UNITED STATES
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GEOLOGICAL SURVEY

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

By

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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

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SUMMARY

This report summarizes aspects of offshore and onshore geology, onshore petroleum production and geological environmental hazards pertinent to the southern part of OCS Lease Sale 53, and presents an appraisal of its petroluem potential. This area encompasses the entire central and northern California continental shelf north of Point Conception. It is bounded on the northeast by the three-mile limit of the State of California OCS, on the southeast by latitude 34.50° north, on the southwest by the 1000 meter isobath, and on the northwest by latitude 42.50° north. The Oregon and Washington part of OCS Lease Sale 53 is described by Snavely and others (1977).

Five sedimentary basins on the shelf have received most attention as potential areas of recoverable hydrocarbons. Several aspects of these basins suggest that they have only moderate to low hydrocarbon potential. The basins are shallow, thus the total volume of possible source and reservoir rocks is low. The thickness of the Miocene to Recent section, the section most likely to contain hydrocarbons, rarely reaches 4,575 m (15,000'). By comparison, the equivalent-aged section in the highly productive Los Angeles and Ventura basins is commonly greater than 6,960 m (20,000') and may be as great as 9,150 m (30,000'). As a consequence of being shallow, the basin sediments may not have been subjected to a thermal regime thought necessary to generate hydrocarbons. Because downwarping that produced the basins was slow, the sediments that accumulated in the basins were predominately fine-grained silts and shales. Although there are some basal and deep water sands of reservoir quality in the prospective section in some of the basins, there is a general lack of thick coarse clastic rock units that form the productive reservoirs in the southern California offshore basins. The principal source rocks in the basins appear to be cherty Miocene shales, however, these rocks generally thin northward, and are not reported from the northernmost basin.

Chances for finding large structurally controlled traps in these basins do not appear great. Many of the most attractive structures were drilled following the 1963 lease sale, and there was no resulting production. Most production from adjacent onshore basins has been low gravity crude from reservoirs developed in fractured Miocene shales. This production has been achieved largely by costly long-term well treatment and dense-drilling, which may be economically infeasible in the offshore.

There may be some potential for production from older rocks beneath the basins, where remnants of clastic marine Eocene rocks survived the extensive pre-Miocene erosion of the shelves, however, these rocks are not widespread, and their structures are complex and difficult to define. Therefore petroleum production from these older rocks is considered moot.

Petroleum resources for the proposed sale areas are estimated in aggregate at probability levels of 5 percent and 95 percent and are based in part upon volumetric and analog methods. The following amounts of oil and gas resources that could be recovered under present conditions of economy and technology are:

	95 Percent Probability	5 Percent Probability	Statistical Mean
Oil (billions of barrels)	0.21	1.98	1.11
Gas (trillions of $feet^3$)	0.29	2.63	1.43

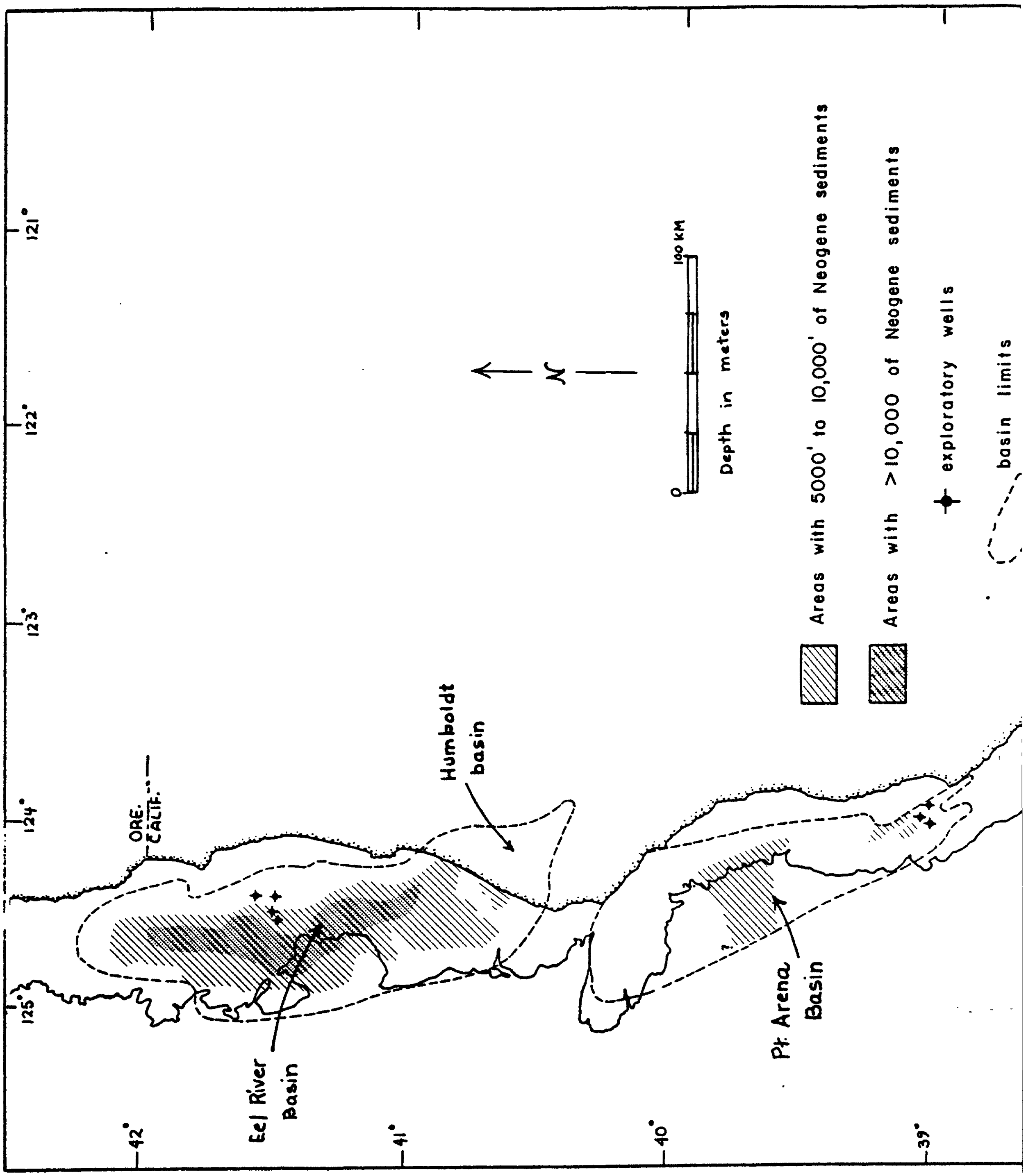
Most of this area is bounded by the San Andreas fault, the longest most seismically active strike slip fault on the continent. Seismically active subsidiary strike slip faults in the OCS appear to be responding to the same tectonic forces. Thus active faults, some accompanied by sea floor rupture, strong ground motion and seismically triggered slumps and slides present environmental hazards. Deep-seated and shallow mass movements of sea floor, some of which are active, have been identified in several basins, but their full extent is not known. Tsunamis have caused damage along this coast; most resulted from distant earthquakes, but one may have been generated locally.

INTRODUCTION

This report summarizes the regional geologic framework, petroleum potential, and environmental geology, that will affect exploration and development in the southern part of proposed area OCS Lease Sale 53. Coverage ranges from detailed, closely spaced geophysical surveys along parts of the coast line, to widely spaced reconnaissance of areas further offshore (Attachment A). In areas where no survey data are available, the summary is drawn entirely from the literature.

The proposed OCS Lease Sale area described in this report encompasses the entire continental shelf of central and northern California, north of Point Conception and is referred to as 53-A. It is bounded on the northeast by the State of California OCS three-mile limit, on the southeast by latitude 34.50^{o} north, on the southwest by the 1000 meter isobath, and on the northwest by latitude 42.50^{o} north (Fig. 1).

The section on Petroleum Resource Appraisal was prepared by E. W. Scott. The geology and environmental hazards in Eel River basin were written by S. H. Clarke, Jr., and M. E. Field respectively. Figures were prepared by P. M. Utter, and the balance of the report was prepared by D. S. McCulloch.



121°
122°
123°
124°
125°
42°
41°
40°
39°
ORE.
CALIF.
N
0
100 KM
Depth in meters
Humboldt basin
Eel River Basin
Pt. Arena Basin
Areas with 5000' to 10,000' of Neogene sediments
Areas with >10,000 of Neogene sediments
exploratory wells
basin limits

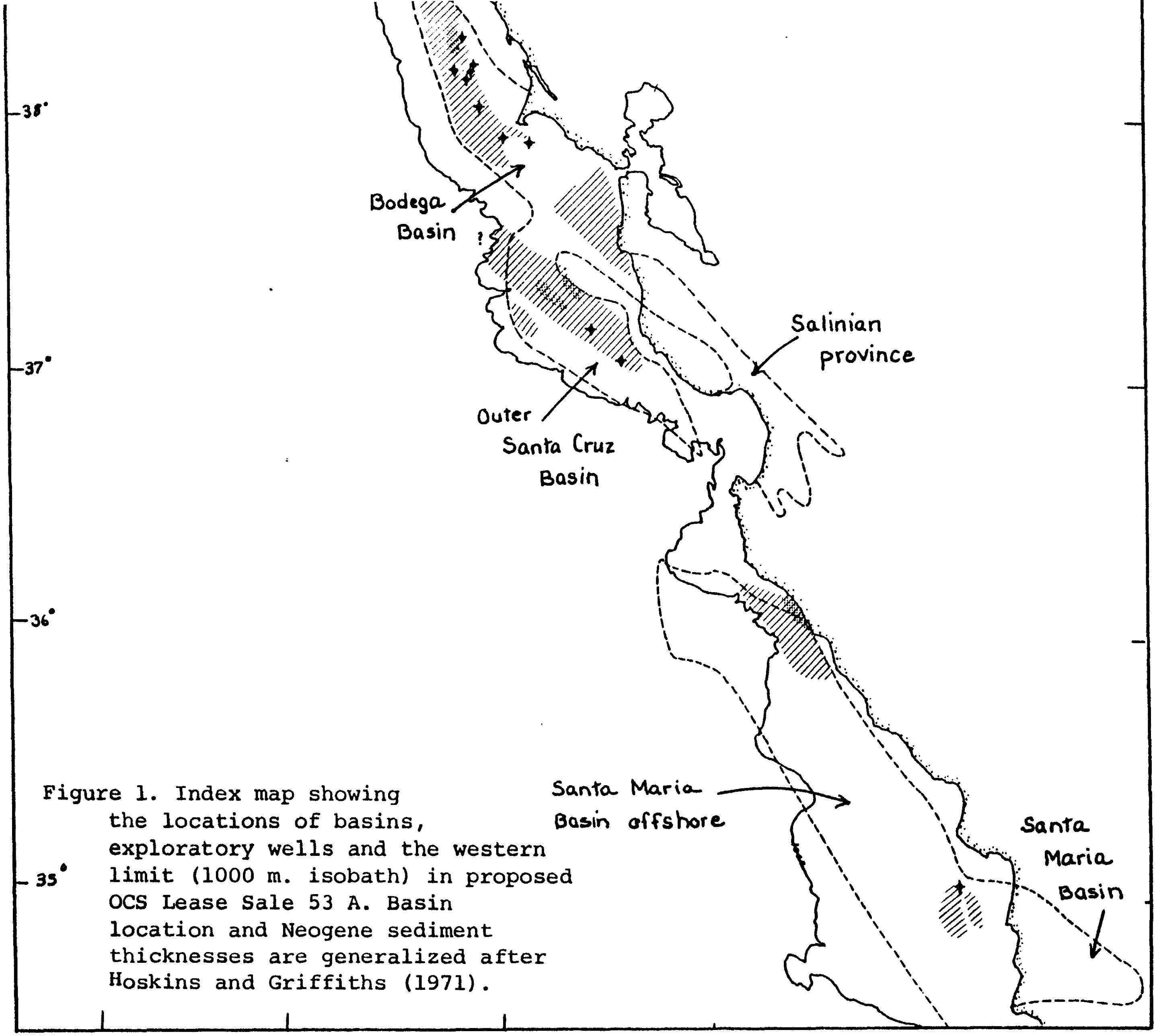


Figure 1. Index map showing the locations of basins, exploratory wells and the western limit (1000 m. isobath) in proposed OCS Lease Sale 53 A. Basin location and Neogene sediment thicknesses are generalized after Hoskins and Griffiths (1971).

REGIONAL GEOLOGIC FRAMEWORK

General Setting

The central and northern California OCS contains five basins that lie on the shelf or partially on the adjacent continental slope (Fig. 1). In late Cretaceous time, before the basins existed, the Farallon lithospheric plate, which lay between the obliquely converging North American and Pacific plates, was being subducted along the western margin of the North American Plate. Following the contact of the North American and Pacific plates to the south, subduction was replaced from south to north by right-lateral strike-slip faulting resulting from the differences in motion of the two plates (Atwater, 1970; Morgan, 1968). Strike slip faulting along the San Andreas and associated faults persists as far north as Cape Mendocino. North of the cape, the small Gorda-Juan de Fuca Plate is now being subducted.

Strike-slip faulting has displaced a sliver of Sierrian-type quartz dioritic "granitic" basement rocks, called the Salinian block (Reed, 1933; Page, 1970) northwestward perhaps 600 km from the southern end of the Sierra Nevada (Wentworth, 1968; Ross, 1970; Silver and others, 1971). The displaced granitic rocks now underlie the northwest-trending Salinian province onshore, and extend offshore to form the basement beneath the central third of the central-northern California shelf. Caught between the two major plates, the Salinian block is not only bounded by major faults, but right lateral shear forces exerted on the block have produced considerable internal strike-slip faulting (e.g., Johnson and Normark, 1974; Ross, 1973; Ross and Brabb, 1973; Kistler, 1973).

North and south of the Salinian block the shelf is generally thought to be underlain by Jurassic, Cretaceous and early Tertiary(?) marine metasediments considered to belong to the Franciscan assemblage. High seismic velocities in the metasediments, their degree of deformation, their metamorphic grade and a widespread angular unconformity that separates them from younger rocks indicate that they were once more deeply buried, and that a considerable part of their erosional history occurred in late Cretaceous or early Tertiary time (Hoskins and Griffiths, 1971). Following erosion marine sedimentation proceeded through early Tertiary time (Eocene and Oligocene?), but renewed deformation and erosion that preceeded a shelf-wide mid-Tertiary marine transgression left only remnants of lower Tertiary deposits. These transgressive deposits (lower and middle Miocene) covered most of what is now the continental shelf, and in places, part of the adjacent slope.

Deformation through the mid Tertiary was probably related to subduction, however, in upper mid-Miocene time, a change in the pattern of deformation, that may have been caused by a change in the relative motion of the Pacific and North American plates (Silver and others, 1971) initiated the formation of both the shelf as we now know it and the present shelf basins. Basement ridges were uplifted generally along the outer margin of the shelf (Curray, 1966) to form the seaward margins of the geologically young, shallow-shelf basins that are the present targets of petroleum exploration. These shelf basins acted as depocenters for marine sedimentation more-or-less continuously until late Pliocene time. Most basins contain down-to-basin normal or high angle reverse faults consistent with right-lateral shear, and most exhibit late Tertiary or Quaternary compressional folding. Deposition prior to mid-Miocene may have been similarly limited by shelf-edge structures, but the location and character of these features are not known.

Santa Maria Basin Offshore.--The southernmost basin in the area of proposed OCS Lease Sale 53-A measures approximately 40 km x 230 km and is elongate parallel to the coast (Fig. 2). It is bounded on the northeast by Franciscan basement rocks that have been elevated along major coastal faults, and on the southwest by the Santa Lucia High, an elevated basement block that forms the relatively shallow Santa Lucia Bank. The northwest end of the basin continues onto the continental slope, and the south end of the basin is defined for purposes of the proposed lease sale as latitude 34.50° N. Basement rocks exposed along the shore are Franciscan-Knoxville rocks of Jurassic-Cretaceous-early Tertiary(?) age. Similar rocks (metasediments, altered basic igneous rocks) have been dredged from acoustic basement on the Santa Lucia High, and from the upper edge of the continental shelf. The structural style of the basin and granite derived coarse clastics of upper Cretaceous and Eocene age from the Santa Lucia High suggested to Hoskins and Griffiths (1971) that the basement may be granitic. Granite cobbles have been dredged from the Santa Lucia High, however, it is possible that they were transported, for other exotic rocks occur in dredge hauls on the shelf. If the basement is granitic, it would necessitate considerable revision of existing tectonic reconstructions of this plate margin which now consider the offshore basement to be Franciscan, and confine the granite basement to the Salinian block which lies onshore and separated from this basin by Franciscan terrane.

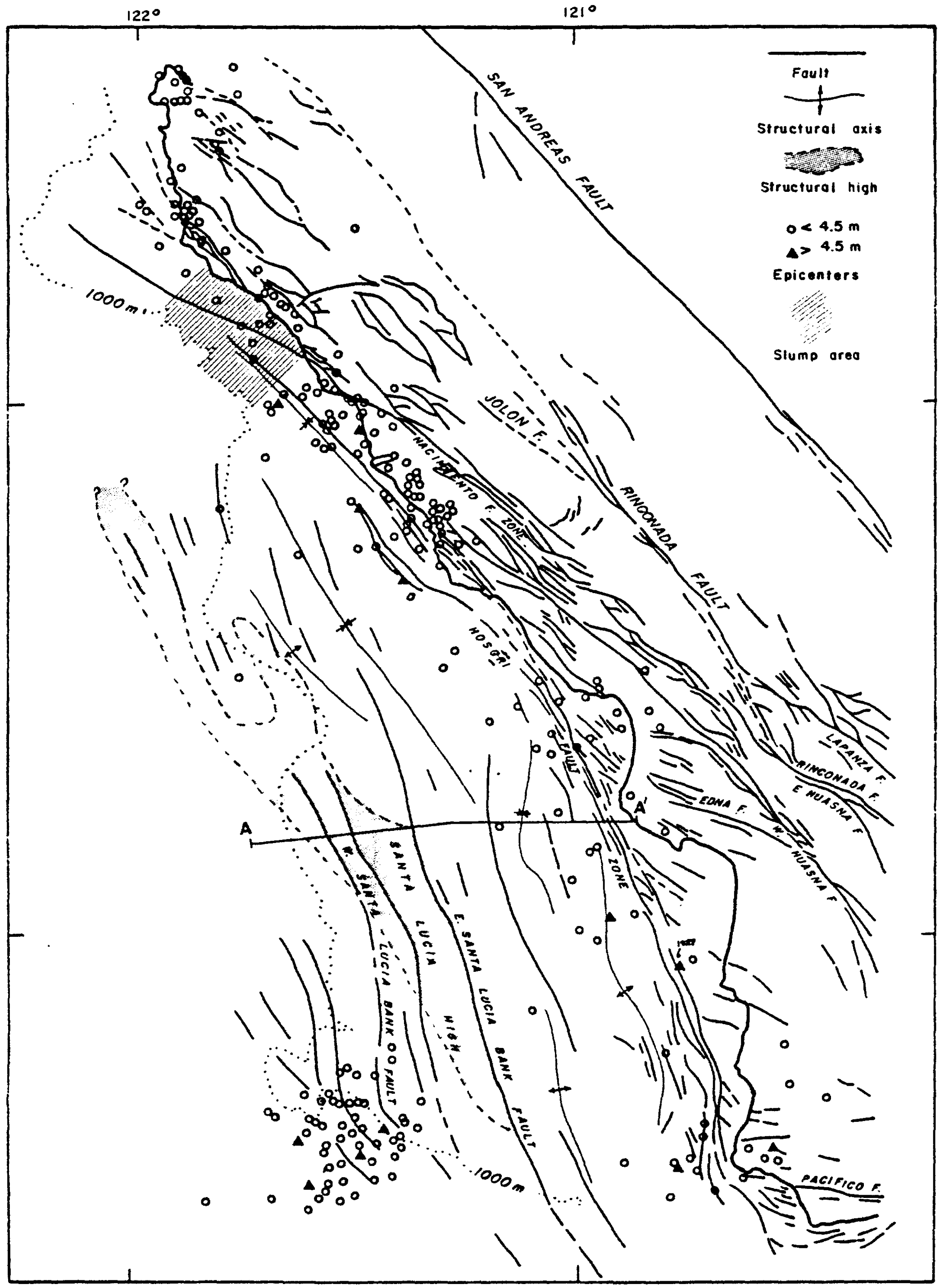


Figure 2. Map of the generalized geologic structure, faults and epicenter locations in the Santa Maria Basin and the adjacent coast. Geology and faulting after Hoskins and Griffiths (1971), Earth Science Associates (1974), Jennings (1975), and unpublished data from H. C. Wagner, E. A. Silver and D. S. McCulloch. Epicenter locations from 1812-1976 from Gawthrop (1975) and Gawthrop (written comm., 1977). Geologic cross-section A-A' on figure 4.

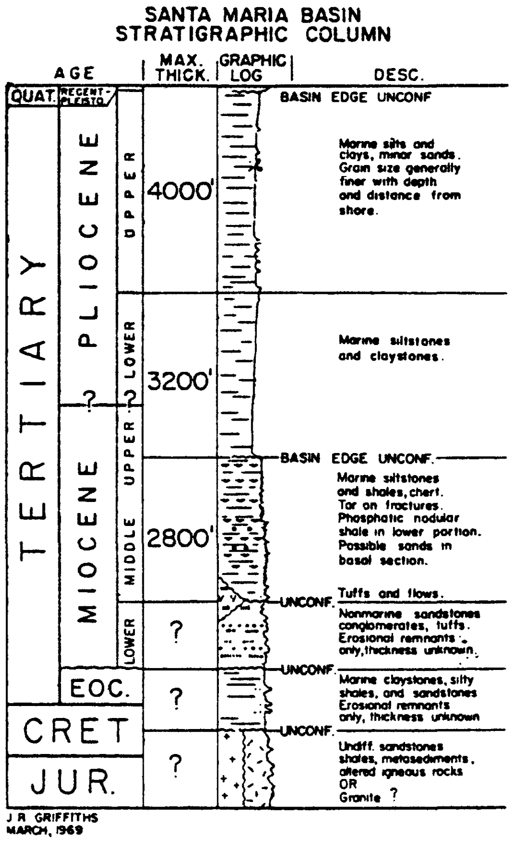


Figure 3.

Stratigraphic column (Hoskins and Griffiths, 1971) showing lithology, age and estimated maximum thickness of rocks in the Santa Maria Basin offshore. Additional work by H. C. Wagner and D. S. McCulloch (unpub. interpretations of seismic reflection profiles) indicates that the middle Miocene unconformity is basin-wide, and that there is an onlap unconformity between rocks thought to be of early and late Pliocene age.

Only limited data are available concerning the character and distribution of post-Cretaceous rocks in the basin. A generalized stratigraphic column for the entire basin is shown on Figure 3. Note that in this and succeeding columns the thicknesses shown are the interval maximum for the entire basin. 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 distribution in the basin is thought to be limited to erosional remnants.

A "true scale" cross section of the basin is shown on Figure 4. Lithologies and ages are inferred from the nearby single test well in the basin (Humble P-060-1, Fig. 1). The lowest Neogene rocks (TK) may be volcanoclastic and contain a few thin flow units. The overlying acousticly thin-bedded, wedge-shaped unit (Tmx) may correlate with a volcanic tuff in the well, and may be equivalent to the onshore Obispo Tuff of early and middle Miocene age (Crawford, 1971) Tmx. A well-bedded unit (Tm) overlies Tmx. Sea floor samples from the Santa Lucia High indicate that these well-bedded strata are middle Miocene foraminiferal silicous shales. The thin-bedded, highly reflective acoustic character of this unit, together with the presence of chert in dredge hauls and dart cores from sea floor exposures suggest that Tm is in part equivalent to the Monterey Formation. The uppermost unit (QT) rests with local unconformity on Tm, and is undivided on the section. It is composed principally of Pliocene and Pleistocene deposits, but it probably includes a minor amount of upper Miocene at its base.

Structural trends (fold axes and faults) in the northern two-thirds of the basin parallel the shoreline. The structures generally appear to have been initiated by at least early Tertiary time, and most persisted into late Miocene, but the associated faulting and deformation is considerably less above the early Tertiary unconformity. Just south of Point Sur there is evidence for present day compression and thrusting in the basin sediments that lie adjacent to the high angle reverse fault that bounds the northeast edge of the basin. This deformation is associated with surface slumping. Structural trends in the southern third of the basin are north-south, oblique to the shoreline and the bounding Santa Lucia High (Hoskins and Griffiths, 1971). Considerable evidence for compression is also present in this

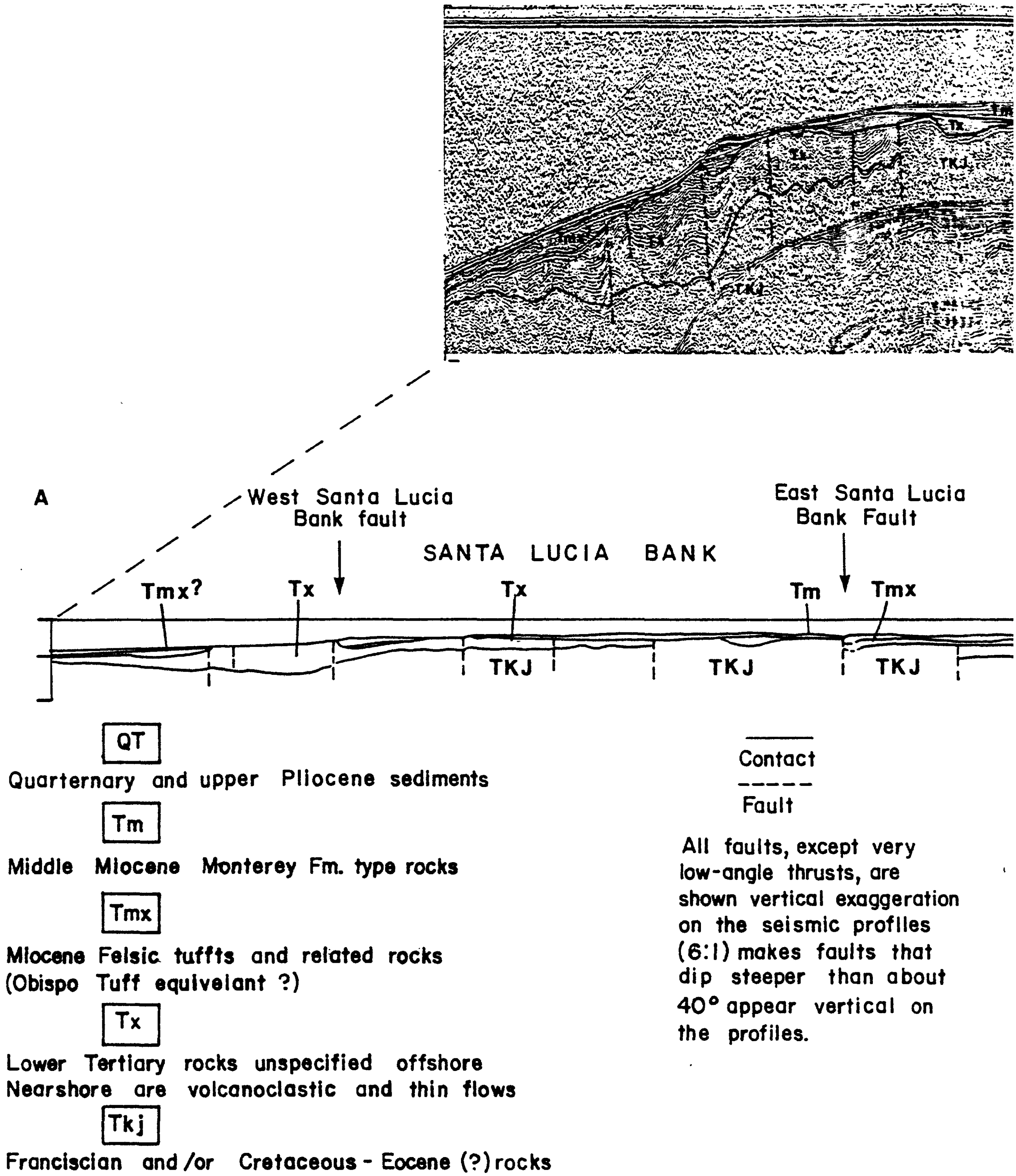
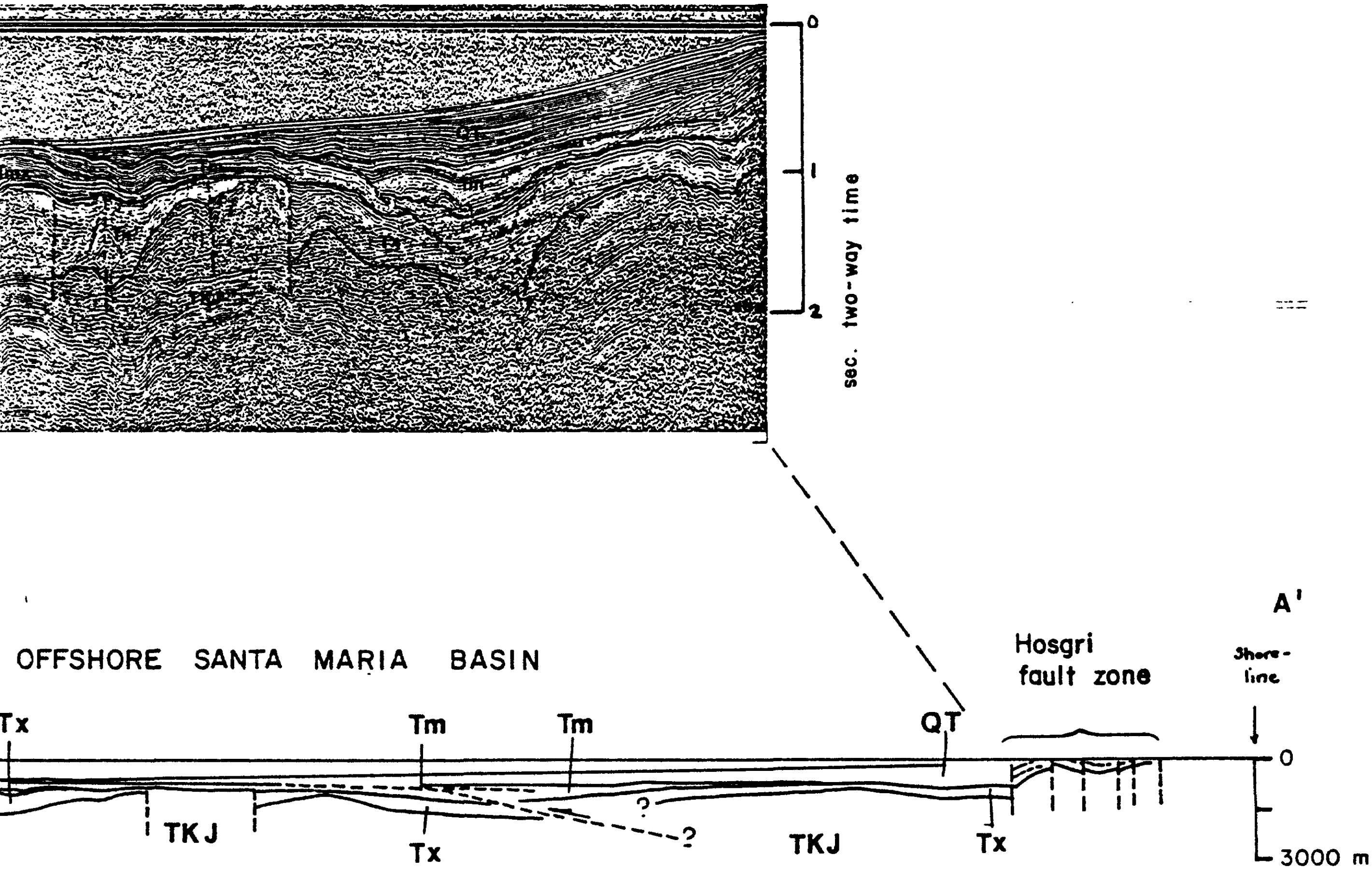


Figure 4. Geologic cross-section in Santa Maria Basin by McCulloch and Wagner,



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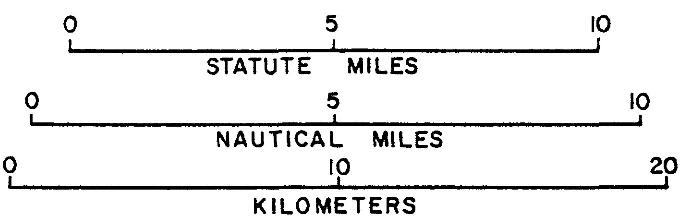
In developing "true" depths for this 1:1 cross-section, velocities are assumed to increase with depth at 5000 ft/sec (1500 m/sec) to 0.5 z where z is the depth to the reflection horizon below the seafloor. The water column is assumed to have a constant velocity of 4800 ft/sec (1440 m/sec).

Only major faults correlated from adjacent seismic reflection profiles are shown on fig.



(unpublished U.S. Geological Survey data). Section located on figure 2.

area. Low-angle thrusting, with a vergenz to the west started by at least early Tertiary time, and appears to have continued through Tertiary and Quaternary time.

Outer Santa Cruz Basin.--This relatively shallow late Tertiary basin, which measures approximately 25 km x 100 km, trends northwest across the shelf and extends onto the slope. It is bounded on the northeast by the Pigeon Point High, a structural high that is the probable southern extension of the quartz diorite cored Farallon High, and on the west by the Santa Cruz High (Fig. 5). Hoskins and Griffiths (1971) suggested that this basin is underlain by granitic rocks on the basis of unstated geophysical data and the proximity of granitic rocks to the east. Two exploratory wells in the basin (Fig. 1, Shell Oil Co. wells P-035-1ET, P-036-1ET) bottomed in upper Cretaceous marine sediments at depths of 2892 and 2358 meters. Silver and others (1971) state that the Outer Santa Cruz High is composed of Franciscan rocks or an early Tertiary equivalent. A dredge haul and dart core recovered undated mafic volcanics from the western flank of this high (unpub. U. S. Geol. Survey data). McCulloch (1973) and Graham (1976) suggested that right-lateral strike-slip displacement along the San Gregorio-Palo Colorado fault (Hoskins and Griffiths, 1971; Greene and others, 1973) may have displaced the southern edge of the offshore Salinian block northwestward approximately 80 km. If so, the Farallon-Pigeon Point High represents the southwest boundary of the Salinian block, and the basement beneath the Outer Santa Cruz basin should be Franciscan or Franciscan equivalent rocks, rather than granitic.

Cretaceous and early Tertiary (Oligocene ?) marine sandstone are

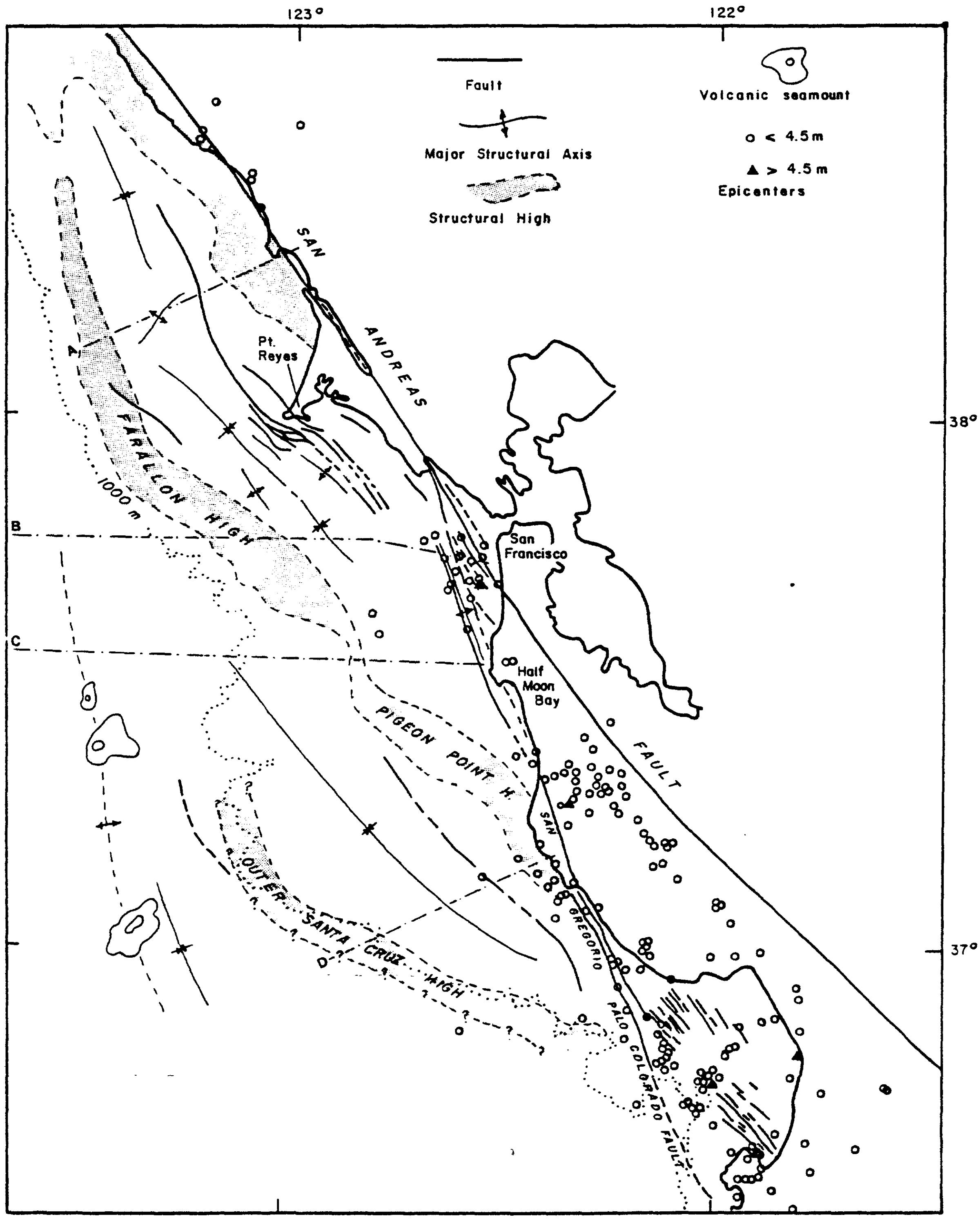


Figure 5. Generalized map of geologic structure, faults and epicenter locations in Outer Santa Cruz and Bodega basins. Geology after Hoskins and Griffiths (1971), Greene and others (1971), and McCulloch (unpublished U.S. Geological Survey data). Epicenter locations for 1812-1976 from Gawthrop (1975) and Gawthrop (written comm., 1977). Geologic cross-sections shown on figure 8 (A, B, C) and figure 7 (D).

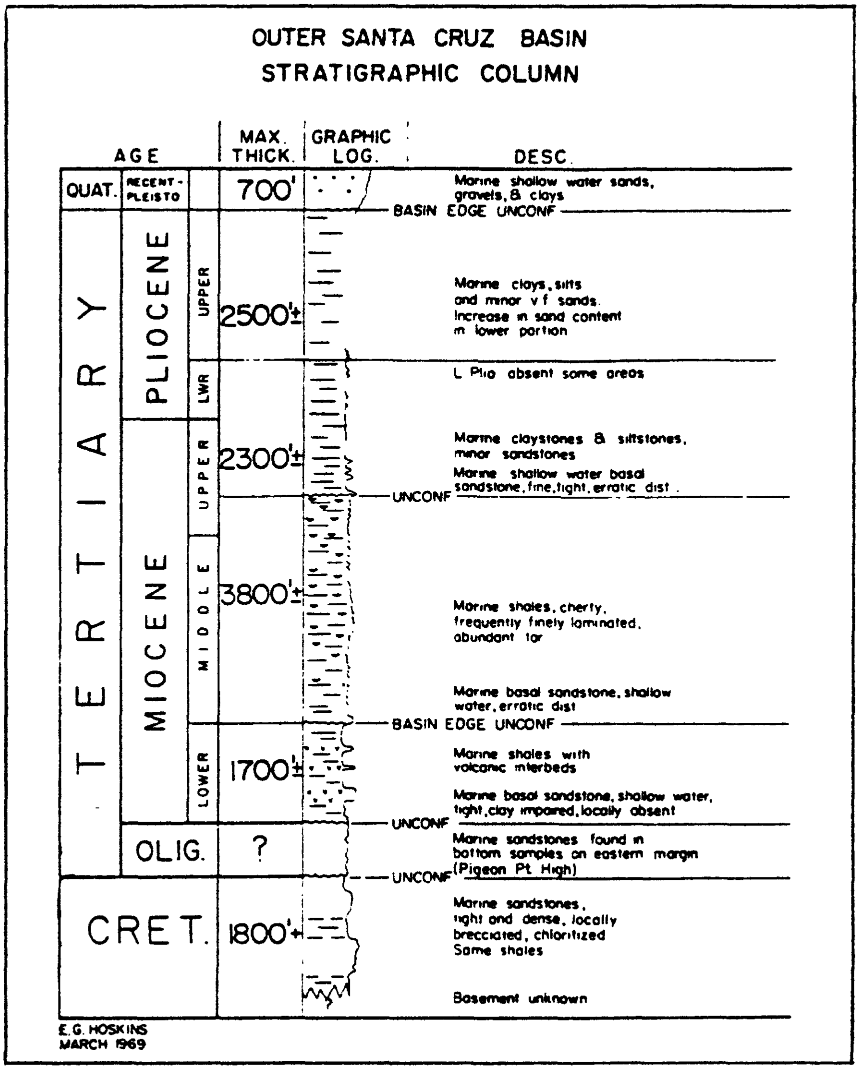


Figure 6. Generalized stratigraphic column for the Outer Santa Cruz Basin (Hoskins and Griffiths, 1971).

present locally beneath the basin (Fig. 6) but their general distribution is not known (Hoskins and Griffiths, 1971). Both the Cretaceous and Oligocene(?) periods of deposition were followed by deformation and erosion. The overlying Neogene units suggest repeated periods of erosion followed by marine sedimentation that reflect the transition from shallow sandy to deep finer-grained deposition. Volcanics (interbeded in marine shales) are limited to the lower Neogene as in the Santa

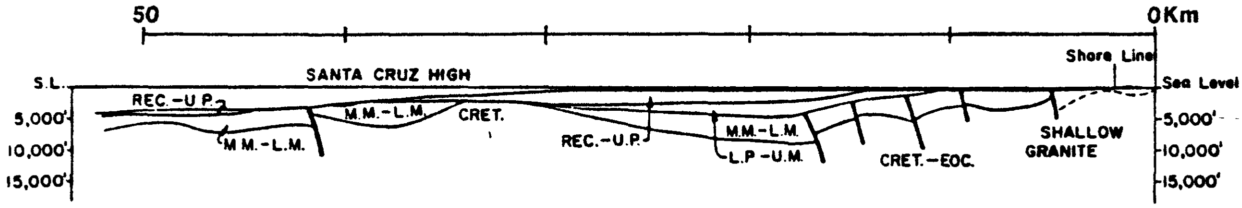


Figure 7. Geologic cross-section of Outer Santa Cruz Basin (Hoskins and Griffiths, 1971). Section located on figure 5.

EXPLANATION
REC. • RECENT
U.P. • UPPER PLIOCENE
L.P. • LOWER PLIOCENE
U.M. • UPPER MIOCENE
M.M. • MIDDLE MIOCENE
L.M. • LOWER MIOCENE
EOC. • EOCENE
CRET • CRETACEOUS

Maria basin offshore. Cherty shales (Monterey Formation?) dominated the deposition until the early late Miocene period of deformation and erosion that accompanied the uplift of the structural highs, and the initiation of the present basin. Relatively fine-grained sediment, primarily silt and clay with a minor amount of sand, accumulated in the basin in upper Miocene and Pliocene time.

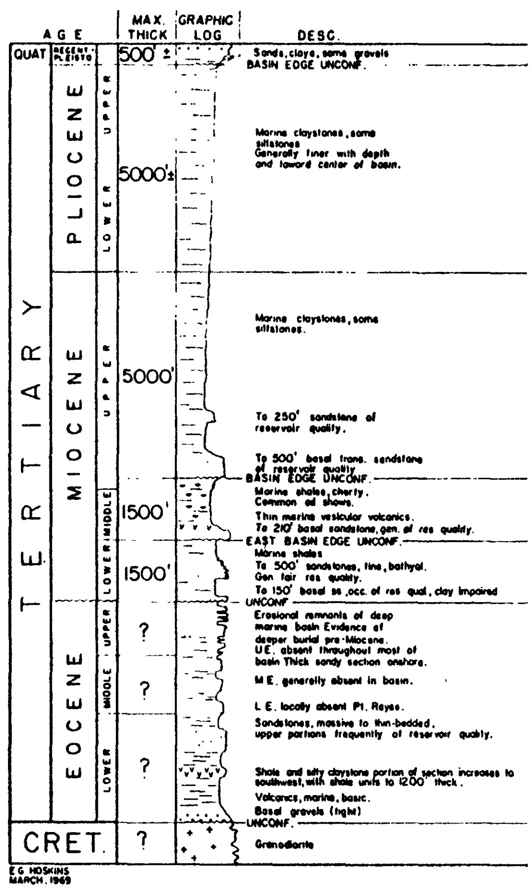
The structural axis of the basin and the Outer Santa Cruz High plunge to the northwest, over the edge of the shelf. The sediments thicken down the slope, and appear to be limited along the toe of the slope by a discontinuous volcanic ridge along which the Mullberry, Guide and Pioneer Seamounts form prominent topographic highs. Beneath the early upper Miocene unconformity the rocks are gently folded and the faults are generally high-angle reverse with a vergenz to the west. The southwestern basin margin does not appear to be fault controlled, for the early Tertiary sediments are upturned along the flank of the Santa Cruz High. The northeastern margin is controlled by a down-to-basin fault that displaces rocks up to at least the upper Miocene unconformity.

Bodega Basin.--"Bodega Basin" as used in this report (Fig. 5) encompasses both the Santa Cruz and Bodega basins of Hoskins and Griffiths (1971). This basin lies northeast of the Farallon-Pigeon Point High. It is bounded on the east by the San Andreas fault and down-to-basin faults along which granite basement has been elevated, and to the southwest in the Gulf of the Farallones by a structural high of deformed Neogene sediments. This basin is approximately 180 km long and has an average width of approximately 25 km. The following summary of the geology of this basin is drawn from Hoskins and Griffiths (1971), Cooper (1971), and the interpretation of single channel seismic reflection records (McCulloch, 1976).

The Bodega Basin overlies the Salinian basement block. Cretaceous granitic rocks have been recovered from Cordell Bank west of Point Reyes and from Farallon Island along the Farallon High to the southwest (Hanna, 1952; Uchupi and Emery, 1941). Similar rocks occur along the eastern side of the basin at Montara Mountain, on the west shore of Tomales Bay and at Point Reyes, but are limited to the southwest side of the San Andreas fault. Granitic rocks have been recovered from the bottom of two exploratory wells in the basin just south and southwest of Point Reyes (Fig. 1, Standard Oil Co. wells P-041-1ET and P-039-1ET at depths of 1423 m and 1707 m). Interpretations of magnetic and gravity data across the Gulf of the Farallones are also consistent with a presumed granitic basement (Griscom, 1966; Cooper, 1971).

Cretaceous rocks are probably limited to scattered remnants in the southern part of the basin, and are thought to be absent to the north. These deposits are primarily marine sandstones with minor amounts of fine-grained sediment, and contain basic volcanics and sills (Fig. 8). Lower Eocene deposits are thin and scattered, and are composed of marine shale and deep marine sandstones. Lower Eocene sediments are absent near Point Reyes but they increase in thickness to the north where lower Eocene rocks lie in sedimentary contact on the granitic basement. Middle Eocene sedimentary rocks may occur locally in the northern part of the basin, but are not known in the south. As in the adjacent Outer Santa Cruz basins, Neogene strata record reported periods of uplift and erosion followed by periods of marine sedimentation. Lower Miocene rocks rest upon an erosional unconformity, and grade vertically from shallow-marine basal sandstones to deeper-marine shales and sandstones. The middle-Miocene sequence is similar, with shallow-marine basal sandstone resting on an erosional unconformity, and grading upward to finer grained rocks containing cherty shale. As previously noted, uplift and erosion of the Farallon-Pigeon Point High occurred in early late Miocene time. Subsidence of the Bodega basin to the northeast was followed by deposition of as much as 3000 m of Neogene marine clays and silts and some sands of late Miocene and Pliocene age.

The tectonic history of this part of the shelf and the Bodega basin is similar to that of the adjacent shelf areas. Episodes of pre-middle Miocene deformation are recorded in the structure and erosional unconformities in Cretaceous and Paleogene rocks. Pre-Neogene structures are complex and may follow a different structural



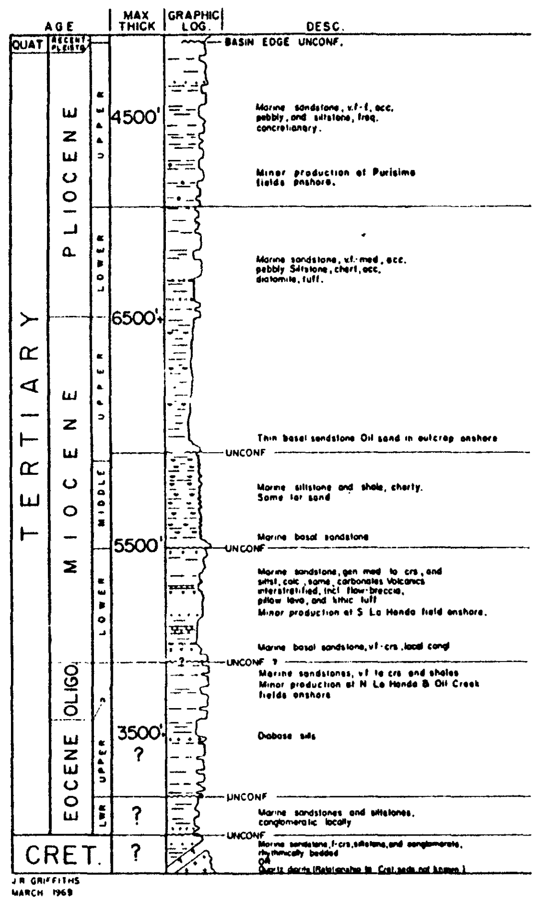


Figure 8. Generalized stratigraphic columns for northern (left) and southern (right) Bodega Basin (Hoskins and Griffiths, 1971).

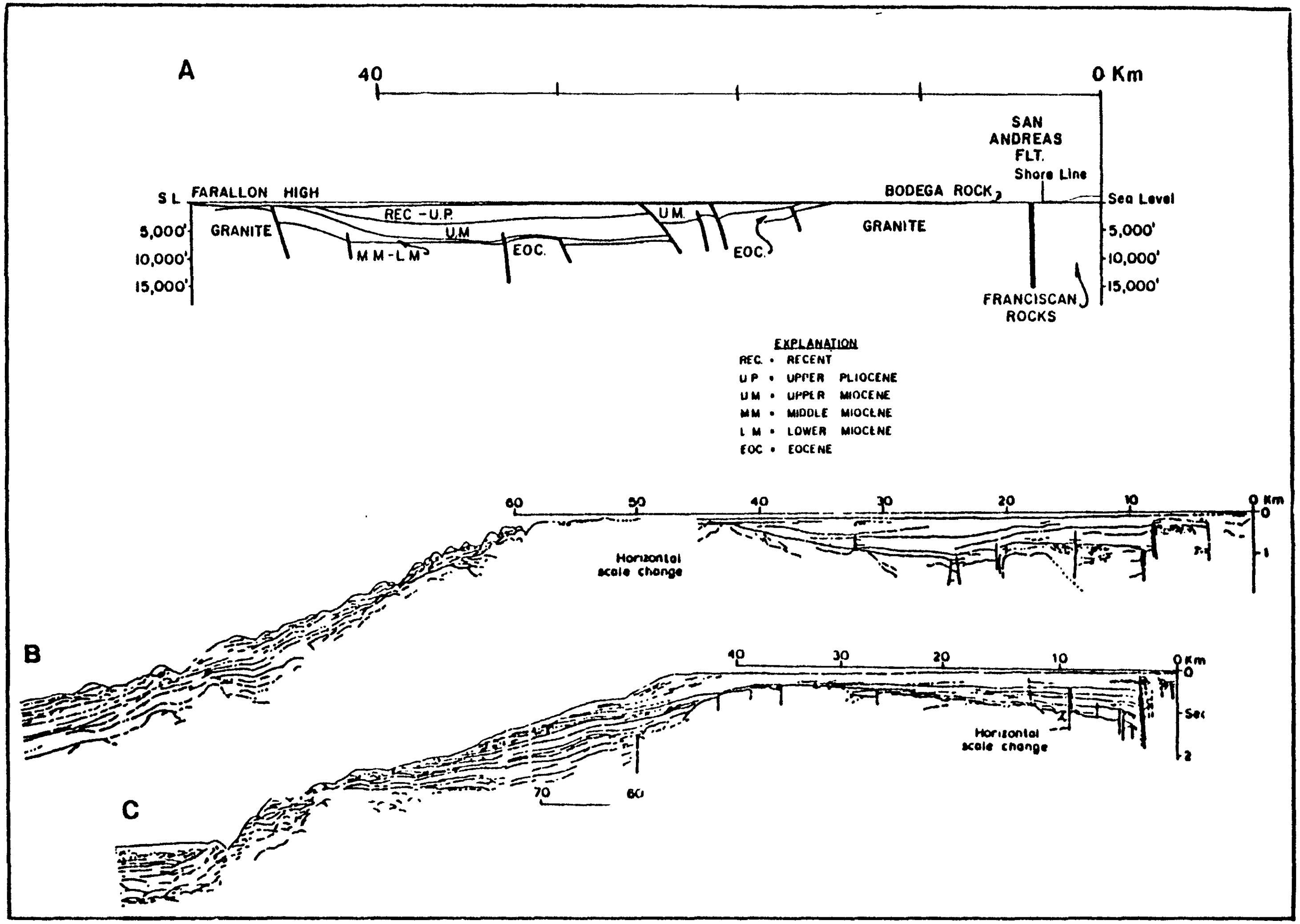


Figure 9. Geologic cross-section of northern Bodega Basin (Hoskins and Griffiths, 1971), and line drawings of seismic profiles in central Bodega Basin (McCulloch, unpublished U.S. Geological Survey data). Cross-section and profiles located on figure 5.

grain than those developed in the younger overlying strata (Hoskins and Griffiths, 1971). Subduction-related tectonics probably came to a close in late Miocene time with the uplift of the Farallon-Pigeon Point High. At about this time lower Neogene sediments began to be compressed into an elongate ridge, nearly parallel to, and just seaward of the San Andreas fault in the Gulf of the Farallones. At the same time, mid-Tertiary strata were deformed within the basin. The end of this deformation within the basin is recorded by an unconformity between the middle and upper Miocene units. Right-lateral shear and regional compression accompanied the transition to strike-slip faulting. Folds developed parallel to the long axis of the basin, and the northeastern-bounding structural high of compressed Neogene sediment underwent additional compression. Compression was accompanied by the development of high angle reverse faults, like those that displace granitic rocks at Point Reyes (Fig. 9) and at the same time a large displacement fault formed along the eastern basin margin west of Montara Mountain. This latest episode of deformation, which began in late Pliocene, continues today.

Point Arena Basin.--The eastern and northern margins of the Point Arena basin are well defined by the San Andreas fault as it runs northwestward from Point Arena and swings westward along the Mendocino Escarpment (Curray and Nason, 1967). The basin has a length of approximately 140 km. The average width of the basin to the 1000 m isobath is about 20 km, however the western edge of the basin lies well offshore of the 1000 m isobath, the depth limit in proposed OCS Lease Sale 53-A, and is formed by a partially buried structural high mapped by Curray (1966). The high trends northwestward away from the coast, giving the basin a width of 30 km at the south and about 55 km to the north (Fig. 10). A Deep Sea Drilling Project core hole (DSDP Leg 18, Site 173, Kulm and others, 1973) drilled on the western bounding ridge penetrated 138 m of lower continental slope deposits consisting of Pleistocene, Pliocene and Miocene grayish green mud, 147 m of upper to lower most Miocene diatomites and 35 m of gray nannoplankton ooze, and bottomed in andesitic basement. Silver (written commun., 1976) dredged graywacke of middle-Eocene to Oligocene age from this ridge about 50 km west of Fort Bragg. Thus the ridge appears to be geologically complex. The basin is reported to be underlain partly by pre-Cretaceous (Jurassic?) metasediments (Hoskins and Griffiths, 1971; Fig. 11). Thick sections of Cretaceous shallow water marine shale, siltstone and fine-grained sandstones crop out on shore to the south, but they thin abruptly to the north in the basin, probably as the result of pre-Eocene erosion. Eocene sediments also thin abruptly to the north in the basin, and are also truncated by an erosional unconformity below lower Miocene strata. Onshore to the south there is a thick section of lower to upper Eocene sandstone and shale, suggesting that if a comparable section existed on the shelf, it was largely removed by the late Paleogene-early Neogene erosion. Lower Miocene deep water marine shales containing a thick but discontinuous basal sandstone rest on the unconformity, recording a transgression and subsequent deep marine deposition. As in the basins to the south,

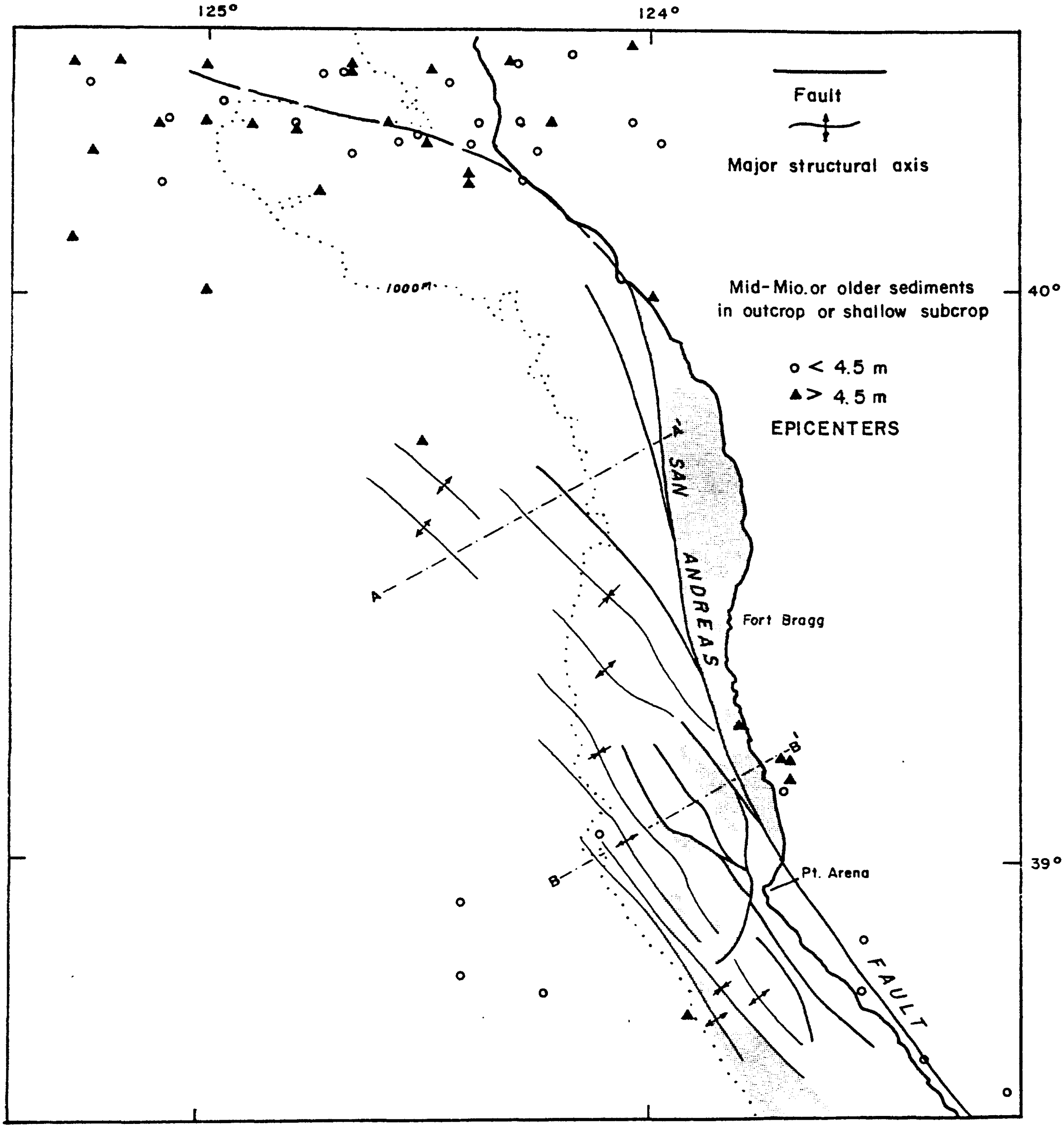


Figure 10. Generalized map of geologic structure and faults in Point Arena Basin (from Hoskins and Griffiths, 1971). Location of earthquake epicenters for 1898 to 1970 from Pacific Gas and Electric (1971). Geologic sections on figure 12.

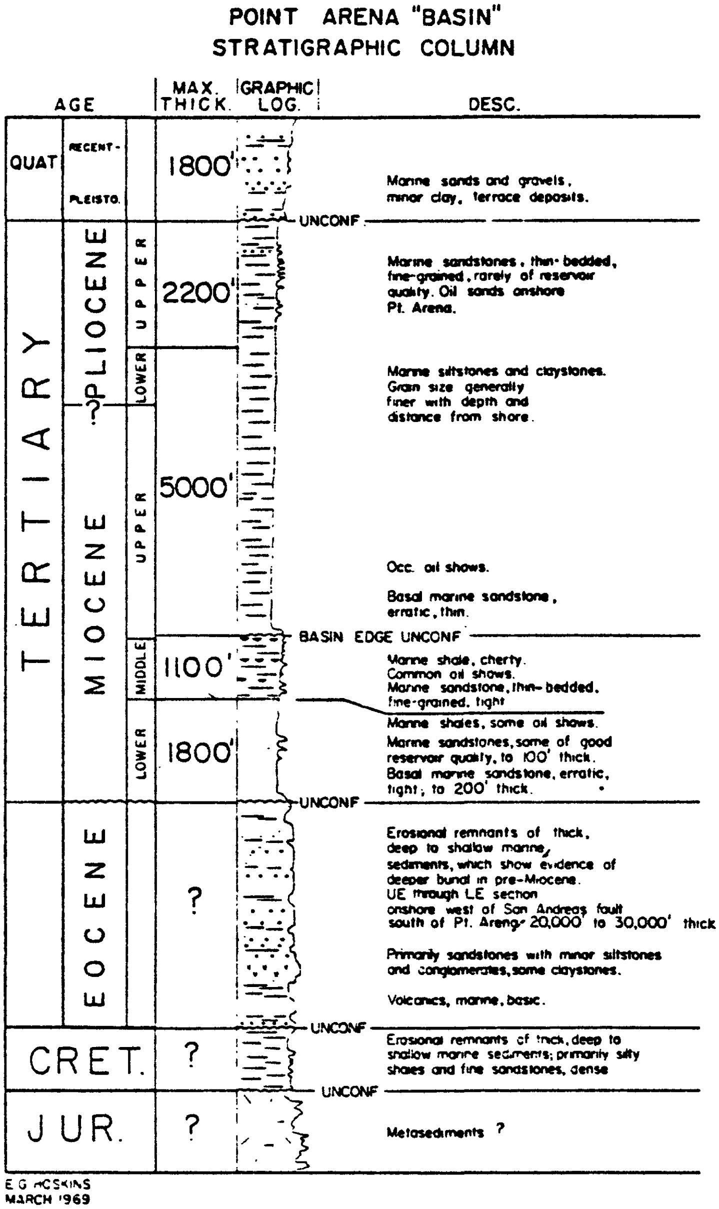


Figure 11.

Generalized stratigraphic column for Point Arena Basin (Hoskins and Griffiths, 1971).

the following middle Miocene is represented by cherty shale. A lower upper Miocene basal marine sandstone rests unconformably on older sediments near Point Arena, but over most of the basin there appears to have been no break between middle and upper Miocene sedimentation. Upper Miocene marine siltstones and claystones grade upward into upper Pliocene marine sandstones, which in turn are truncated by an unconformity at the base of the coarser Pleistocene section.

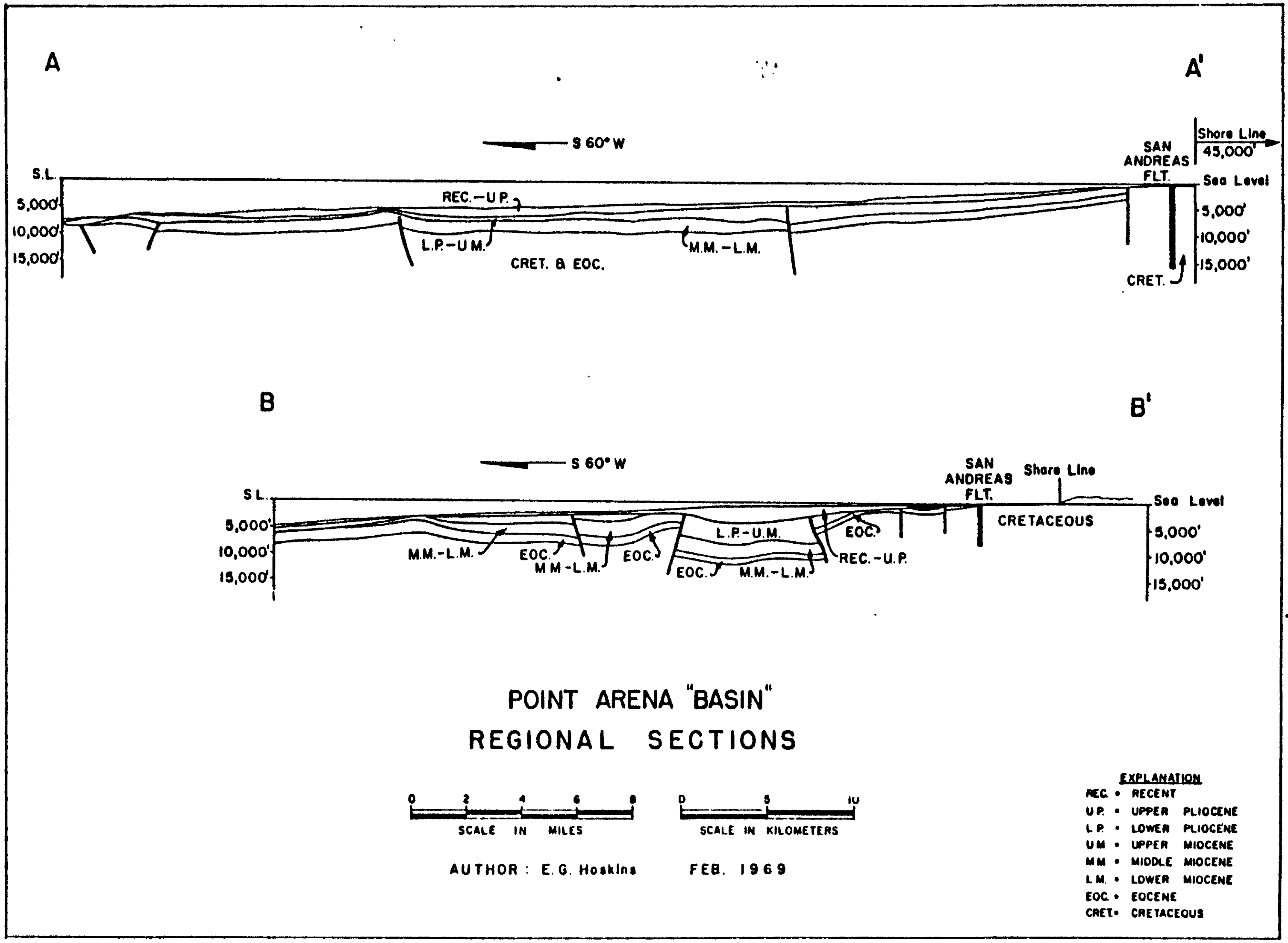


Figure 12. Geologic cross-sections in Point Arena Basin (Hoskins and Griffiths, 1971). Sections located on figure 10.

Little is known of the pre-Neogene tectonic history of the basin except that several episodes of deformation and erosion occurred during Cretaceous and Paleogene time. Judging from the degree of induration of early Eocene sediments, a considerable thickness of overyling rocks may have been removed. Likewise little is known of the history of the western boundary ridge. Seismic reflection profiles (Silver, 1971; Kulm and von Huene, 1971) across the ridge and age determinations from the DSDP core hole suggest that Miocene and younger strata are little deformed. Neogene structure is complex at the south end of the basin, but is relatively simple to the north (Fig. 12). Deformation of the south end of the basin may have started with the uplift that produced the early late Miocene unconformity in the Point Arena area. However, the major high-angle reverse faults, some with verticle displacements of about 2000 m and the fold axes that lie parallel to the elongate basin were largely formed in upper Pliocene time. These faults and folds trend northwest, and diverge northward from the San Andreas fault.

Eel River Basin.--The basin extends from near Cape Mendocino (40°30'N) on the northern California coast northward for 200 km (125 mi) to Cape Sebastian (42°20'N) in southern Oregon, and from the coastline seaward to the continental slope, an average distance of about 70 km (44 mi) (Fig. 13). The south end of the basin extends inland for about 50 km (30 mi) in the lower Eel River-Arcata Bay area. Little has been published concerning the ages and lithologies of rocks offshore, and the geologic history of the basin is reconstructed largely from exposures onshore. The geology of the on-land portion of the basin has been

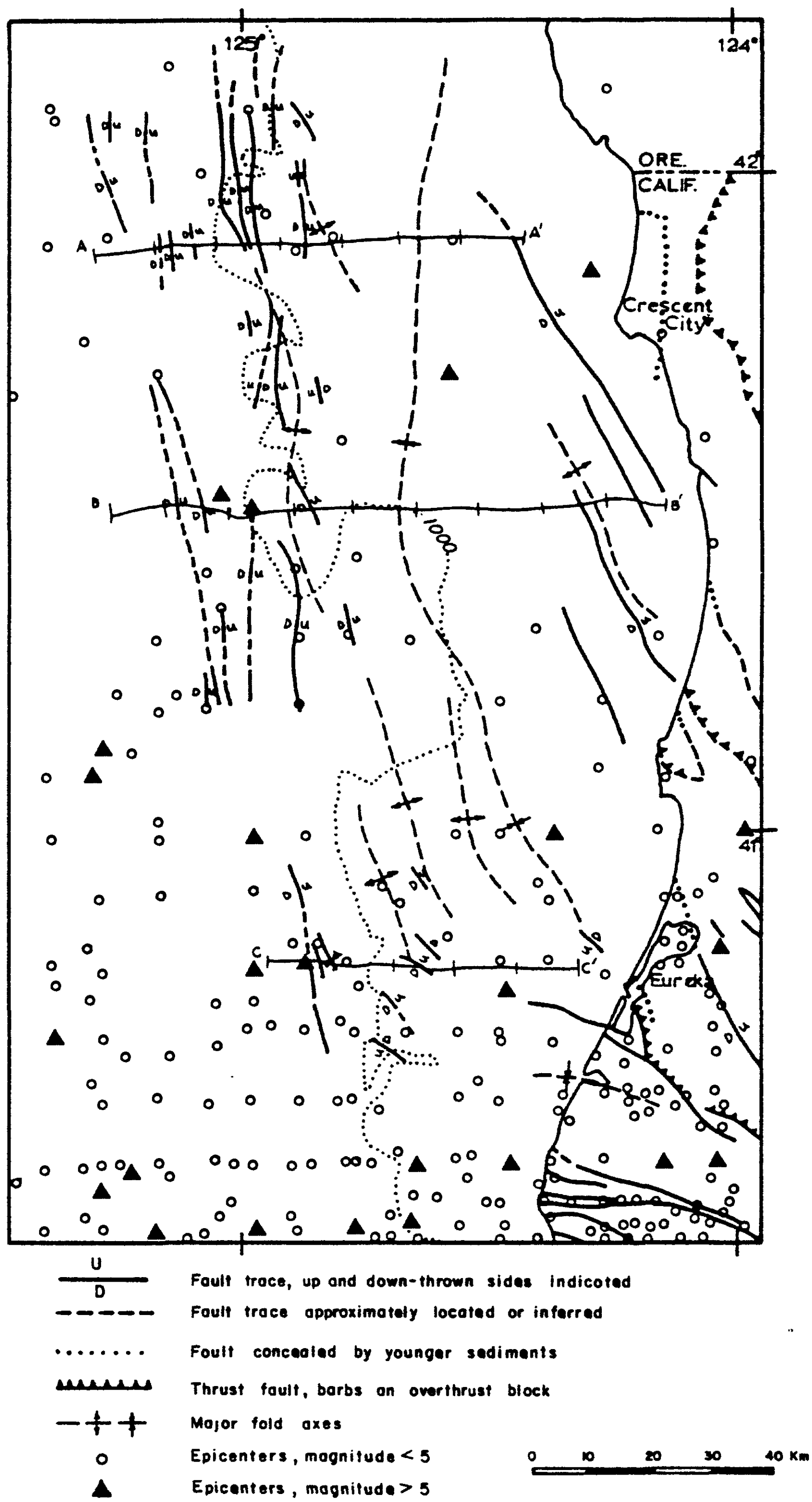


Figure 13. Generalized map of geologic structure and faults in Eel River Basin. Fault locations from Silver (1969, 1971), Hoskins and Griffiths (1971), and Jennings (1975). Location of earthquake epicenters for the period 1853 to 1973 from Couch (1974). Line drawings of profiles A-A', B-B', C-C' shown in figure 15.

described by Ogle (1953), and that of the surrounding region by Irwin (1960) and Bailey, Irwin, and Jones (1964). The geology of the offshore basin is described generally by Hoskins and Griffiths (1971), and the regional structure is discussed by Silver (1969, 1971a, 1971b).

Basement rocks in the onshore Eel River basin are mostly massive graywacke with some chert, basalt-greenstone, shale, limestone and schist assigned to the coastal and central belts of the Franciscan complex of Berkland and others (1972) of Late Jurassic to Eocene age (Fig. 14). This eugeosynclinal assemblage probably underlies the basin offshore as well. The Yager Formation, Eocene in age (Evitt and Pierce, 1975), is in fault contact with Franciscan basement rocks of the central belt in the lower Eel River area, but depositionally overlies relatively young (upper Cretaceous-Eocene) rocks of the coastal belt a short distance to the southwest (Ogle, 1953; Irwin, 1960). It is at least 765 m (2500 ft) and perhaps as much as 3060 m (10,000 ft) thick, and consists of dense, well-indurated mudstone, siltstone, and shale, with lesser graywacke and conglomerate containing locally-derived Franciscan detritus (Ogle, 1953).

Regional deformation occurred between Eocene and middle Miocene time, and Neogene strata unconformably overlie Eocene and older rocks in the Eel River basin both onshore and offshore (Ogle, 1953; Hoskins and Griffiths, 1971). The Wildcat Group comprises an essentially conformable sequence of mostly marine late Miocene to Pleistocene strata about 3670 m (12,000 ft) thick (Ogle, 1953). Predominant lithologies are weakly consolidated mudstone, siltstone and claystone, with subordinate amounts of sandstone and conglomerate, and minor lignite and

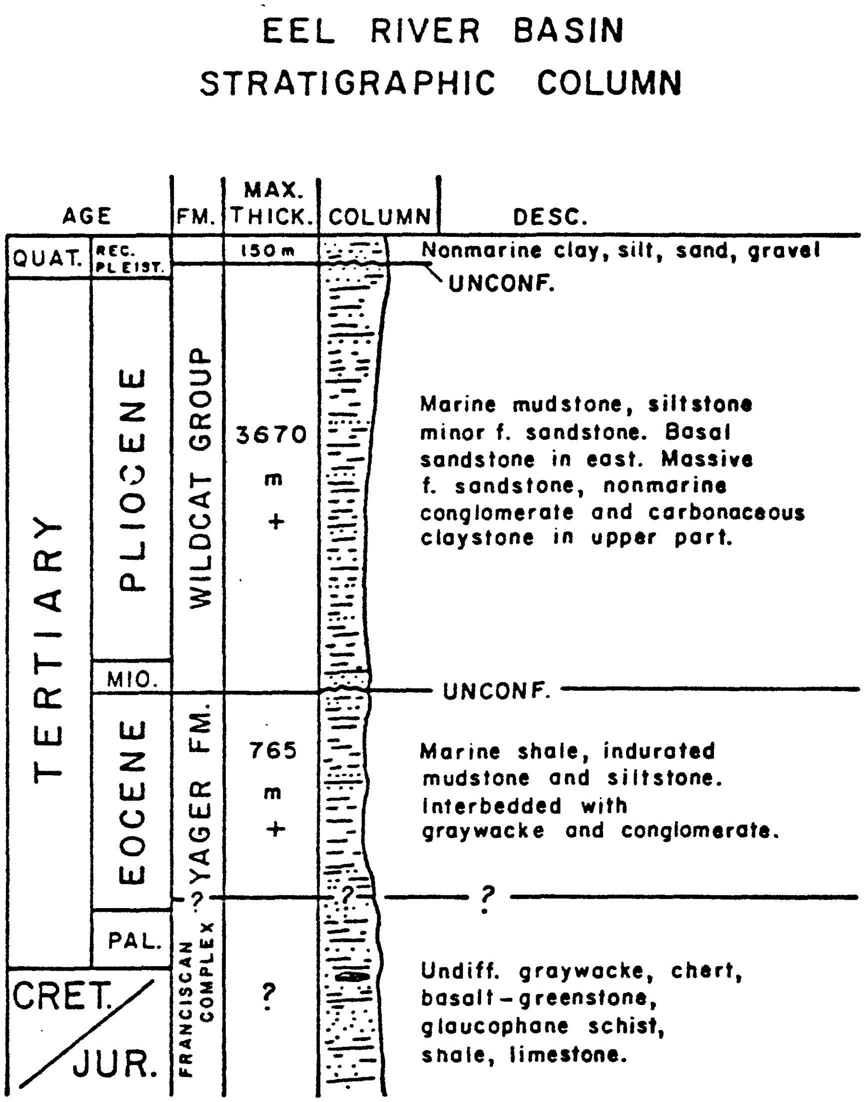


Figure 14.

Stratigraphic column, Eel River Basin (modified after Ogle, 1953; Hoskins and Griffiths, 1971).

tuff. Units of this group appear to record a northward transgression over basement during late Miocene, followed by alternate deepening and shallowing of the basin, a marine regression during late Pliocene, and finally by emergence and marginal marine and non-marine deposition in late Pliocene and Pleistocene time. Episodic marginal uplifts are indicated by coarse Franciscan debris and conglomerates of Pliocene mudstone fragments in some units, and by local unconformities within the group (Ogle, 1953). The section coarsens upward, reflecting late

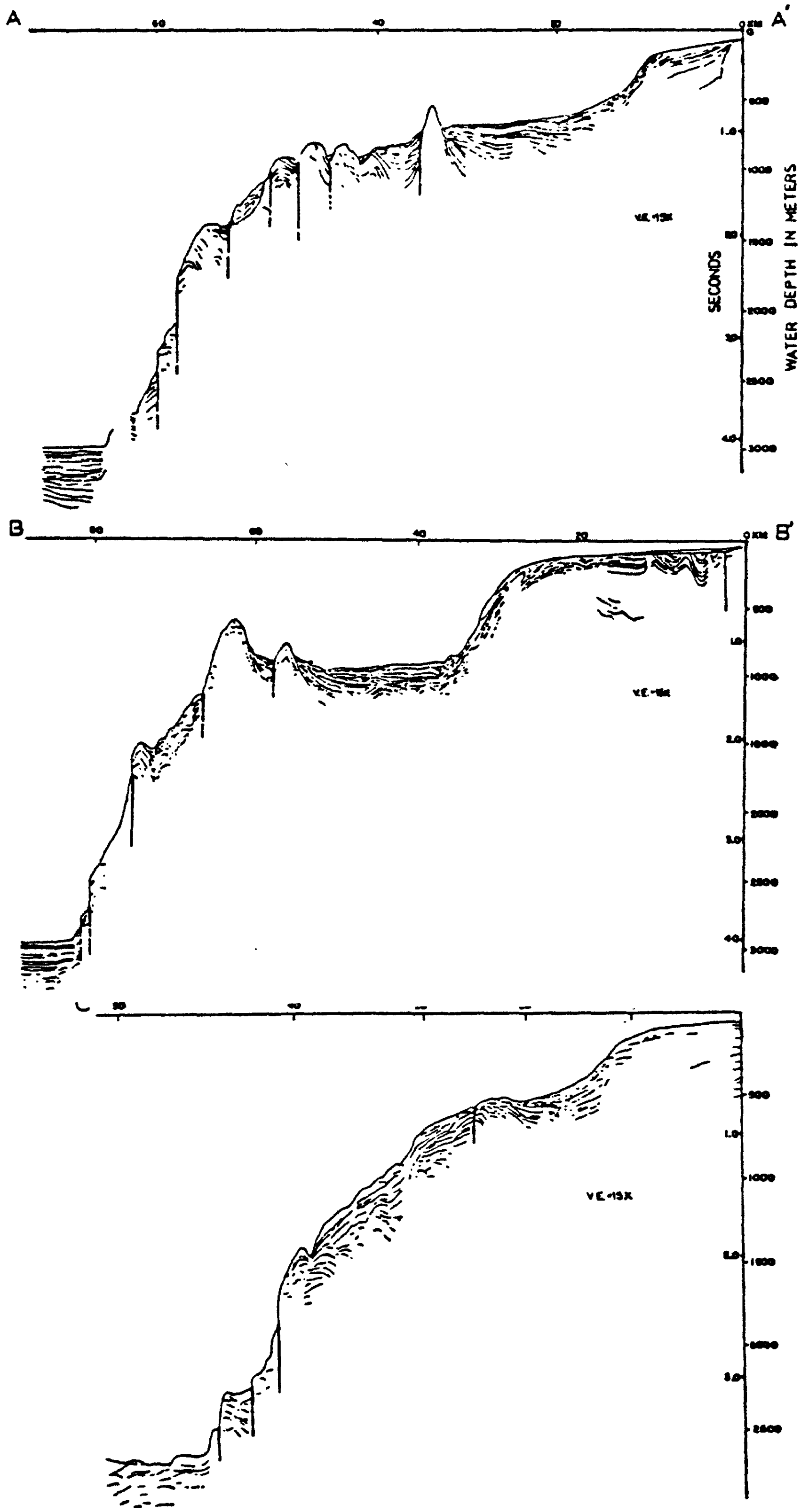


Figure 15 Line drawings from seismic profiles across the Eel River basin (Silver, 1969). See figure 13 for location of lines.

Pliocene regression, and eastward, reflecting the presence of a landmass nearby. Similar, predominantly shallow-marine, strata that are approximately correlative with the Wildcat Group are preserved in a graben located about 16 km (10 mi) to the north (Manning and Ogle, 1950), and in the Crescent City area (Back, 1957).

The close of Wildcat deposition was marked by basin margin warping and uplift that continued into Pleistocene time, culminating in basin-wide deformation that followed older structural trends (Ogle, 1953). Pleistocene and Holocene clays, sands, silts and gravels unconformably overlie Wildcat strata in onshore parts of the basin. These deposits have an aggregate thickness of about 150 m (500 ft) and were deposited in shallow-marine and coastal plain environments. As in the Wildcat Group, the marine section becomes finer grained northwestward, suggesting that the basin deepened in that direction.

The axis of the Eel River basin trends N. 80° W. onshore (Ogle, 1953), but swings to a near northerly orientation offshore (Hoskins and Griffiths, 1971; Silver, 1971a). Folds onshore parallel the basin margin and associated faults are thrusts and high-angle reverse faults, apparently reflecting NE-SW to N-S compression of the basin (Ogle, 1953). Pleistocene strata are gently folded along older structural axes of the Wildcat Group.

Major structures offshore also parallel the basin trend. On the continental slope and adjacent marginal plateau folds involving Pliocene and possibly younger strata are expressed in the sea floor and are cut by high-angle reverse faults having dip separations that are predominantly west-side down (Fig. 15; Silver, 1971a). This structural pattern is interpreted as resulting from E to NE directed compression of the continental margin related to Quaternary underthrusting of the Gorda Plate. A major northwest-trending fault showing Quaternary displacement separates thick sections of Mesozoic and Cenozoic rocks south of Crescent City (Jennings, 1975). Associated with this fault are en-echelon folds that are stepped to the right (Silver, 1971a). First motion studies of earthquakes during 1962-1965 indicate right-slip (Bolt and others, 1968) and Silver (1971a) interprets this motion as the result of shear interaction between the Pacific and North American lithospheric plates.

PETROLEUM GEOLOGY

Previous Petroleum Exploration in Proposed OCS Lease Sale 53-A

Exploration of the proposed OCS Lease Sale 53-A has been underway 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 shot an extensive network of shallow and deep penetration seismic reflection profiles over the entire shelf, and collected sea floor 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 these shelf basins and some in anticipation of OCS Lease Sale 53-A. A partial tabulation of the 1963 leasing events is given in Table 1. Following the 1963 lease sale, nineteen exploratory wells were drilled from ships (Table 2). Most targets appear to have been structural rather than stratigraphic traps. With the exception of the Santa Maria basin onshore, production from the adjacent onshore basins is almost entirely from structural traps. No significant hydrocarbons were encountered in the offshore drilling, and all wells were abandoned.

Petroleum in Adjacent Developed Areas

The offshore area in proposed OCS Lease Sale 53-A lies adjacent to three onshore basins (Fig. 1). Santa Maria basin onshore and basins in the adjacent Salinian province may be quasi-equivalents of the Santa Maria offshore and Bodega basins, however, the onshore basins are thought by some to be separated from the offshore basins by major faults that may have had considerable late Neogene strike-slip displacement (Graham, 1976; Hall, 1975). Eel River basin, lying north of the region of Neogene strike-slip faulting clearly extends ashore as in the Humboldt basin. Petroleum production from all of these onshore basins has been relatively small. Humboldt basin has had no significant oil production, and cumulatively, as of Jan. 1973, the others had produced a total of approximately 0.8 billion barrels, which consistuted approximately 6% of California's onshore oil production.

In the Santa Maria basin onshore nearly 75 percent of the oil (0.5 billion bbls) is produced from fractured shale reservoirs of middle Miocene and Pliocene age. Many fields in this basin have reservoir characteristics that pose difficult economic and technical problems; if similar reservoirs are found offshore, they may prove uneconomic to exploit. Per well recoveries 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. Declines typically are rapid in the first few years, but field

TABLE 1: PARTIAL OCS LEASING HISTORY--CENTRAL AND NORTHERN CALIFORNIA, 1963

Basin	# leases offered	# leased	Total of winning bonuses	# of subsequent wells drilled (see Table)	Status
Eel River		17		4	quit claimed
Point Arena	21	5	$557,843	3	" "
Bodega (and Santa Cruz)	41	27	$6,585,981	9	" "
Outer Santa Cruz	13	2	$162,432	2	" "
Santa Maria		6	$1,307,231	1	" "
Total		40		19	

life is long with resulting high operating costs. Some of the fields produce low gravity oil only after extensive steam injection. Variable oil gravities and extensive tar sands create development problems both from technical and environmental standpoints. In general, higher gravity oil is found in the deeper reservoirs.

Production from fields in the onshore Salinian province adjacent to the Bodega Basin has been quite low. The principal onshore fields (La Honda, Halfmoon Bay, Oil Creek) produced a 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 the San Ardo Field, nearly 250 km southeast of Half-moon Bay, where oil and gas are recovered from a coarse sandstone 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 (Calif. Div. Oil and Gas, 1975; Calif. Div. Oil and Gas, 1960). Humbolt basin (the onshore Eel River basin) has had no significant oil production. The small, now abandoned,

TABLE 2. EXPLORATORY WELLS DRILLED ON OCS LANDS

(after 1963 Federal OCS Lease Sale)

Company and Well Name		Basin	Total Depth		Spudded	Abandoned
			Meters	Feet		
Humble	P-012-1	Eel River	9034	2964	7-30-64	8-19-64
Humble	P-007-1	Eel River	273	897	7-01-64	7-27-64
Shell	P-019-1ET	Eel River	1981	6500	7-11-65	7-30-65
Shell	P-014-1ET	Eel River	2249	7377	6-17-65	7-7-65
Shell	P-032-1ET	Point Arena	2106	6909	11-26-66	1-13-67
Shell	P-033-1ET	Point Arena	1438	4719	10-24-66	11-11-66
Shell	P-030-1ET	Point Arena	3242	10,636	3-10-65	6-10-65
Shell	P-027-1ET	Bodega	986	3234	11-17-64	11-29-64
Shell	P-058-1ET	Bodega	2402	7882	1-18-67	2-07-67
Shell	P-053-1ET	Bodega	2456	8059	12-2-64	12-26-64
Shell	P-055-1ET	Bodega	2279	7477	10-12-64	11-6-64
Shell	P-055-2ET	Bodega	2213	7261	1-3-65	1-23-65
Shell	P-055-2AET	Bodega	2224	7297	1-25-65	2-15-65
Shell	P-051-2ET	Bodega	3190	10,466	8-2-64	10-3-64
Shell	P-041-1ET	Bodega	1433	4700	9-20-63	12-13-63
Shell	P-039-1ET	Bodega	1717	5632	2-16-65	3-3-65
Shell	P-036-1ET	Outer Santa Cruz	2283	7490	2-10-67	3-17-67
Shell	P-035-1ET	Outer Santa Cruz	2357	7736	9-01-67	9-28-67
Humble	P-060-1	Santa Maria	2444	8020	9-29-64	1-08-65

field at Petrolia produced only 350 barrels from a stratigraphic trap in Lower Cretaceous (Lower Capetown) sandstone and shale. Principal production has been gas, but again, the total has been small. Through December 1975, Tompkins Hill (Eureka) produced 63 billion cubic feet, and Table Bluff, now abandoned, produced 0.1 billion cubic feet. Production in both gas fields was from thin, lenticular, very-fine sands of the Pliocene Rio Del Formation in anticlinal traps (Calif. Div. Oil and Gas, 1976, Calif. Div. Oil and Gas, 1961).

Appraisal of the OCS Potential

Santa Maria Basin--Miocene source rocks similar to those on shore should be present within the offshore Santa Maria Basin. Seismic data indicate that the offshore upper Tertiary section is thin. The total volume of Miocene or younger rocks in the basin is approximately 7500 cubic km. There are only two relatively small areas where burial is as great as 3050 meters (10,000 feet), a depth believed necessary for a thermal regime sufficiently high to generate hydrocarbons from these source rocks (Fig. 1). However, a higher than normal temperature gradient exists onshore and may be present offshore as well, perhaps providing a thermal regime adequate for petroleum generation at depths somewhat less than 3050 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.

Reservoir beds are not known to be present offshore, but it is anticipated that fractured shale in the middle Miocene Monterey Formation will be a primary objective. This presupposes that the onshore and offshore lithologies and diagenetic history of the Monterey Formation are similar. Pliocene sandstone reservoirs onshore are limited to the northeast part of the basin and are not expected to extend far offshore. Potential reservoirs within the offshore Santa Maria basin are unknown but may be present as transgressive deposits laid down before the middle Miocene marine transgression. There appear to be local continental deposits of possible Oligocene age beneath the Miocene rocks, but in general the Miocene section rests on probable Franciscan basement. The single test well in the OCS area penetrated approximately 2150 meters of Pliocene and Miocene strata and 300 meters of volcanic rocks of probable Miocene age before bottoming in Franciscan basement. Areas around the margins of the offshore basin, where Miocene fractured shale reservoirs may be present, possibly contain low gravity oil.

Outer Santa Cruz Basin--The most probable source beds are tar-impregnated mid-Miocene cherty shales that are found throughout the basin. Cretaceous rocks below the lower Miocene erosional unconformity are highly deformed and dense, and are considered to have little hydrocarbon potential. Pre-Miocene reservoir beds are not known, but Hoskins and Griffiths (1971) say that the data are insufficient to conclude that such reservoir rocks are totally missing. Minor oil shows are present in upper Miocene and Pliocene rocks, but these rocks generally are fine-grained and of poor reservoir quality. If production from fracture porosity is contemplated, it may necessitate a considerable and long term effort comparable to the development from fracture porosity in the Santa Maria basin onshore.

Bodega Basin--There are reservoir quality sands of Eocene age in the basin but they are dense, having been deeply buried before being exhumed by the nearly shelf-wide erosion in Oligocene time. Although the Eocene section might be considered a prospective target, Eocene structures are difficult to define by seismic profiling and commonly do not coincide with younger overlying structures (Hoskins and Griffiths, 1971). In addition, onshore production, although largely from Eocene sands, has been trivial.

Reservoir quality sands are also present in Miocene basal and deep water marine units and at the base of the Pliocene. Tar and oil shows are common in the middle Miocene cherty shales, and some occur in the basal Pliocene sands. The major structures in upper Miocene and younger rocks are simple, large, closed anticlines. Although these structures and associated reservoir quality sands might be presumed to be attractive prospects, Hoskins and Griffiths (1971) say that "prior to drilling, Bodega basin appeared to have good potential... Such is not the present case insofar as the Miocene and younger basin is concerned, as tests (8 dry holes) have been drilled on all major structures".

Point Arena Basin--The most likely prospective section is composed of early Miocene and Pliocene sediments. There may be reservoir quality deep water marine sands in the basin, but their distribution is probably erratic. Oil shows are common in the middle and upper Miocene shales and cherty shales. Major structures associated with these potential source beds are elongate northwest-trending anticlines. In the southeast part of the basin the folds parallel, and are often bounded by high-angle reverse faults with large vertical components of displacement. Although these structures appeared to be the most likely prospects, three wells located on these structures in the southeastern end of the basin were dry.

Reservoir quality sands may also be present in the underlying Eocene rocks; however, as in the basins to the south, these rocks are dense. Eocene rocks are present at the south end of the basin, but thin rapidly toward the northwest. Furthermore, target structures in the Eocene may be difficult to define for as Hoskins and Griffiths (1971) note ". . . exploration below Miocene cherty shales is imprecise with present technology, to say the least".

Eel River Basin--The onshore extension of the basin, which constitutes approximately 10% of the area of the entire basin, has produced only a moderate amount of gas from Pliocene sandstone, and an insignificant amount of oil from late Cretaceous sandstone and shale. If the onshore is representative of the basin as a whole, offshore prospects may be for gas. The prospective section is probably the upper Miocene-lower Pliocene Wildcat Group (maximum thickness of 3670 m), composed mostly of marine siltstone and claystone. Hydrocarbon shows offshore are limited (Hoskins and Griffiths, 1971) and Miocene cherty shales, the probable source beds in basins to the south, are not reported here. Reservoir quality marine sandstone, within the Wildcat Group onshore, are fine-grained and lenticular, and their distribution is sporadic. Structures associated with the Mio-Pliocene section offshore are generally north--northwest trending gentle folds, some of which are bounded by parallel faults. Four wells drilled on these structures in the east central part of the basin were dry. There is evidence of shale flowage and diapirism in the basin (Hoskins and Griffiths, 1971), with the possiblity of related structural traps.

The underlying Eocene section is composed of well indurated, fine-grained marine sediments with minor graywacke and conglomerate. Hoskins and Griffiths (1971) indicate that Eocene strata are present only in scattered erosional remnants on the Franciscan basement. Thus, Eocene rocks appear to have little potential, either as source beds or reservoirs.

PETROLEUM RESOURCE APPRAISAL

The area of offshore California that is considered for the proposed OCS Lease Sale 53-A includes parts of five separate provinces of the

Pacific Coast Offshore Region. These provinces are, from north to south; Eel River, Point Arena, Bodega, Outer Santa Cruz and Santa Maria. Oil potential for Eel River basin appears to be so low that no probabilities were calculated. Geological estimates of the amounts of undiscovered recoverable oil and gas resources for the five provinces are:

Basin	95% Probability	5% Probability	Statistical Mean
OIL - (Billions of barrels)			
Eel River	--	--	--
Point Arena	0*	0.80	0.20
Bodega	0*	0.53	0.13
Outer Santa Cruz	0*	0.98	0.34
Santa Maria	0*	0.92	0.44
GAS - (trillions of cubic feet)			
Eel River	0*	1.30	0.32
Point Arena	0*	0.80	0.20
Bodega	0*	0.53	0.13
Outer Santa Cruz	0*	0.98	0.34
Santa Maria	0*	0.92	0.44

*The possibility of no occurrence of commercial oil or gas in a frontier province is quite real, consequently a marginal probability is assigned. The probability estimates of no oil or gas for each of the five provinces are:

Eel River........60% Point Arena........60%
Bodega...........60% Outer Santa Cruz...50%
Santa Maria......15%

The application of marginal probability estimates to the five provinces results in a "0" amount of resource at the 95% probability level.

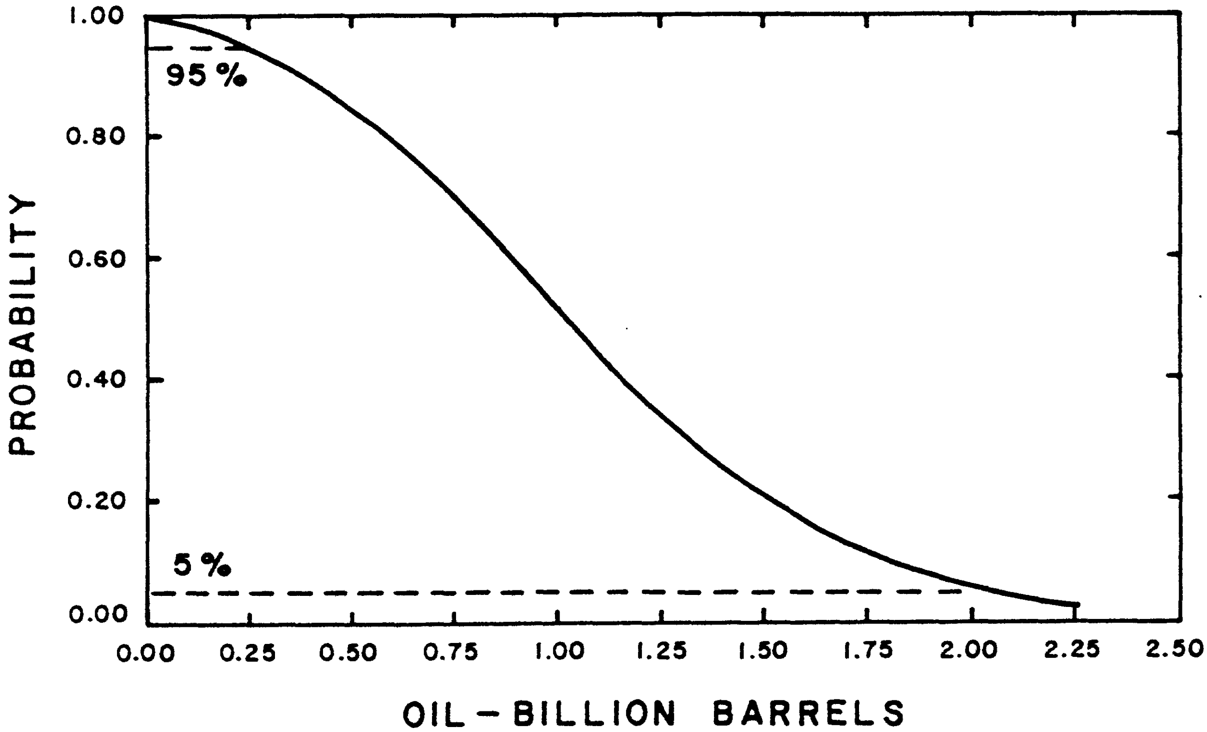
The geological resource estimates quoted are based in part on volumetric and analog analytical methods. They represent, however, estimates for the total province areas between water depths of 0 to 2500 meters (0 to 8200 feet), an area somewhat greater than the proposed sale area, which is limited to a water depth of no more than 1000 meters (3280 feet). With the basic understanding that the resources under consideration are defined as being recoverable under present conditions of economy and technology, most, if not all, of the estimated amounts of oil and gas can be allocated to those portions of the provinces lying between water depths of 0 to 1000 meters.

The areas assessed also include both State and Federal acreage and no attempt has been made for separate estimates. On an areal basis, it is estimated that slightly more than 90% of the area between 0 and 1000 meter water depths is under federal jurisdiction. For water depths less than 200 meters, the percentage of federal acreage drops to slightly less than 70%.

A resource estimate was made for the entire area by aggregating the figures for the five provinces by Monte Carlo simulation techniques. The resultant figures for estimated amounts of recoverable oil and gas for the Central and Northern California offshore area are:

	95% Probability	5% Probability	Statistical Mean
OIL - (billions of barrels)	0.21	1.98	1.11
GAS - (trillions of cubic feet)	0.29	2.63	1.43

The following log normal probability curves (Fig. 16) show the estimates of undiscovered oil and gas resources of the California offshore area that are related to the proposed OCS Lease Sale 53-A. The



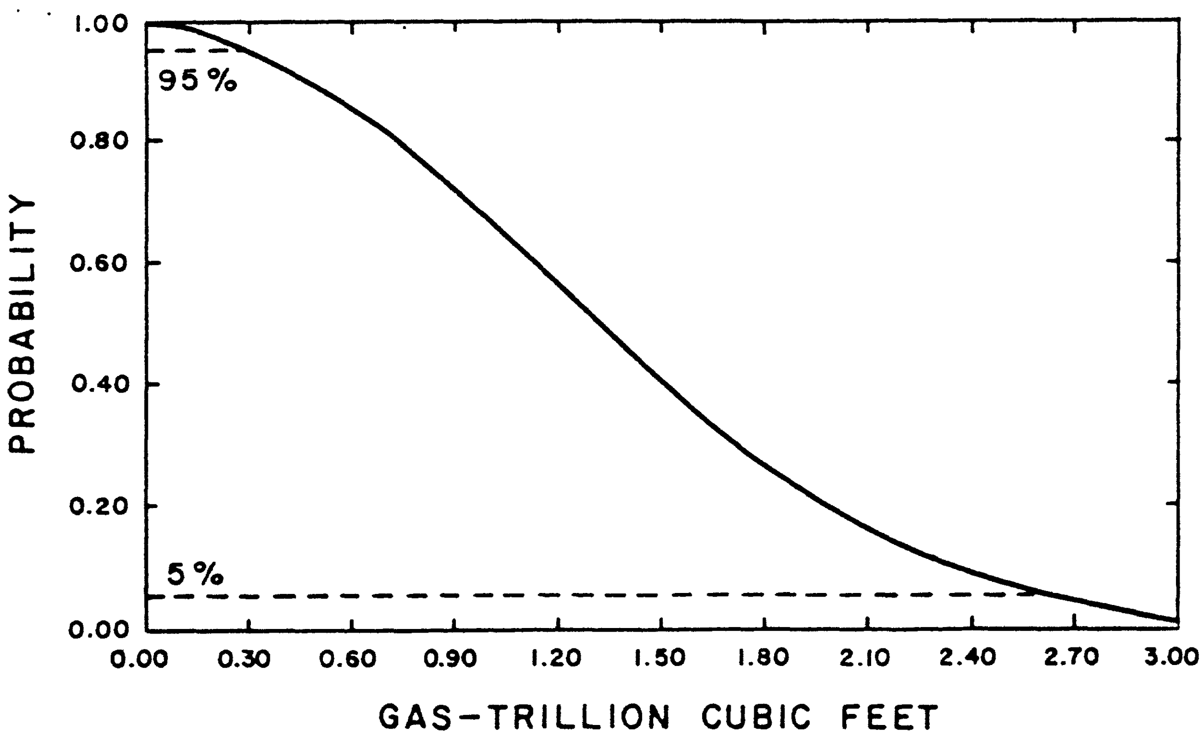


Figure 16. Log normal probability curves for estimates of undiscovered recoverable oil and gas resources in proposed OCS Lease Sale 53-A

95% and 5% probabilities are indicated by dashed lines--other probability estimates can be read directly from the curves.

A report titled "Geological Estimates of Undiscovered Recoverable Oil and Gas Resources in the United States" was published by the U. S. Geological Survey as Geological Survey Circular 725 (1975). Primary emphasis of that study was placed on onshore provinces and offshore provinces of the continental shelf to water depths of 200 meters. The results of that study pertaining to the areas under consideration for OCS Lease Sale 53-A have been included in this report and are part of the estimates of the individual provinces and the aggregation.

ENVIRONMENTAL HAZARDS

Instability of the sea floor, whether from seismic activity or sedimentary processes, is recognized as the principal hazard to emplacement of platforms and pipelines in the marine environment. Hazards related directly to seismic activity include ground shaking, fault rupture, generation of tsunamis, and earthquake-induced ground failures such as liquefaction and slumping. Faults showing displacement of either the sea floor or young (<11,000 years) sediments as well as those associated with historical earthquakes are considered active and therefore potentially hazardous to development. Instability of the sea floor can also result from dynamic (e.g. wave surge) and static (e.g. gravity) forces acting independently of seismic activity. Some areas of the sea floor are prone to mass movement (e.g. slumps, slides) or other forms of sediment transport (flows, creep, or current scour). Oil and gas seeps, while not inherently hazardous, may provide clues to the location of fractured reservoir rocks and shallow over-pressured gas pockets that can pose a danger to drilling operations.

Santa Maria Basin--Active faults have been mapped in offshore Santa Maria basin, and on the adjoining mainland (Jennings, 1975; Wagner, 1974; Earth Science Associates, 1974; McCulloch, Silver, and Wagner, unpublished data). The principal offshore faults (West Santa Lucia Bank fault, East Santa Lucia Bank fault, and Hosgri fault; Fig. 2) all appear to have associated seismic activity and/or appear to have segments along which the Quaternary sea floor deposits have been offset (Wagner, 1974). Some sea floor offsets and offset sediments are of Holocene age. Farthest seaward is the West Santa Lucia Bank fault along which there are escarpments that have downward displacement toward both the sea and shore. The East Santa Lucia Bank fault bounds the northeast side of the bank, and forms a major shoreward-facing sea floor escarpment that locally exhibits as much as 40 m of relief. The Hosgri fault forms a zone 3-5 km wide along the northeastern edge of the area. Displacement of Holocene sediment and of the sea floor has been noted in this zone between San Simeon Point and Point San Luis. Lack of continuous faulting offshore near San Simeon Point suggests that a branch of the Hosgri fault may connect onshore with the San Simeon fault zone which also shows evidence of Quaternary movement (Hall, 1975). Interpretation of seismic profiles indicates a zone of thrust faulting in the southern end of the basin that may be active. This north trending zone lies along the axis of the basin, and measures approximately 20 km wide and 50 km long. Sediment at least as young as Pliocene has been displaced by the thrusting, and Gawthrop's (1975) first motion studies of seismic events in this zone indicates north striking thrusts with a vergenz to the west, and a northeastern compressional component. This deformation is compatible with right lateral shear.

Studies of plate motion indicate that there should be about 5.5 cm/yr horizontal displacement between the North American and Pacific plates in this area (Atwater, 1970). Because only about 2.5 cy/yr displacement is occurring on the San Andreas fault, the balance of the displacement can be expected to occur as faulting and folding in the area west of the fault, including the offshore Santa Maria basin. Hypocenters for these earthquakes are thought to be shallow, and to lie at 15 km or less beneath the surface. Epicenters of about 550 instrumentally recorded earthquakes for the periods 1934 - 1969 and 1969 - 1974 were catalogued and where necessary relocated on maps by Gawthrop (1975). About 100 of these earthquakes are in the offshore area and of these roughly 10 percent have magnitudes greater than 4.5. As he notes, many small earthquakes may have gone undetected because this area lies at the margin of the seismic detection networks. Gawthrop (1975) also has noted pre-1934 earthquakes as listed by Townley and Allen (1939). The largest offshore earthquake, the Lompoc earthquake of Nov. 19, 1927, had a magnitude of 7.3 - 7.5 and was initially plotted near the southern end of the Santa Lucia Bank faults. Re-analysis of epicenteral data by Smith (1974), Hanks and others (1975), Gawthrop and Engdahl (1975), and Gawthrop (1976) have moved the location progressively eastward, and the latest location places it very nearly on a segment of the Hosgri fault. Records indicate tsunami activity and abnormally high waves and tidal variations at the time of the Lompoc earthquake in late 1927 (Gawthrop, 1976). The tsunami and seismic records suggest that sea floor rupture occurred along a segment of the Hosgri fault roughly 70 km long between Point San Luis and Point Arguello. Additional tsunamis that may have affected this area are listed in Townley and Allen (1939).

Deep-seated lateral displacements of rock masses and shallow slumps and slides occur in the northern end of the basin (Fig. 2). Large blocks of Neogene rocks (uppermost Miocene, Pliocene and Quaternary) are found as discrete blocks of relatively coherent seismic reflectors that are laterally bounded and underlain by zones of contorted bedding. Shallow slumps are superimposed on these blocks. The sea floor in the area is highly disrupted by chaotic slump topography, in contrast to its normal smooth surface. Unmodified slump toes on the sea floor and the absence of ponded young sediment in the topographic depressions indicate that these failures are active. The shallow failures are probably gravity-driven but seismic profiles suggest that the deep seated failures may be caused by seaward thrusting associated with high-angle reverse faulting along the northeastern edge of the basin. Comparable deep-seated and shallow failures may occur in the area of active thrusting in the southern part of the basin.

Outer Santa Cruz and Bodega Basins-- Active faulting in Bodega Basin is largely limited to its eastern margin (Fig. 5). In Monterey Bay, at the south end of the basin, seismically active faults displace Holocene deposits and the modern sea floor (Greene and others, 1973). These faults strike northwest obliquely toward, and terminate against, the seismically active San Gregorio-Palo Colorado fault. First motions indicate that the faults in the bay and the San Gregorio - Palo Colorado fault are moving with right lateral strike slip displacement. To the north, in the Gulf of the Farallones just west of San Francisco, young faults displace Holocene deposits at the sea floor, but the redistribution of sea floor sediment is so rapid that displacement of the sea floor is minimal. These faults occur in a wide zone between the San Andreas and the fault-bounded structural high that lies along a possible northwestern extension of the San Gregorio - Palo Calorado fault. There are a few epicenters further offshore that lie along the margins of the outer Santa Cruz High and the Farallon - Pigeon Point High, but their relation to possible faulting is not known.

No slumps or slides have been recognized in Bodega basin south of Point Reyes where there is relatively good high resolution seismic profiling information. North of Point Reyes and in the outer Santa Cruz basin there are insufficient data to establish the presence or absence of slumps or slides.

Tsunamis have been reported in this area, but they are generally associated with water level changes of less than about 1 meter. The greatest change in water elevation reported in Iida and others (1967) for the period from the first observation of a tsunami in San Francisco in 1812 to 1967 was 4.6 meters reported at Half Moon Bay in 1859. Iida and others (1967) give the location of the probable epicenter as San Francisco (Oct. 18, 1859). A magnitude 7.4 earthquake (April 11, 1946) in the eastern Aleutian Islands produced tsunamis of 3.5 meters in Santa Cruz and Half Moon Bay, but the amplitudes were considerably smaller where measured along adjacent parts of the coast. The Great Alaskan Earthquake (M 8.5, March 1964) that generated the highly destructive tsunamis at Crescent City to the north had only a minor effect along the shore of Bodega basin, producing only a 1.3 meter rise in water at San Francisco (Iida and others, 1967; Wiegel, 1970).

Point Arena Basin--There are inadequate publicly available acoustic reflection records to examine potential geologic hazards related to faulting or slumping and sliding in this basin. In addition, the basin is not well covered by existing seismograph networks, and it is possible (as suggested by the relatively high proportion of M >4.5 earthquakes reported; Fig. 10) that smaller earthquakes that indicate not only acivity but also possible location of active faults, are not detected. The potential for strong ground motion over the entire basin is great, for the San Andreas lies within 10 to 30 km of the 1000 meter isobath. In addition, several M >4.5 earthquakes have occurred along the western edge of the basin. The combined potential for strong ground motion and the fine-grained muds on the basin floor (Welday and Williams, 1975) suggest that slumps and slides may exist.

Eel River Basin--Within the general area of the Eel River Basin over 250 earthquakes, 23 having magnitudes greater than 5, have occurred between 1853 and 1973 (Fig. 13; Couch and others 1974). First motion studies by Bolt and others (1968) for the period 1962-1965 show right lateral motion along prominent northwest trending faults. The basin overlies the actively subducting Gorda plate, consequently an earthquake of magnitude 7.0 to 7.5 with a hypocenter depth of 40-50 km can be expected to occur in the offshore regions of northern California (Smith, 1975).

Most faults in the basin are high-angle and oriented north to northwest. Most on which movement can be determined are down-thrown to the west. The lack of high-resolution seismic reflection data makes it difficult to specify which faults are active, however, interpretations of seismic profiles across the continental margin by Silver (1969, 1971a) show that the most of these faults are associated with offsets in the sea floor, thus many have been active during Quaternary time (<2,000,000 years). Earthquake epicenters appear to coincide with a prominent northwest-trending fault southwest of Crescent City (Fig. 13, suggesting that it is active (Bolt and others, 1968). First motion studies of 1962 - 1965 epicenters along the fault (Bolt and others, 1968) suggest that this and possibly other northwest-trending faults are undergoing right-lateral strike slip motion (Bolt and others, 1968).

Shale flowage and diapirism described from the Oregon-Washington continental shelf to the north (Rau and Grocock, 1974) may also be occurring in the Eel River basin (Hoskin and Griffiths, 1971). Sea floor movement and faulting attendant to diapir growth may be hazardous to sea floor installations.

The frequent large earthquakes generated along major structural planes (Mendocino and Blanco fracture zones, Juan de Fuca Ridge, Queen Charlotte Islands and Fairweather faults) in northwestern North America generate tsunamis that effect shallow regions of the northern California shelf and coast. For example, Crescent City has had a long history of tsunamis. The largest was generated by the 1964 Alaska earthquake which produced waves as high as 6.3 m that caused eleven deaths and about nine million dollars of damages (Iida and others, 1967).

Many of Silver's (1969, 1971a) seismic profiles across the continental margin show evidence of downslope mass-movement, but little is known of the general distribution of slumps and sediment slides on the northern California shelf. Mass movement may be a hazard in some areas due to the nature of the sediments present and the sea floor gradient. The portion of the basin lying between the continental shelf and Klamath and Eel Plateaus at depths of 200 to 800 meters (plateau slope of Silver, 1969) has an average slope of 2° to 3°, and a maximum slope of 6° west of Gold Bluffs. Slopes within the Eel Canyon locally exceed 11°. Little information exists on the thickness of unconsolidated Quarternary sediments in this region, but even though the sediment cover may be sparse, slumping may occur. On tectonically-active shelves studied elsewhere numerous slumps have been identified on slopes of 3° to 6°, even in areas of relatively thin sediment cover (Greene and others, 1975). Onshore data suggest that older poorly consolidated deposits may also be prone to failure. Slumps and debris slides involving interbedded sandstones and mudstones of the Rio Del and Pullen Formations and other units of the Wildcat Group, and older deposits of the Yager Formation are common in the onshore Eel River Valley area (Ogle, 1953). At least one slump was triggered by an earthquake (Ogle, 1953). These onshore units crop out on the shelf and may be susceptible to similar mass failures.

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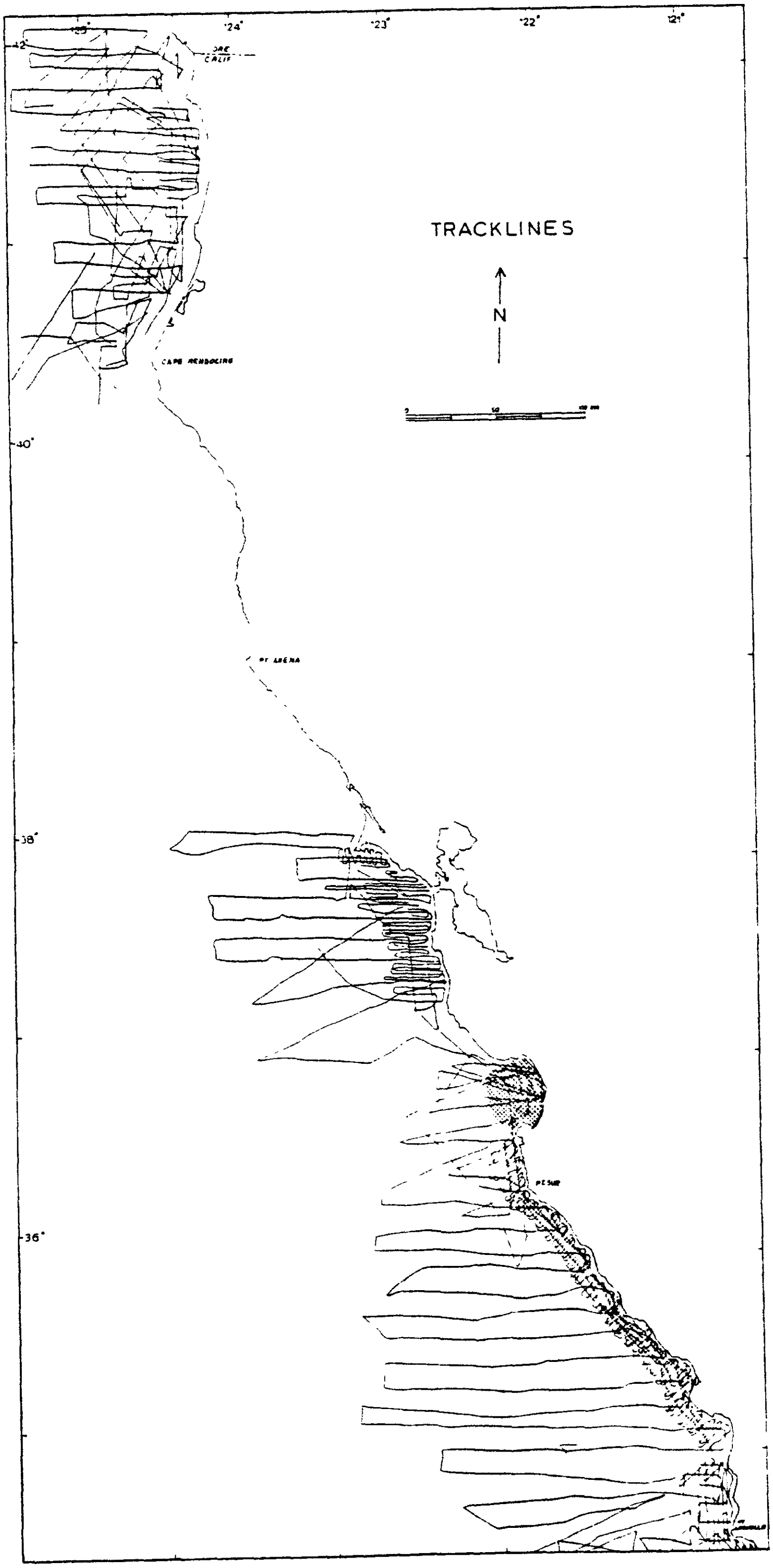

es of U.S. Geological Survey cruises, central and northern California borderland.