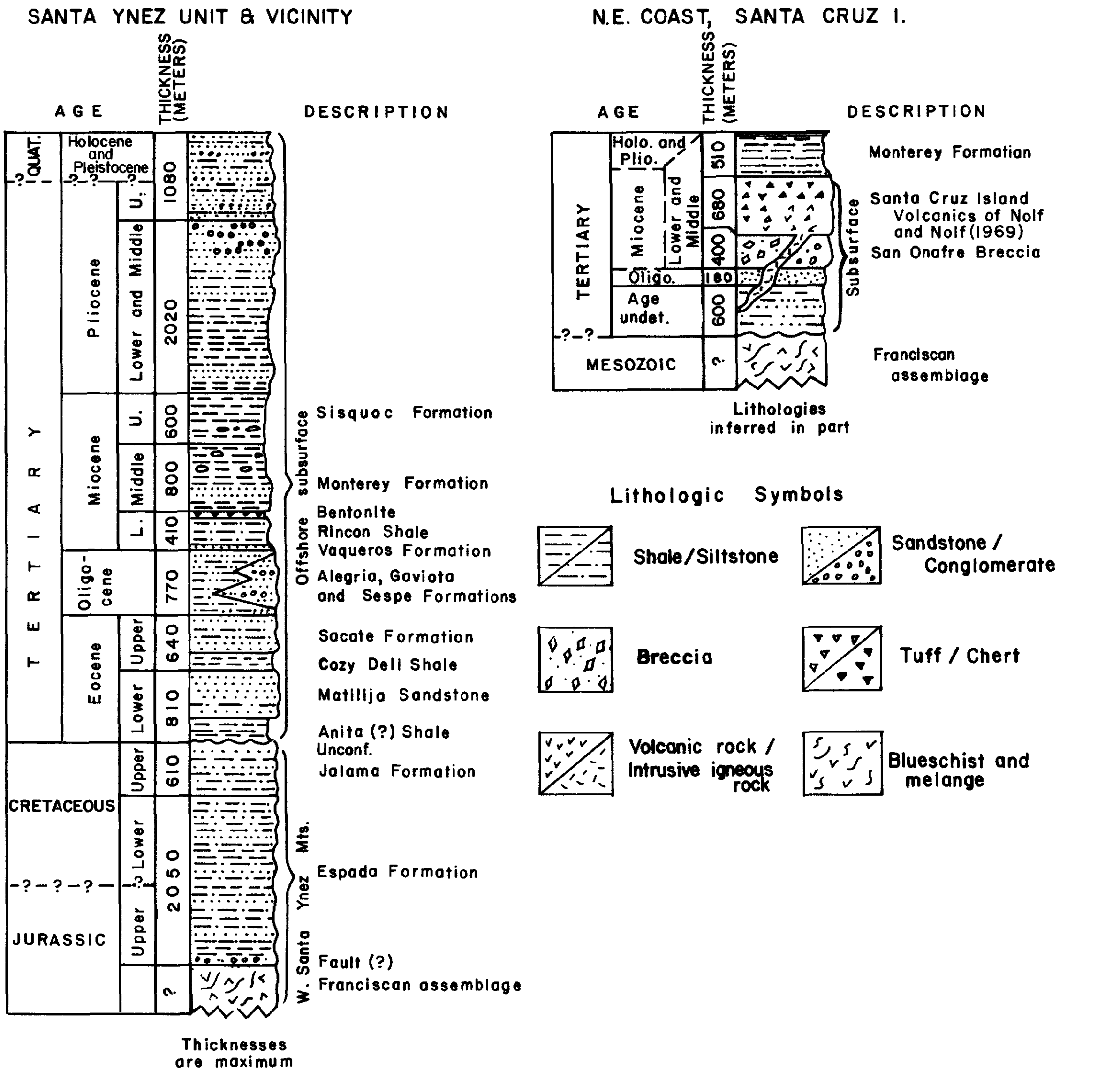


Figure 14. Generalized stratigraphic columns, Santa Barbara Channel region. Nomenclature, modified from Vedder and others (1976), does not necessarily follow the usage of the U.S. Geological Survey.

regional compression during late Pliocene to Holocene time between the same blocks, resulting in reverse dip-slip and significant north-south shortening by folding; and (4) possible, Neogene clockwise rotation locally of at least 75° based on paleomagnetic measurements in volcanic rocks (Kamerling and Luyendyk, 1977).

Subsidence of the Ventura basin probably accompanied regional Miocene to Pliocene north-south crustal extension by normal faulting combined with large left-lateral displacement on the Malibu Coast fault to the south (Crowell, 1976). The subsequent deformation, which may have begun as early as late Pliocene time, continues today and reflects regional north-south compression; reverse faults associated with the deformation dip both inward from the outer margins of the province (the Santa Ynez and Santa Monica faults) and outward, away from the center of the thick accumulation of late Cenozoic sediments (the Oak Ridge and San Cayetano-Red Mountain faults) (Yeats, 1976). The effects of compressional stress may diminish toward the west (by giving way to right-lateral shear effects), as suggested by the northwestward bend of structural trends west of Point Conception and San Miguel Island and by the change from east-west to northwest trends of contours of Bouguer gravity anomalies in the central to western part of the channel.

PETROLEUM APPRAISAL

Petroleum exploitation in the Santa Barbara Channel and adjoining area has concentrated on Oligocene and younger strata. Production data are summarized below:

	Eastern onshore (Ventura Basin)	Santa Barbara Channel (offshore)
Eocene-----------------	18	1
Oligocene--------------	303	26
Lower Miocene rocks----	6	253
Middle Miocene rocks---	65	3
Upper Miocene or overlying rocks-------	1,805	166

Five oil fields (Dos Cuadras Offshore, Carpinteria Offshore, Rincon, San Miguelito, and Ventura) along the Rincon anticlinal trend form a nearly continuous giant field. Structures are believed to extend westward from the Dos Cuadras Offshore field into the Federal Ecological Preserve and the Federal Buffer Zone, in which petroleum development is prohibited (fig. 12). Although no single structure has been demonstrated to extend westward from the Rincon trend through the gap south of the Coal Oil Point-Capitan part of the coast, the 5-Mile trend lies along the western projection of the Rincon trend and may include a general westward continuation of the same structural zone.

The only OCS leaseholds presently producing in the region are on the Dos Cuadras and Carpinteria Offshore fields. Both fields are on the Rincon anticlinal trend and most of the production to date has been from Pliocene strata. Four potentially commercial fields have been delineated in the Santa Ynez Unit, and the unit operator is now proceeding with development. Three potential oil fields have been reported in the southeastern part of the channel region, and another potential oil field has been reported along the Pitas Point anticlinal trend, south of the Dos Cuadras Offshore and Carpinteria Offshore fields, and a potential commercial oil field also has been discovered north of San Miguel Island.

Within the Santa Barbara Channel region, the largest continuous unleased areas are: (1) the central deep, chiefly the area enclosed by the minus 500-m depth contour; (2) the lower part of the Pescado Fan, north of the western sill of the Santa Barbara Basin and west of the central deep; (3) the parts of the Channel Islands slope and Channel Islands platform that lie north of the west half of Santa Cruz Island and eastern and central parts of the Santa Rosa Island; (4) the Hueneme-Mugu slope and fan; and (5) the Federal Ecological Preserve and Federal Buffer Zone. There are also a few smaller areas, ranging from one to about four parcels in size, west of Ventura and northeast of Santa Cruz Island.

Little is known about the central deep. The very thick Pleistocene and Holocene deposits there are generally flat lying, and the thickness and structure of potential oil-bearing strata below them are unknown. Projection from adjacent areas of known structural trends suggests that the upper Miocene to upper Pliocene strata of the Ventura basin are likely to be thinner on the south side of the Santa Barbara Channel than on the north. The geology of the lower part of the Pescado Fan is uncertain. Fan deposits conceal the structure and stratigraphic relations of older strata on available acoustic profiles. On the shelf and upper slope north of Santa Rosa and Santa Cruz Islands Miocene to upper Plicoene strata are represented by thin, discontinuous, and possibly shallower water deposits. Anticlinal structures are present, but exploratory drilling to date has not located significant oil or gas reserves.

Nearly 80 percent of oil and gas production from Santa Barbara Channel oil fields has come from Pliocene strata. However, in the giant Santa Ynez Unit, significant quantities of oil and gas occur only in Miocene and older strata (Monterey, Vaqueros, Sespe, Alegria and Sacate Formations and the Matilija Sandstone).

ENVIRONMENTAL HAZARDS

Seismicity and faulting.--Twenty four earthquakes of local magnitude 6 (Richter Scale) or larger have occurred in southern California during the past 60 years. Six of these are of special interest because they either (1) originated in the Channel region, (2) originated in the same structural province (western Transverse Ranges) and are associated with displacements and ground motions similar to those expected from earthquakes originating in the Channel region, or (3) originated in adjacent structural provinces and had sufficient intensity to cause damage in the Channel region. The seismic activity implies contemporary fault movement at depth. The region also shows geologic evidence of Holocene fault displacement and geodetic evidence of contemporary differential vertical movement. In the vicinity of Ventura vertical uplift over the last 100,000 years, measured from deformed movement terraces, is calculated to average as much as 7.7 m/1,000 years (K. R. Lajoie, oral commun., 1978).

Seafloor instability.--Seafloor instability generally is associated with unconsolidated Holocene sediments where there are slope gradients of 1.0° or more. A veneer 1 to 5 m thick of late Quaternary sediments of clay, silt, sand, and gravel, is known to cover the entire slope from Point Conception to Ventura (Fischer, 1976). These deposits thicken locally, such as in buried terrestial stream channels. Areas of thick Holocene deposits such as the Oxnard Plain, Oxnard Shelf, central deep, and Pescado Fan are likely sites for unstable seafloor conditions.

Submarine landslides have been mapped in the Santa Ynez Unit and on the upper part of the Hueneme-Mugu slope (Duncan and others, 1971). Deposits showing varying degrees of disturbed bedding are known to occur along Goleta, Oxnard, and Channel Islands slopes. Additional study is required to appraise and analyze fully sea-floor instability in the Santa Barbara Channel region.

Tsunamis.--The east-trending embayment of the Santa Barbara Channel strongly mitigates the effects of seismic sea waves generated in the northern Pacific Ocean area, and the Channel Islands of the southern California borderland offer a sheltering effect to the populated area along the north and east coast of the Santa Barbara Channel. Maximum run-up for 100-year and 500-year tsunamis generated outside the immediate channel area is estimated to be 3.2 m and 6.6 m, respectively (Houston and Garcia, 1974). The height of the largest tsunami that could be generated within the channel is not known. In general, seismic sea waves resulting from strike-slip faulting probably result in limited destructive effect; however, oblique-slip and dip-slip faults possibly could generate major sea waves.

Hydrocarbon seeps.--Natural hydrocarbon seeps are common in the Santa Barbara Channel region. Although seeps are not inherently hazardous, they may provide clues to potentially hazardous conditions associated with fractured reservoir rock and shallow gas pockets. Fischer and Stevenson (1973) mapped 1,250 active gas or oil seeps within a 18-km^2 area off Coal Oil Point. Seeps are primarily restricted to the north margin of the channel where active folding and faulting are inferred to be the major contributing factors.

CALIFORNIA CONTINENTAL BORDERLAND

GEOGRAPHY

For the purpose of this report, the northern limit of the California Continental Borderland is arbitrarily placed at the south margin of the northern Channel Islands. However, it is noteworthy that pre-Miocene structures on these islands are similar to those of the borderland, whereas the geomorphology and post-Miocene geologic features are more analogous to those of the Transverse Ranges province. The California Continental Borderland extends southward as far as Cedros Island, and westward to the base of the Patton Escarpment.

The borderland encompasses a large terrane with local relief comparable to the east scarp of the Sierra Nevada. It contains 19 major topographic basins that range from 35 to 58 km long and 10 to 40 km wide and that have depths of 400 to more than 2,000 m. These basins are bounded by mainland, island, and bank slopes that typically are steep to gently rounded, upward-convex curves and are cut by numerous submarine canyons. Distances to these basins from sources of sediment on the mainland range from 0 to over 200 km. South of lat 31° N., the borderland is about half as wide as it is to the north, and it lacks the regularly spaced northwest-trending basins and ridges. The dominant feature in the southern borderland is a large composite basin that extends northward from Vizcaino Bay to about lat 31° N., where it separates into several smaller basins.

GEOLOGY

Northern part of California Continental Borderland.--North of lat 31° N. there are three broad, northwest-trending terranes that possibly are fault bounded and allochthonous to one another. An inner borderland terrane (terrane III, fig. 15) lies east of a line that extends approximately along the west margin of San Clemente Island and thence to the eastern part of the Santa Cruz Island fault. This line coincides roughly with part of the pre-Pliocene East Santa Cruz Basin fault system postulated by Howell and others (1974). The east boundary of terrane III onshore is the Newport-Inglewood fault zone; southeast of Newport Beach the position of the boundary is uncertain. Terrane III comprises a high pressure-low temperature basement assemblage of schistose rocks (Catalina Schist) that is intruded and overlain by Miocene plutonic and volcanic rocks (fig. 16). Overlying and buttressing against these metamorphic and igneous units are late Cenozoic clastic rocks, most of which are middle Miocene and younger. The only known pre-Miocene strata in terrane III are Paleogene or Cretaceous siltstone, sandstone, and conglomerate blocks that are enclosed in a Miocene dike swarm at the southeast end of Santa Catalina Island (Vedder and Howell, 1977).

The central borderland terrane (terrane II, fig. 15) extends from terrane III westward to a northwest-trending lineament that approximately parallels the west slope of the Santa Rosa-Cortes Ridge from the west flank of Garrett Ridge to the edge of the platform southwest of San Miguel Island. Except for the mafic plutonic rocks and greenstone exposed on Santa Cruz Island, crystalline basement in this area is unknown. Cretaceous to Eocene strata make up thick sections and are widespread; locally, they are overlain by marine and nonmarine Oligocene sedimentary rocks, Miocene volcanic and volcaniclastic rocks, and correlative and younger clastic rocks (figs. 16 and 17).

The outer borderland terrane (terrane I, fig. 15) extends from terrane II westward to the base of the Patton Escarpment. Basement rocks in this area are composed of schistose rocks, mafic volcanic rocks, zeolite-bearing arenite and argillite, and ultramafic blocks. These rocks are somewhat similar to the Coastal Belt facies of the Franciscan assemblage in northern California. Late Oligocene and younger marine clastic and volcanic rocks fill sedimentary basins and drape slopes in this basement terrane (fig. 16).

The juxtaposition of these terranes implies a geologic history that presumably includes

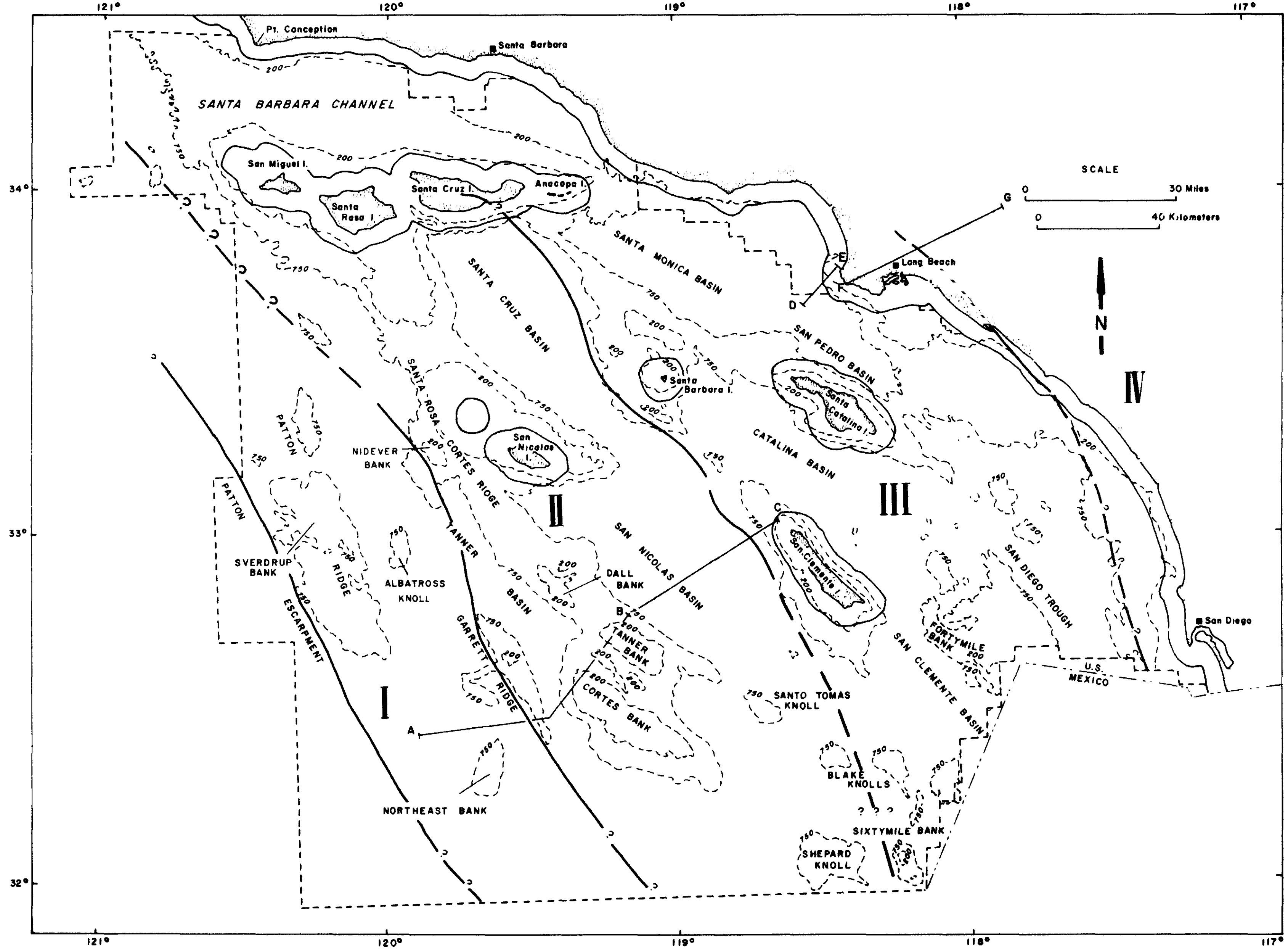
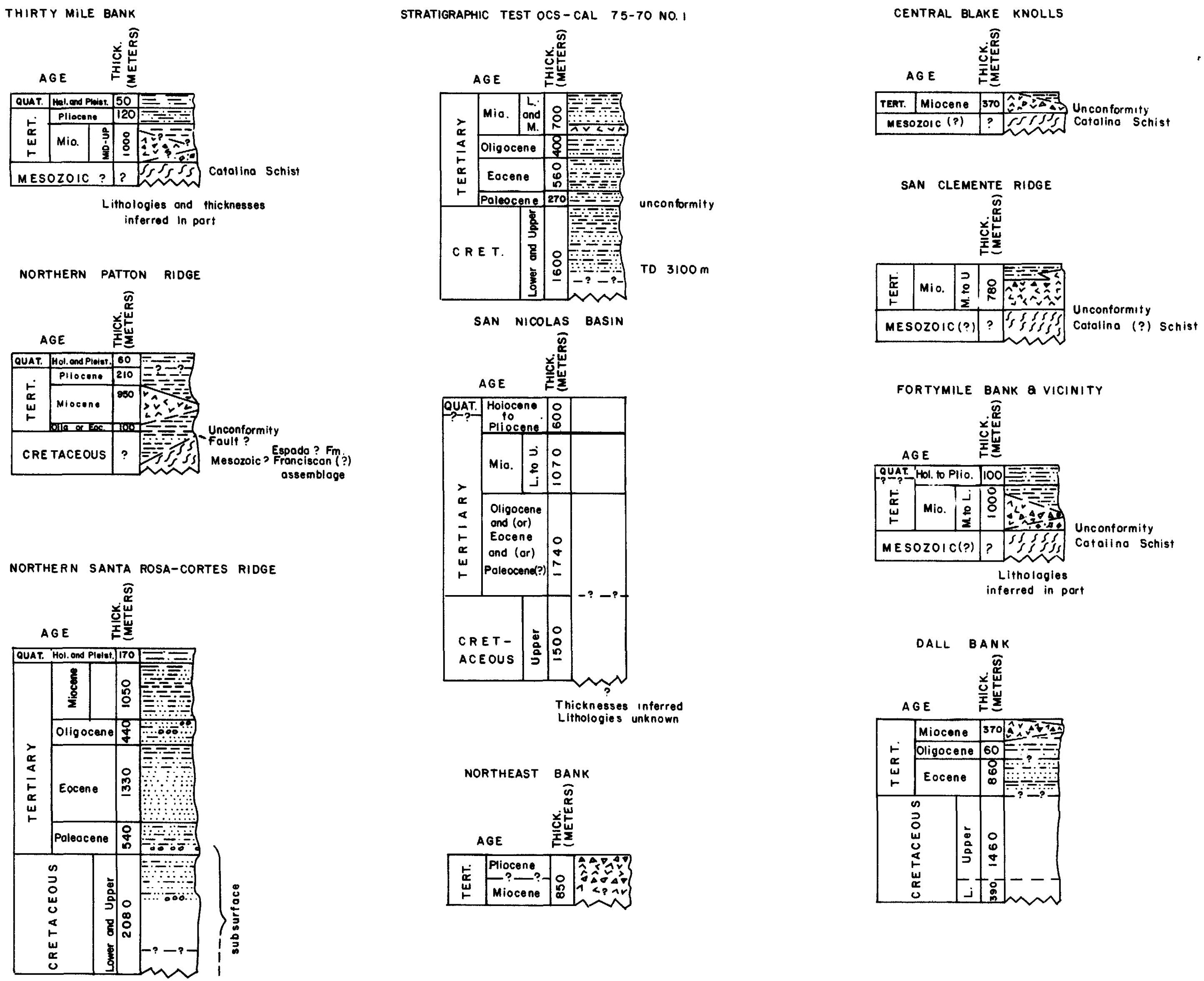


Figure 15. Boundaries of proposed OCS Lease Sale 48. The three-mile line is indicated by a solid line along the mainland coast and around the islands. The 200-meter and 750-meter depth curves are shown by short dashed lines. Areas within heavy solid lines denoted by Roman numerals are geologic terranes. East boundary of terrane I is dashed and queried where its location is uncertain.



THIRTY MILE BANK
AGE
THICK. (METERS)
QUAT.
Hol. and Pleist.
50
TERT.
Pliocene
120
Mio.
MID-UP
1000
MESOZOIC ?
?
Catalina Schist
Lithologies and thicknesses inferred in part
NORTHERN PATTON RIDGE
AGE
THICK. (METERS)
QUAT.
Hol. and Pleist.
60
TERT.
Pliocene
210
Miocene
950
Olig. or Eoc.
100
CRETACEOUS
?
Unconformity
Fault ?
Mesozoic ?
Espada ? Fm.
Franciscan (?) assemblage
NORTHERN SANTA ROSA-CORTES RIDGE
AGE
THICK. (METERS)
QUAT.
Hol. and Pleist.
170
TERTIARY
Miocene
1050
Oligocene
440
Eocene
1330
Paleocene
540
CRETACEOUS
Lower and Upper
2080
subsurface
STRATIGRAPHIC TEST OCS-CAL 75-70 NO. 1
AGE
THICK. (METERS)
TERTIARY
Mio.
L. and M.
700
Oligocene
400
Eocene
560
Paleocene
270
CRET.
Lower and Upper
1600
unconformity
TD 3100 m
SAN NICOLAS BASIN
AGE
THICK. (METERS)
QUAT.
Holocene to Pliocene
600
TERTIARY
Mio.
L. to U.
1070
Oligocene and (or) Eocene and (or) Paleocene(?)
1740
CRETACEOUS
Upper
1500
Thicknesses inferred
Lithologies unknown
NORTHEAST BANK
AGE
THICK. (METERS)
TERT.
Pliocene
Miocene
850
CENTRAL BLAKE KNOLLS
AGE
THICK. (METERS)
TERT.
Miocene
370
MESOZOIC (?)
?
Unconformity
Catalina Schist
SAN CLEMENTE RIDGE
THICK. (METERS)
TERT.
Mio.
M. to U.
780
MESOZOIC(?)
?
Unconformity
Catalina (?) Schist
FORTYMILE BANK & VICINITY
AGE
THICK. (METERS)
QUAT.
Hol. to Plio.
100
TERT.
Mio.
M. to L.
1000
MESOZOIC(?)
?
Unconformity
Catalina Schist
Lithologies inferred in part
DALL BANK
AGE
THICK. (METERS)
TERT.
Miocene
370
Oligocene
60
Eocene
860
CRETACEOUS
Upper
1460
L.
390

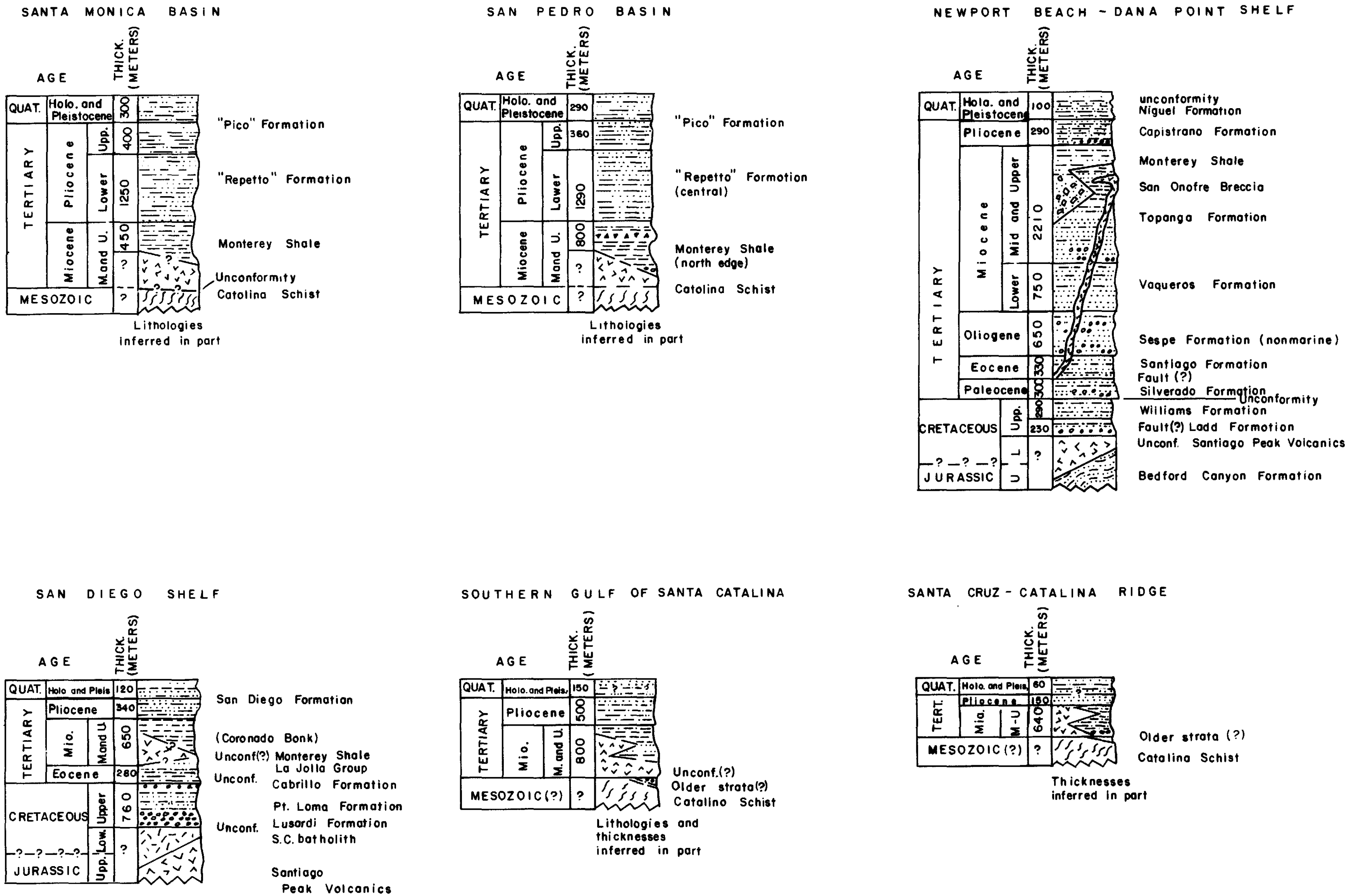


Figure 16. Stratigraphic columns, California Continental Borderland. Most stratigraphic units are unnamed. Rock types, where known, are generalized. Except for the OCS-CAL 75-50 No. 1 well, thicknesses are estimated from seismic profiles. Nomenclature, modified from Vedder and others (1976), does not necessarily follow the usage of the U.S. Geological Survey.

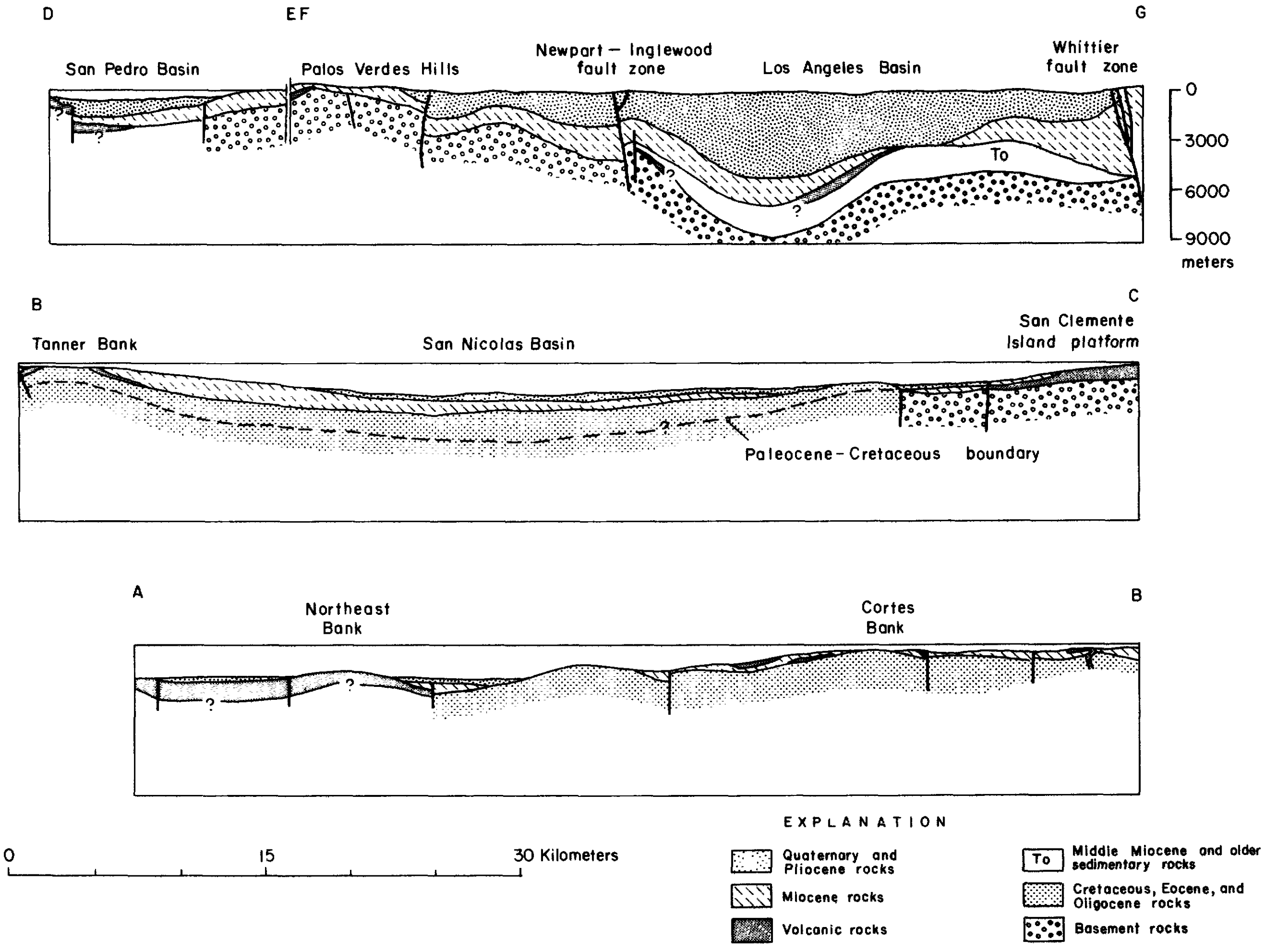


Figure 17. Generalized geologic sections through the California Continental Borderland and Los Angeles basin. Location of sections indicated on figure 15 (Vedder and others, 1974, and unpublished data).

episodes of subduction and transform faulting. We believe that the late Cenozoic geologic evolution of the borderland resulted from tectonic instability of the continental margin along the boundary between the Pacific and North American plates. A network of ridge-and-basin features developed as a result of right-lateral shear, which may have begun along the plate boundary about 30 m.y. ago (Atwater, 1970).

The structure of basins and banks in the eastern part of the borderland is complex; folds near the mainland coast along the seaward extension of the Newport-Inglewood fault zone are comparatively small and steep-flanked, and faults occur both as zones of in echelon breaks and as single traces. Most of the major folds and faults are oriented northwest (fig. 18). Some large anticlinal structures such as Coronado Bank are broad and nearly symmetrical, but little is known about their development. Faults that can be dated by stratigraphic analysis range in age from middle Miocene to Quaternary and have both strike-slip and dip-slip separations. Most small folds probably are post-Miocene to pre-late Pleistocene in age.

Faults in the western part of the borderland are more diverse in age and displacement. Although the dominant structural trend is northwest, there are two conspicuous east-west fault zones; one zone is located in the vicinity of the northern Channel Islands, and the other is located south and east of San Nicolas Island. Strike-slip separation is evident on some faults, such as the San Clemente fault, and most show some amount of normal offset. High-angle reverse faults such as the curved fault along the saddle between Santa Cruz and San Nicolas Basins, also are common. Some offsets are possibly pre-Pliocene, such as the postulated East Santa Cruz Basin fault system of Howell and others (1974), but more commonly they are Pliocene and younger. Pre-middle Miocene thrust faults are inferred in the basement rocks of Santa Catalina Island (Platt, 1975).

Large anticlines generally trend west-northwest at angles oblique to the major fault zones and at places appear to be arranged in echelon (fig. 18). Topographic highs reflect anticlinal structures in many places, and broad downwarped structural lows form both Santa Cruz and San Nicolas Basins. Many anticlines, for

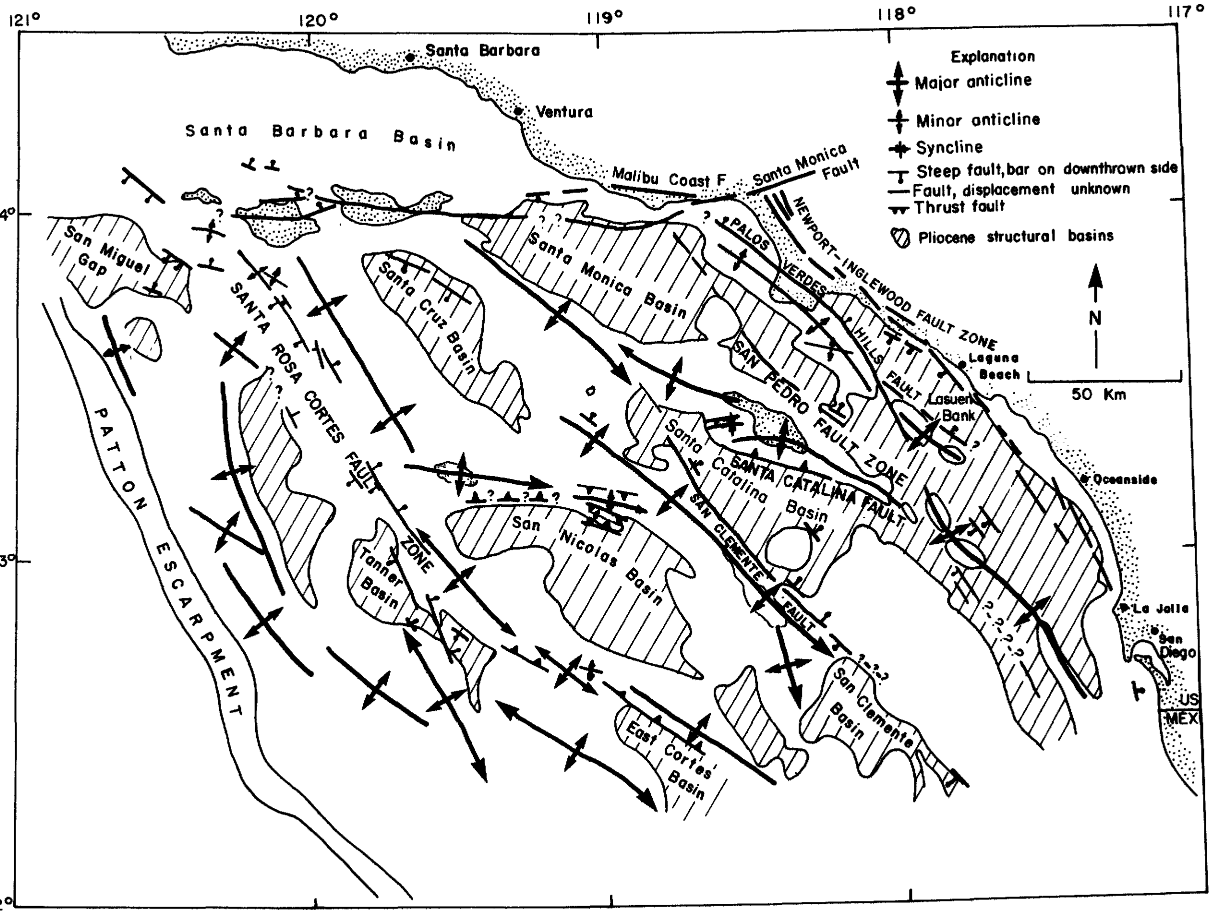


Figure 18. Tectonic map showing major structural trends and basins of the California Continental Borderland area (Junger, 1976).

example, those that underlie Tanner Bank and the San Nicolas Island platform, are very large, nearly symmetrical, and have gentle dips on their flanks. Numerous small folds are superimposed on major upwarps such as the Santa Rosa-Cortes Ridge, but these seem to die out basinward. Some anticlines deform sediments as young as Pleistocene, such as in the central San Nicolas Basin, and others probably are as old as early Miocene, such as the main anticline on northwestern Santa Rosa-Cortes Ridge, in which Miocene strata truncate Paleogene strata on both limbs. An episode of local deformation is suggested by an unconformity between the middle and late Miocene sequences on the flanks of the central part of Santa Rosa-Cortes Ridge.

Southern part of California Continental Borderland (Baja California).--Geologic data from the borderland off Baja California are insufficient to determine the southern extent of the geologic terranes that characterize the borderland farther north. The bathymetry of this region (Krause, 1965) indicates that the continental borderland narrows considerably south of lat 31° N. Rock types similar to those in the northern part have been dredged from ridge tops off Baja California (Doyle and Bandy, 1972); these include silicic and mafic plutonic rocks, metasedimentary rocks, phosphorite, and late Cenozoic sedimentary rocks.

Cretaceous and younger rocks on the mainland coast of Baja California are similar to units of the same age in the Peninsular Ranges north of the Mexican border. Moreover, complex geologic relations in the Mesozoic rocks exposed on Cedros Island and the neighboring Vizcaino Peninsula resemble those inferred for rocks of similar age in western California (Jones, Blake, and Rangin, 1976).

A major thrust, analogous to the "Coast Range thrust" of California, separates a lower plate consisting of tectonized high pressure-low temperature rocks from a relatively undisturbed upper-plate terrane. The superjacent rocks include mafic plutonic and volcanic rocks that are thought to be part of an ophiolite, Late Jurassic to Eocene sedimentary rocks depositionally overlying the ophiolite, and an andesitic volcanic suite (possibly a remnant Jurassic arc-complex) that is intruded locally by a 140-m.y.-old tonalite pluton. Clastic Neogene rocks overlie an unconformity that probably cuts all of these pre-Oligocene rocks.

At present, these Neogene rocks occur in isolated basins, suggesting that the episode of right shear and crustal extension that disrupted the southern California borderland also affected the southern part of the borderland (Blake and others, 1978).

The offshore extent of the Mesozoic and early Cenozoic structural relations is not known. However, the structure of the borderland west of Baja California resembles the area to the north, and the north- to northwest-trending pattern of folds and faults probably developed in late Cenozoic time. The right-lateral shear presumably commenced after the southward migration of the triple junction separating the Farallon, Pacific, and North American plates (fig. 3).

PETROLEUM APPRAISAL

Appraisals of the petroleum potential of the southern California borderland have been prepared recently by Vedder and others (1974, 1976) and Taylor (1976) and have been supplemented by information from a stratigraphic test well OCS-CAL 75-70 No. 1 on Cortes Bank (Paul and others, 1976).

Estimate undiscovered recoverable oil resources, southern California borderland.
[From Taylor, 1975. Values in billions of barrels of oil.]

	Depth (meters)	95 percent probability	5 percent probability
Inner basin area			
Terrane III, offshore----	0-200	0.4	2.0
Terrane IV, offshore-----	> 200	.2	2.0
Outer basin area			
Terrane I----------------	0-200	0	.24
Terrane II---------------	> 200	0	1.6

Organic matter in Tertiary rock samples from the ridges is thermally immature; and recent exploratory drilling at several areas in terrane II has produced unfavorable results confirming the above low estimates for the outer basins.

An appraisal of the petroleum potential of the U.S. part of the California Continental Borderland and adjoining Santa Barbara Channel indicates the following amounts of oil and gas resources.[1]

	95 percent probability	5 percent probability	Statistical mean
Oil (billions of barrels)-----	1.9	5.8	3.6
Gas (trillions of cubic feet)--	2.2	6.3	3.9

[1] These figures, compiled in September 1976, represent that part of the OCS area between water depths of 0 to 2,500 m with the exception of the eastern basins where only the area with water depths greater than 200 m has been considered in the estimate. In this region most of the water-covered area above the 200-m depth is State owned, and much of that outside the 3-mile limit is either excluded from the sale or is already under lease. State acreage, Federal reserves and reservations, and Federal leases granted at previous sales are included in the rest of the general sale area as assessed, but data are not available to make an assessment of these restricted or untested tracts.

ENVIRONMENTAL HAZARDS

Seismicity and faulting.--Within the southern California borderland only a few published studies deal with identifying conditions that could be hazardous to petroleum exploration and production (Vedder and others, 1969; 1976; Ziony and others, 1974; Field, Clarke, and Greene, 1977). Published studies are restricted in general to the Mugu-Santa Monica, San Pedro, and Newport-San Diego shelves, parts of the Santa Rosa-Cortes Ridge, and the Tanner-Cortes Banks area. Geologic phenomena investigated in these areas include faults, seismicity, seafloor instability, sediment erosion, and hydrocarbon seeps.

The borderland is cut by numerous faults (fig. 19), many of which are identified as active because they either cut the seafloor, cut young sediment (< 11,000 years old), or can be correlated with historic seismic events. Earthquakes of magnitude 4.5 or greater have been frequent on the San Pedro shelf and in the vicinity of the Santa Cruz-Catalina Ridge; locations of these epicenters are shown in figure 19 (Hileman, Allen, and Nordquist, 1973; Teng and Henyey, 1975). Because Tanner and Cortes Banks lie beyond the limits of the seismographic network, there are no reliable epicenter data.

Four major fault zones transect the inner basins and banks area; these are the Palos Verdes, Malibu Coast, Newport-Inglewood, and Rose Canyon fault zones (fig. 19). Many faults associated with these zones may be active (Ziony and others, 1974; Jennings, 1975). Most of the active faults in the Mugu-Santa Monica shelf area are short and discontinuous; the Malibu Coast fault is the largest and most likely to generate a major earthquake. In the San Pedro shelf area, the Palos Verdes fault is more than 64 km long and locally offsets the seafloor. Earthquake epicenters along its trace verify its continuing activity. Many other faults that extend upward to the seafloor must be considered environmentally hazardous, as they cut beds of Holocene age (Greene and others, 1975, plate 13).

The longest Quaternary fault mapped in the inner basins and banks area is the San Clemente fault; the northwestern segment is at least 80 km long and the southeastern segment more than 24 km long (Jennings, 1975). Several earthquakes have been reported in the vicinity of this fault; one of these, recorded near the southeast extension of the fault in 1941, had a magnitude of 5.9 to 6.0 (Lamar and others, 1973). In addition, many smaller faults cut the area, some of which appear active (figs.

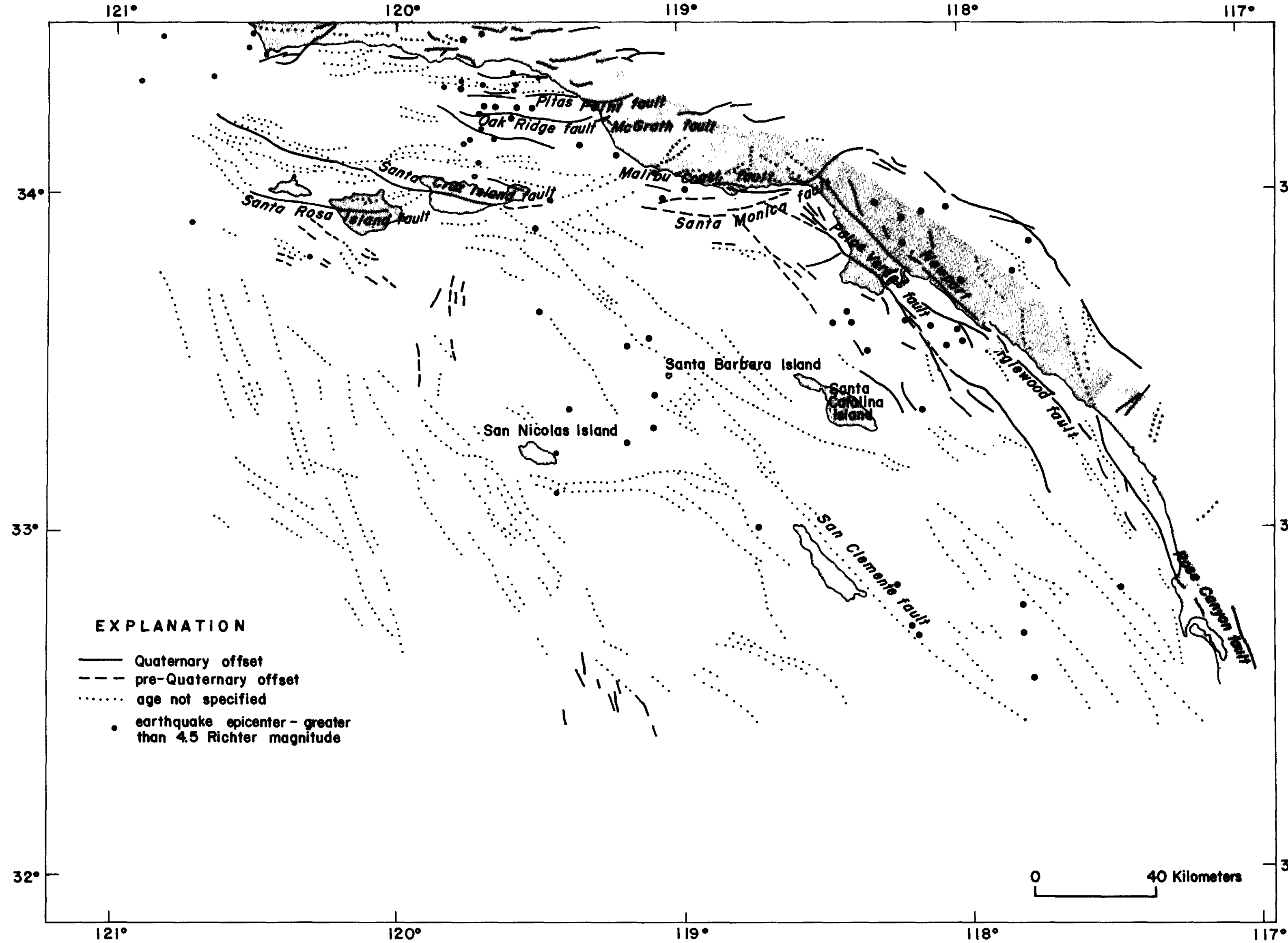


Figure 19. Location of major faults and earthquake epicenters in the California Continental Borderland. Abbreviations of faults are: rc = Rose Canyon fault; ni = Newport-Inglewood fault zone; pv = Palos Verdes fault; sc = San Clemente fault; sm - Santa Monica fault; mc = Malibu Coast fault; mg = McGrath fault; or = Oak Ridge thrust; pp = Pitas Point fault; sci = Santa Cruz Island fault; sri = Santa Rosa Island fault; escb = east Santa Cruz Basin fault (from Field, Clarke, and Greene, 1977).

18 and 19). The northern Santa Rosa-Cortes Ridge also seems to be tectonically unstable, having had at least 20 earthquakes ranging in magnitude from 2.5 to 4.5 during the period 1932-1973 (Greene and others, 1975). Faults are numerous, but are most common along the ridge crest where relatively small apparent vertical separations are characteristic (Greene and others, 1975, plate 5). Beneath the flanks of the ridge, faults are less numerous but have greater apparent vertical separations than those on the ridge top. Seafloor offsets above displaced seismic reflectors suggest that some faults are active. In the Tanner-Cortes Banks area, faults are concentrated along the northern flank of Cortes Bank and in the structural saddle between the two banks (Greene and others, 1975, plate 2). Many of these faults displace either Holocene sediment or the seafloor.

Seafloor instability.--Detailed high-resolution surveys have not covered the entire borderland, and for the areas surveyed, they do not extend basinward beyond the upper slopes of ridges. Areas known to be prone to submarine sliding occur along the mainland shelf and slope where the thickness of unconsolidated Quaternary deposits varies greatly (Field, Clarke, and Greene, 1977).

The location of slide-related scarps and thicknesses of slump deposits suggest that most surface failures occurred at the shelf (or ridge) edge or on the upper slope. The relative importance of earthquakes, gravitational loading, and dynamic loading from storm waves in triggering these and other seafloor failures in the borderland is not known (Field, Clarke, and Greene, 1977).

Distribution of sediment types on the northern part of the Santa Rosa-Cortes Ridge (clastic sand on the edges, foraminiferal sand in the center) suggests that bottom currents may be strong on the perimeter and of lesser strength in the center. Both the sparse sediment cover on the ridge top due to the isolation from sediment sources and the abundance of rocky outcrops devoid of sediment suggest the influence of strong current activity (Greene and others, 1975, plates 8 and 9). On Tanner and Cortes Banks, strong current activity is suggested by areas of exposed bedrock and by the thinness of the sediment cover over much of the nearby area (Greene and others, 1975, plates 1, 2, and 4). The low silt and clay content, relatively good sorting, and coarseness of bank-top sediments also suggest current action, although the coarseness is partly a reflection of the abundant supply of coarse biogenic debris.

Tsunamis.--Locally generated tsunamis have been recorded along the coast between Point Mugu and the Mexican border; however, these are few in number and have not caused major damage. One tsunami was noted in 1879 at Santa Monica, and two others were reported in 1925 (uncertain) and 1933 at Long Beach (Iida and others, 1967). The 1933 seismic sea wave resulted from the March 10, 1933 Long Beach earthquake. Although tsunami damage in this area has been minimal, the region is seismically active, and inundation along the coastal lowlands could result from tsunamis.

Hydrocarbon seeps.--Known hydrocarbon seeps in the borderland are located on the Santa Monica shelf. Oil and gas seeps are present in the northern part of Santa Monica Bay along the probable extension of the Palos Verdes fault, and offshore between Point Vicente and Point Fermin (Wilkinson, 1971; Greene and others, 1975; Henyey and others, 1975). Wilkinson (1971) shows two oil seeps and one gas seep in the San Pedro shelf area.

Oil and gas seeps have not been detected in recent surveys of the northern Santa Rosa-Cortes Ridge and Tanner and Cortes Banks, nor have they been reported in literature on this region. However, the presence of hydrocarbons in sediment samples and the large number of faults in these areas suggest that surface seeps and subsurface gas-charged sediments may be present.

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