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Geology, Environmental Hazards, and Petroleum Resources for 1982 OCS Lease Sale 73, Offshore Central and Northern California

by

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M. E. Field, E. W. Scott, and P. A. Utter

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INTRODUCTION

This report summarizes the regional geologic framework, petroleum potential, and environmental geology that will affect exploration and development in the proposed OCS Lease Sale 73 area. This report is a slightly modified version of the formerly released USGS Open-File Report 80-2007 which was released in 1980 under the title of "A Summary Report of the Regional Geology, Environmental Geology, OCS Resource Appraisal, Petroleum Potential, and Operational Considerations in the Area of Proposed Lease Sale 73, Offshore California." The report contained four chapters, A through D, and was compiled by D. S. McCulloch.

The area included in Lease Sale 73 was subsequently redefined, removing the Southern California Borderland and placing it in Lease Sale 68.

This current revision of Open-File Report 80-2007 reflects these boundary changes and differs from the original report in the following ways:

1) Chapters A and D of the original report (taken from Vedder and others, 1980), have been omitted. These chapters dealt with the Southern California Borderland and with operational considerations, respectively.

2) Former chapter B, the section on the regional geology of central and northern California (pages 1-70 of this report), is nearly identical with the original, except for changes in the Planning Area Boundary shown on Figure 1.

3) Former chapter C, Petroleum Resource Appraisal (pages 71-76), has been updated to show changes in conditional estimates in the deeper waters of the offshore Santa Maria basin that lies on the central California continental shelf.

Coverage ranges from detailed, closely spaced geophysical surveys along parts of the coastline, to widely spaced reconnaissance of areas farther offshore (see Appendix, p.70). In areas where no survey data are available, the summary is drawn entirely from the literature.

The proposed OCS Lease Sale 73 described in this report encompasses the continental shelf of central and northern California, north of Point Conception. It is bounded on the east by the State of California three-mile limit, on the south by latitude 34.50° north, on the west by the planning area boundary, and on the north by latitude 42° north (Fig. 1).

REGIONAL GEOLOGIC FRAMEWORK

General Setting

Proposed OCS Lease Sale 73 contains five basins that lie on the shelf or partially on the adjacent continental slope of central and northern California (Fig. 1). In Late Cretaceous time, before the basins existed, the Farallon

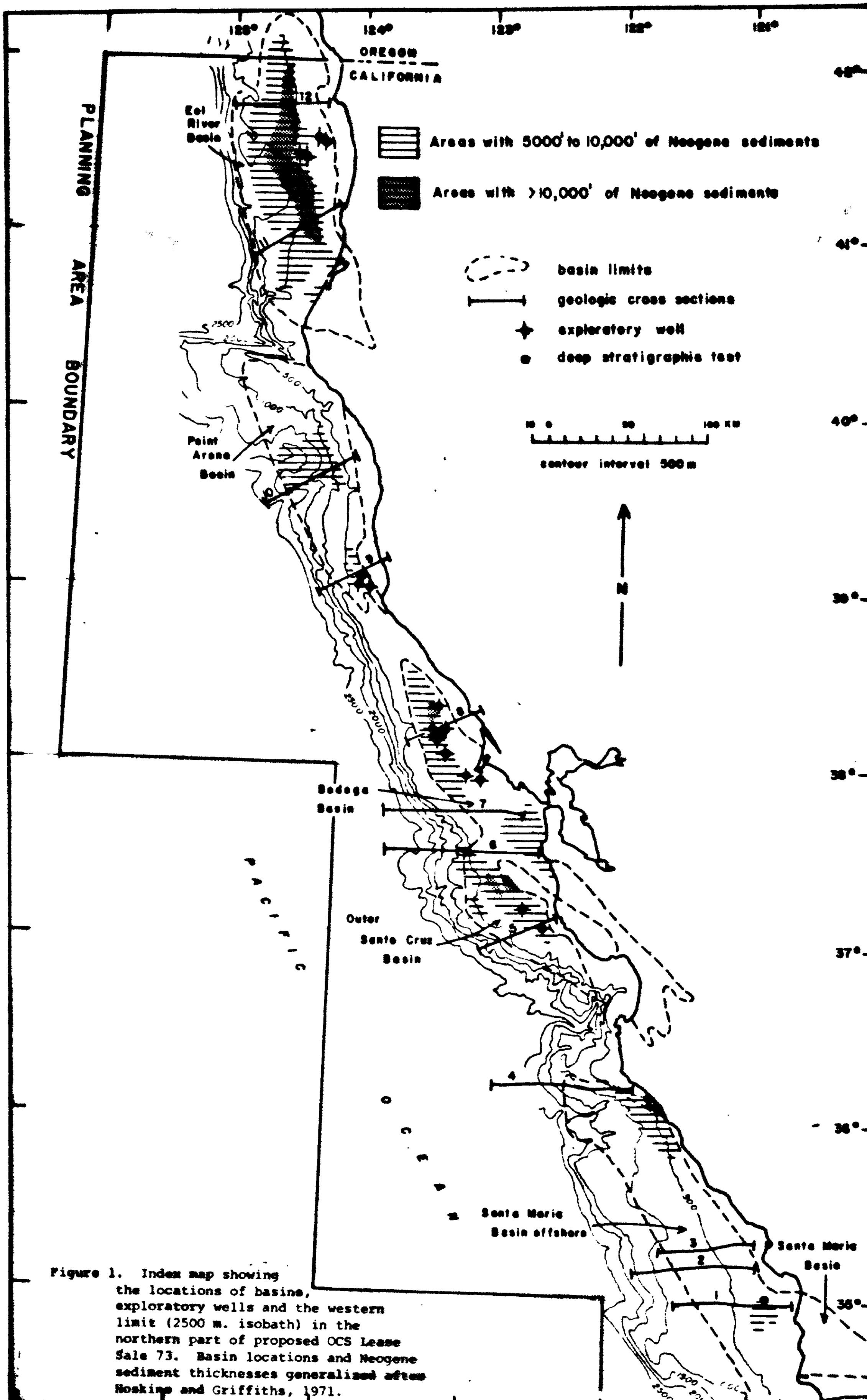


Figure 1. Index map showing the locations of basins, exploratory wells and the western limit (2500 m. isobath) in the northern part of proposed OCS Lease Sale 73. Basin locations and Neogene sediment thicknesses generalized after Hoskins and Griffiths, 1971.

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.

Granitic and gneissic basement rocks of the Salinian block (Reed, 1933; Page, 1970) underlie the northwest-trending Salinian province onshore, and extend offshore to form the basement beneath the central third of the central-northern California shelf. This block is separated from the cordilleran on the east by the San Andreas fault, and from the Nacimiento block on the west by the Sur-Nacimiento fault. As Ross (1978) pointed out, the Salinian block is an allocthon surrounded, and probably underlain, by Franciscan rocks (Ross and McCulloch, 1979) and contrary to generally accepted models its source probably is not the cordilleran to the east from which is differs significantly, but it, like rocks in central Alaska (Jones and others, 1976),may have been carried thousands of kilometers to the north by pre-Neogene strike slip displacement. Preliminary paleomagnetic work (Champion and others, 1980) suggests that the Salinian block may have lain as much as 2500 km to the south in Late Cretaceous time, and study of Upper Cretaceous sedimentary rocks on the Salinian and the adjacent Nacimiento block has suggested to Howell, McLean and Vedder (1980) that these blocks, originally juxtaposed by strike slip faulting, were then moved northward together, and arrived at the latitude of southern California by early Eocene time.

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 and Peterman, 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 the present continental shelf, and in places, part of the adjacent slope.

Deformation through the mid Tertiary was related to subduction, however, in upper mid-Miocene time, a change in tectonic forces 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. Blake and others (1978) suggested that the shallow shelf basins may have been produced by a change in relative plate motion that resulted in extension of the plate boundary. More recent recalculation of relative plate motion indicates no period of extension (Eli Silver, oral comm., 1980) and Howell and others (1980), citing the evidence for strike slip and compression during basin formation, have attributed basin origin to an interval of wrench tectonics. The 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 along their eastern margins consistent with right-lateral shear, and most exhibit late Tertiary or Quaternary compressional folding. Deposition prior to middle Miocene time 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 73 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 shallow Santa Lucia Bank formed by the Santa Lucia High, a structural block that is bounded on the east by the Santa Lucia Bank Fault. The northwest end of the basin continues onto the continental slope. The basin shallows to the south as it approaches the western end of the Transverse Range, but it continues south and east, and joins the western end of the Santa Barbara basin on the south side of the Transverse Range. The basin structure effectively truncates the western end of the Transverse Range. Geophysical evidence also suggests such a termination. A gravitational low associated with the Santa Barbara basin has been mapped as continuing to the northwest around Points Conception and Arguello into the southern end of the offshore Santa Maria basin (Larry Beyer, oral comm., 1979) and northwest-trending aeromagnetic anomalies that parallel Transverse Range structures in the Point Sal area are truncated along a magnetic anomaly associated with the Hosgri Fault (McCulloch and Chapman, 1977).

Basement rocks exposed along the shore are Franciscan-Knoxville rocks of

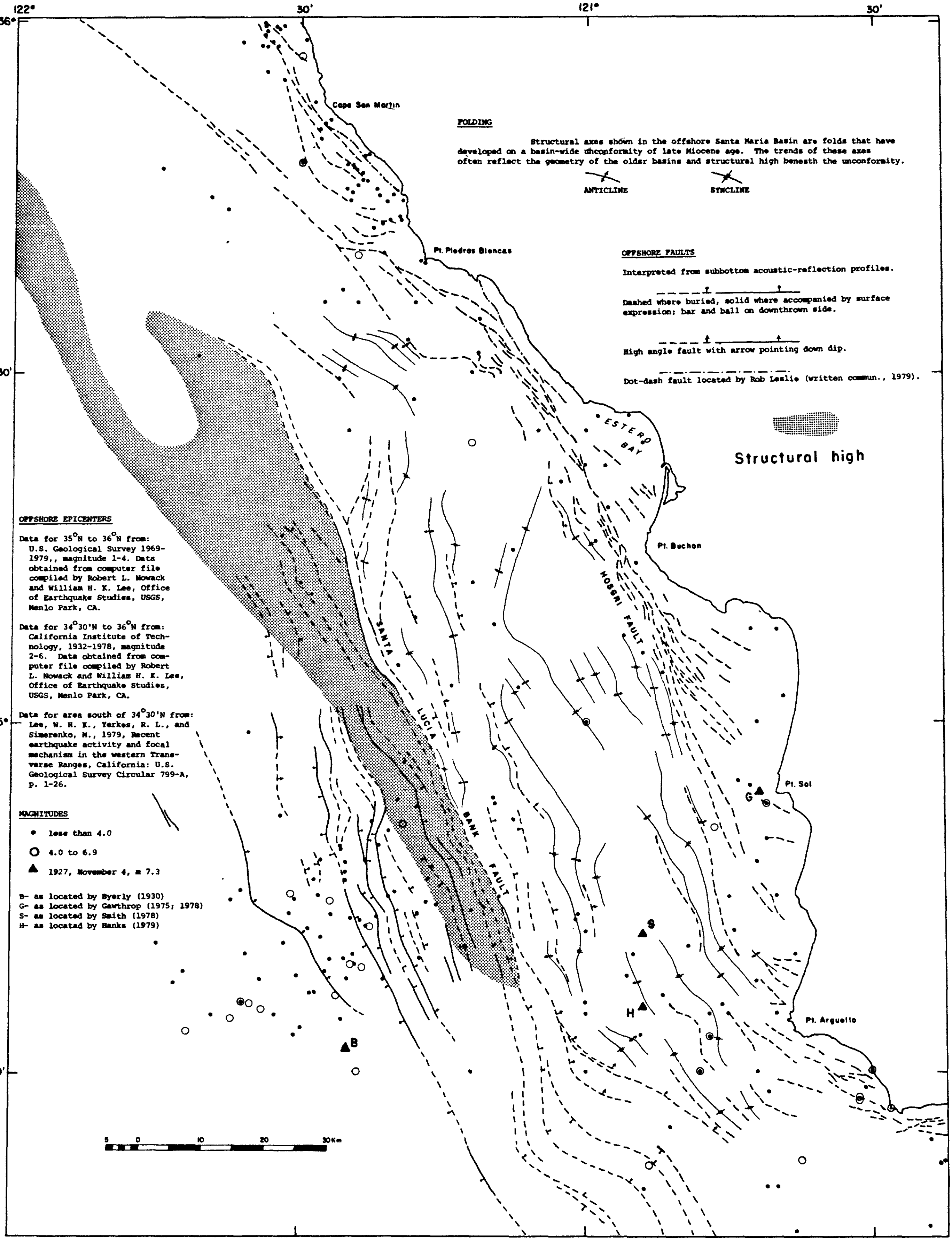


Figure 2. Faults, Post-Late Miocene Folds and Epicenters in the Offshore Santa Maria-Point Arguello area, California.

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, (e.g. Page and others, 1979), and confine the granite basement to the Salinian block which lies onshore and separated from this basin by Franciscan terrane.

The shallow Santa Lucia Bank is formed by the fault bounded Santa Lucia structural high. Vertical separation on the Santa Lucia Bank fault on the eastern margin of the high was accompanied by considerable strike-slip displacement. The magnetic signature of the rocks differs across the fault; to the west the total magnetic intensity is flat, at about a constant value, whereas to the east of the fault, irregularities with amplitudes of as much as 200 gammas are present (Page and others, 1979). There is also a considerable difference in the thickness of the Miocene and Pliocene aged sections across the fault. Northwestward transport of this structural high is also suggested by the similarity of the physiography and gross structure of this part of the shelf with that of the California Borderland to the south (McCulloch and others, 1980).

Only limited data are available concerning the character and distribution of post-Cretaceous rocks in the basin. A generalized stratigraphic column for

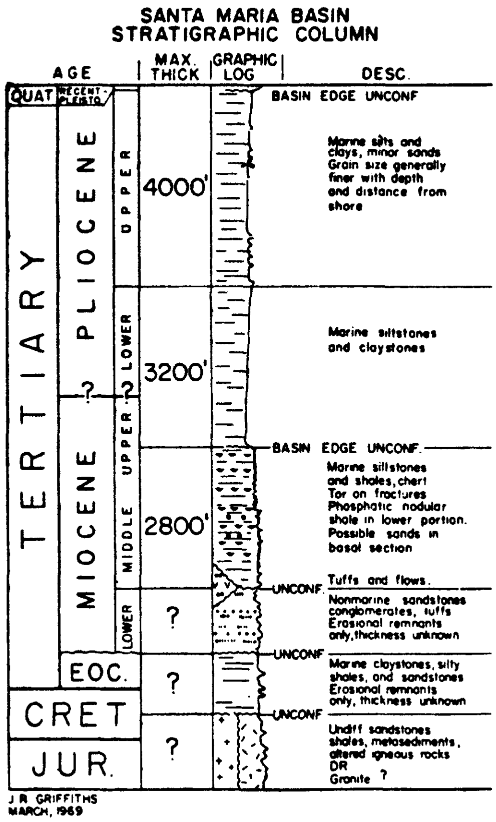


Figure 3.

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.

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.

Geologic interpretations of four acoustic profiles across the basin are shown on Figure 4. Lithologies and ages are inferred from two test wells in the basin, Humble P-060-1 and OCS-CAL 78-164 No. 1 (McCulloch and others, 1979; Fig. 1) Basement rocks (TKJ_1, TKJ_2) are thought to be equivalent to rocks of the Franciscan complex, but to differ in origin. TKJ_1 rocks are possibly older in part than TKJ_2 rocks, and are an extension of similar rocks found exposed along the eastern edge of the basin. TKJ_2 basement rocks west of the Santa Lucia Bank fault may have originated as a subduction zone complex. Both TKJ_1 and TKJ_2 rocks and superjacent early Tertiary sedimentary rocks of possible Eocene and Oligocene age were deformed and eroded leaving only small erosional remnants of the lower Tertiary deposits in topographic depressions. In late Oligocene and early Miocene time (represented by the lower part of unit Tmo) volcaniclastic rocks were deposited on this erosion surface. These rocks, that are probably equivalent to the Lospe and Obispo Formations onshore, thin northward and are missing from the northernmost profile on Figure 4. In middle and early late Miocene time well-bedded silicious marine shales and cherts (upper part of unit Tmo) were deposited in relatively deep marine water over the shelf. These rocks are referred to the Monterey Formation onshore. Unit Tmo was deformed sometime in the late Miocene by folding and numerous east dipping and moderately steep faults. Some faults offset the basement rocks more than unit Tmo, which suggests reactivation of older faults. The late Miocene folding and faulting probably resulted from compression related to subduction of the adjacent oceanic plate along the foot of what is now the Santa Lucia Escarpment (Page and others, 1979). Erosion removed some of the tops of the folded Tmo rocks before the following deposition of marine silt and clay (unit Tpm) which are referred to the late Miocene and early Pliocene Sisquoc and Pico formations onshore. Folding occurred once more but this time without the faulting that accompanied the earlier deformation. Sedimentation followed the folding, and in middle to late Pliocene time marine sediment (unit Tp, referred to the Foxen Mudstone onshore) covered the basin floor. The final episode of deposition recognized on the section (unit Q) is represented by the well bedded sediment of Quaternary (Pleistocene and

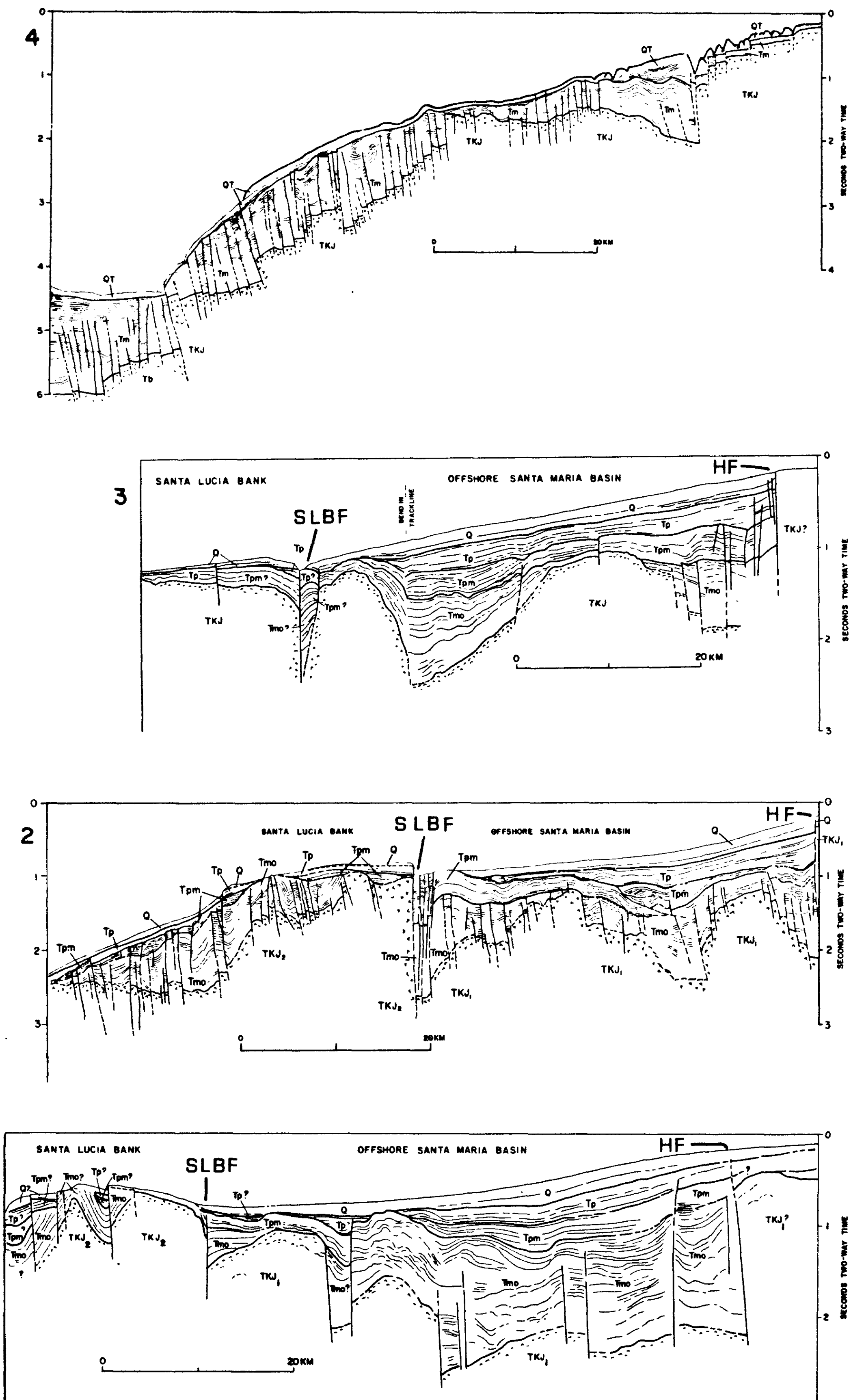


Figure 4. Geologic interpretations of acoustic profiles across Offshore Santa Maria Basin. SLBF = Santa Lucia Bank Fault; HF = Hosgri Fault. Vertical exaggeration approximately 10 to 1. Profiles located on Figure 1; geologic units described in text.

Holocene) age. An acoustically transparent surface layer, recognizable in high resolution records, is thought to represent Holocene deposits. The large vertical separation on the Santa Lucia Bank fault (Fig. 4) makes it impossible to trace seismic reflectors from the basin to the Santa Lucia bank. Therefore rock ages west of the fault have been inferred by the similarities of character of the acoustic reflectors, by the degree of deformation, and by the sequence of the depositional, deformational, and erosional events (unconformities) seen in the basin.

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. 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 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. Geological 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 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 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 late Miocene and Pliocene time.

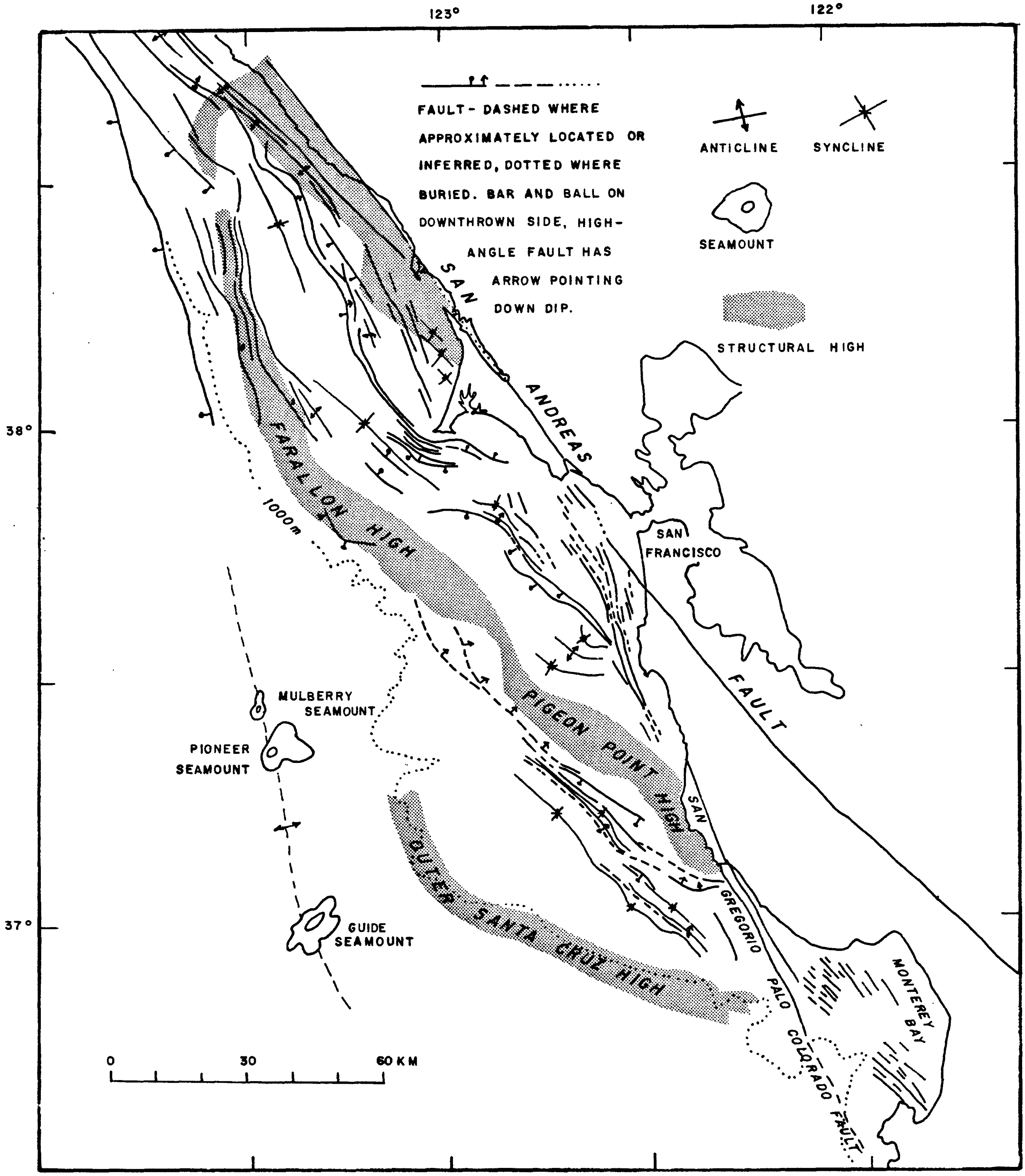


Figure 5. Generalized map of geologic structure and faults in Outer Santa Cruz and Bodega basins. Mapping in Monterey Bay after Greene and others, 1973. Mapping from Monterey Bay to Point Reyes by D.S. McCulloch, and north of Point Reyes, modified after Rubin, in McCulloch and others, 1980).

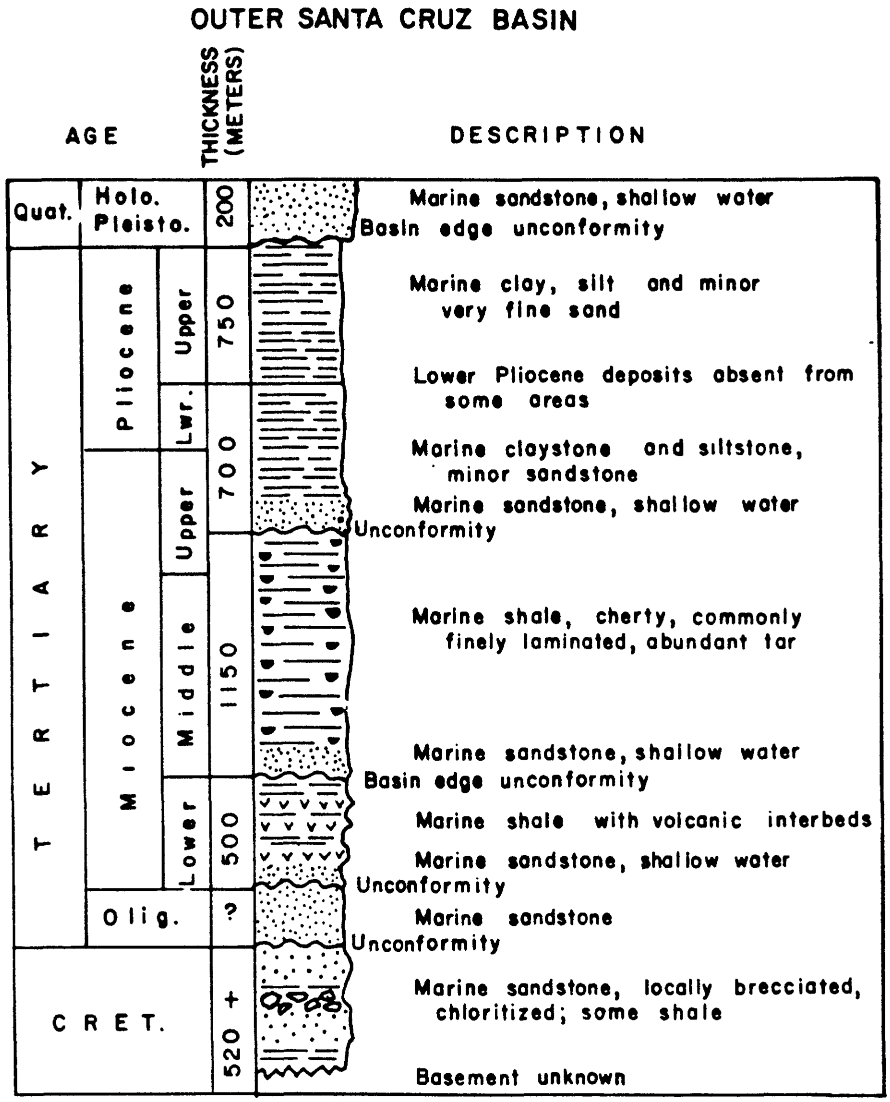


Figure 6. Generalized stratigraphic column for Outer Santa Cruz Basin, central California (After Hoskins and Griffiths, 1971).

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 Mulberry, Guide and Pioneer Seamounts form prominent topographic highs. Beneath the early late 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 lower Tertiary sediments are upturned along the flank of the Santa Cruz High. The northeastern margin is controlled by a down-

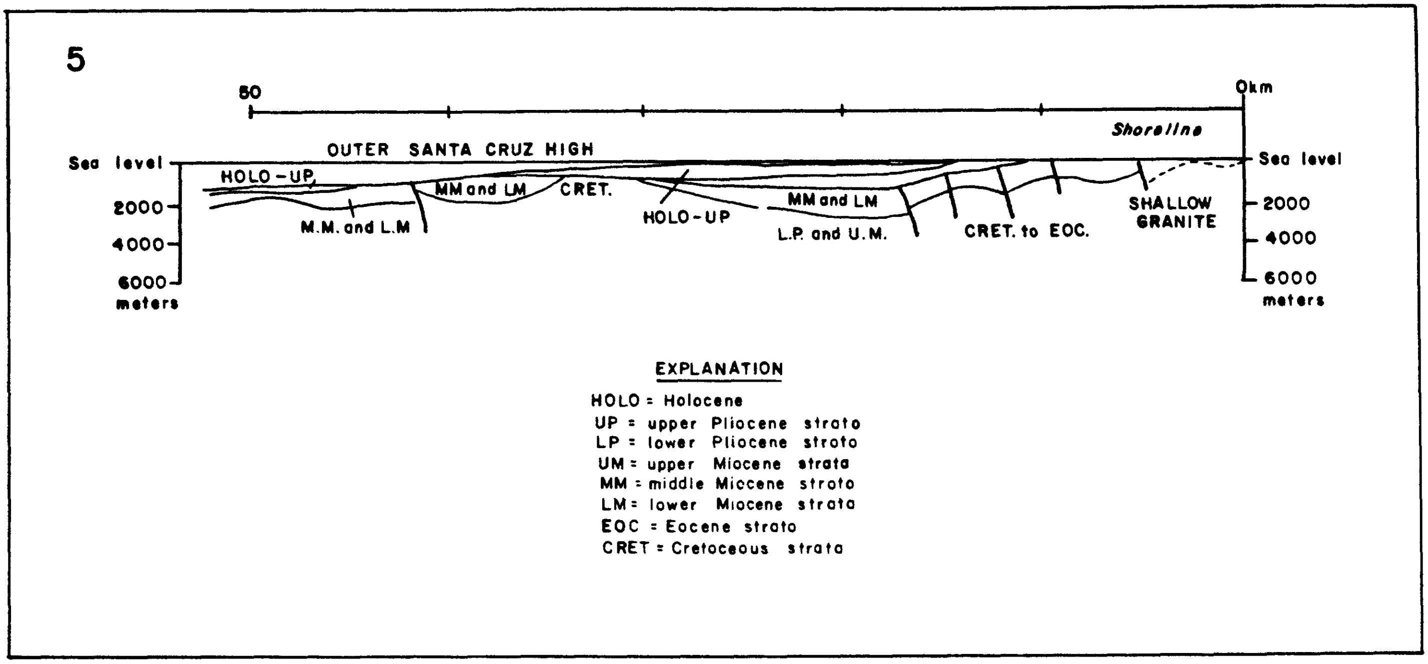


Figure 7. Geologic cross section of Outer Santa Cruz Basin (Hoskins and Griffiths, 1971). Section located on Figure 1.

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 on 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 basin , Neogene strata record repeated 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

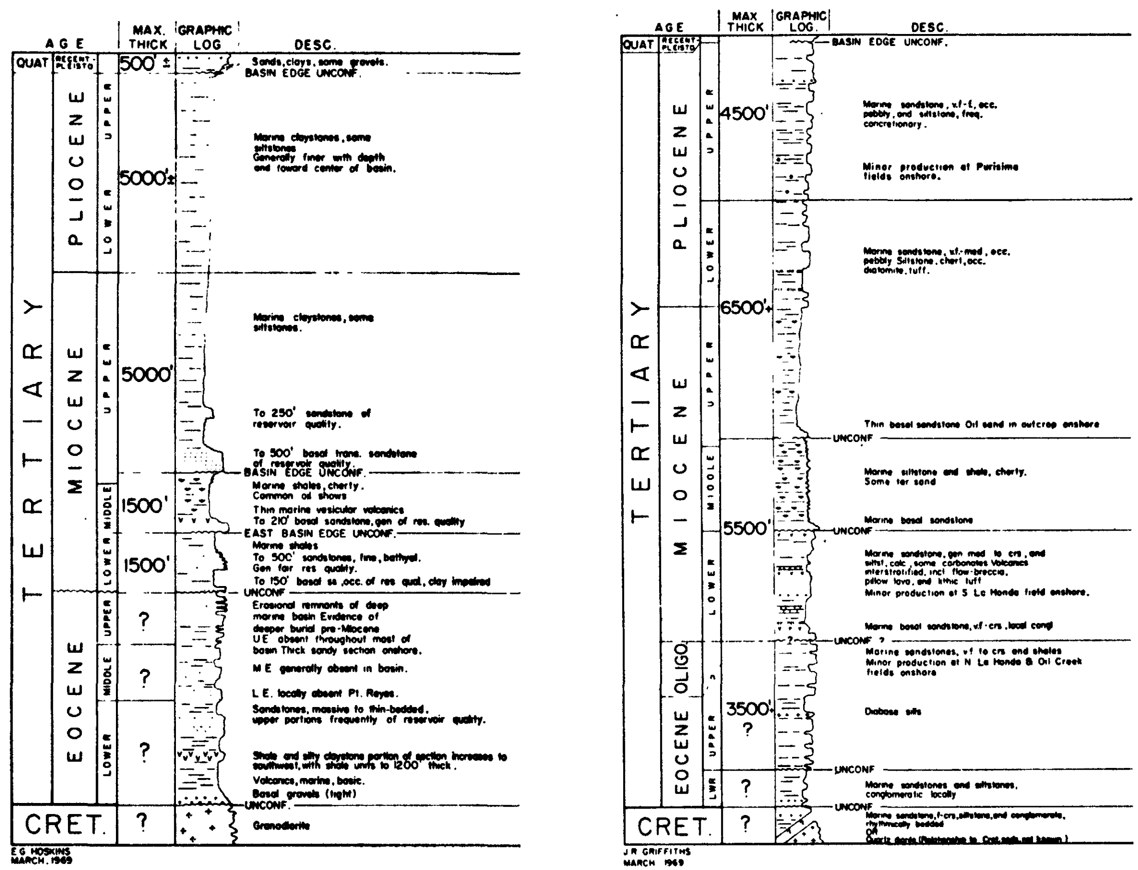


Figure 8. Generalized stratigraphic columns for northern (left) and southern (right) Bodega Basin (Hoskins and Griffiths, 1971).

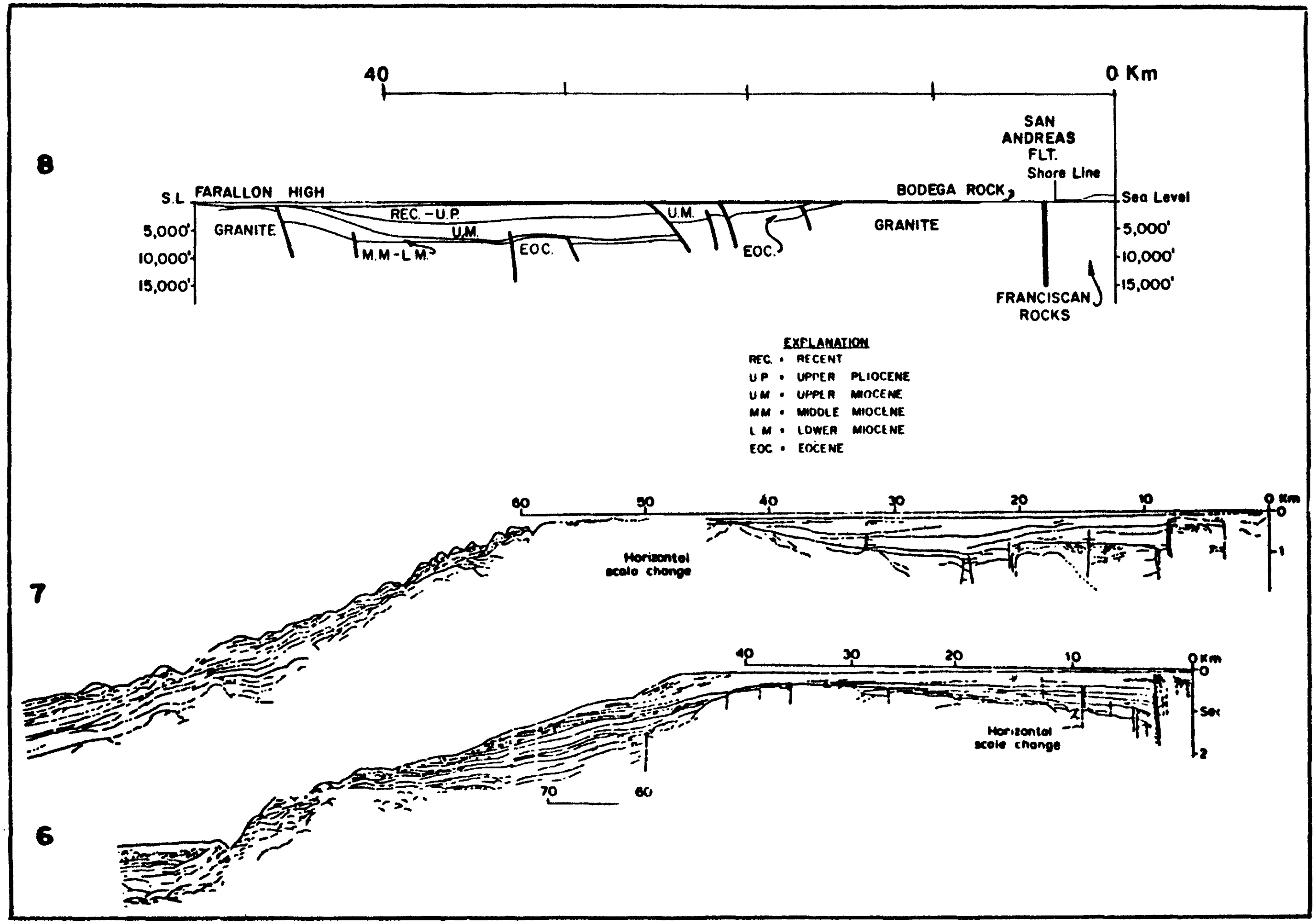


Figure 9. Geologic cross section of northern Bodega Basin (Hoskins and Griffiths, 1971), and line drawings of seismic profiles in central Bodega Basin (McCulloch, unpublished U.S. Geological Survey data). Cross section and profiles located on figure 1.

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 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, middle 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, 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 lowermost 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 onshore 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, the following middle Miocene is represented by cherty shale. A lower upper Miocene basal marine sandstone rests unconformably on older sediments

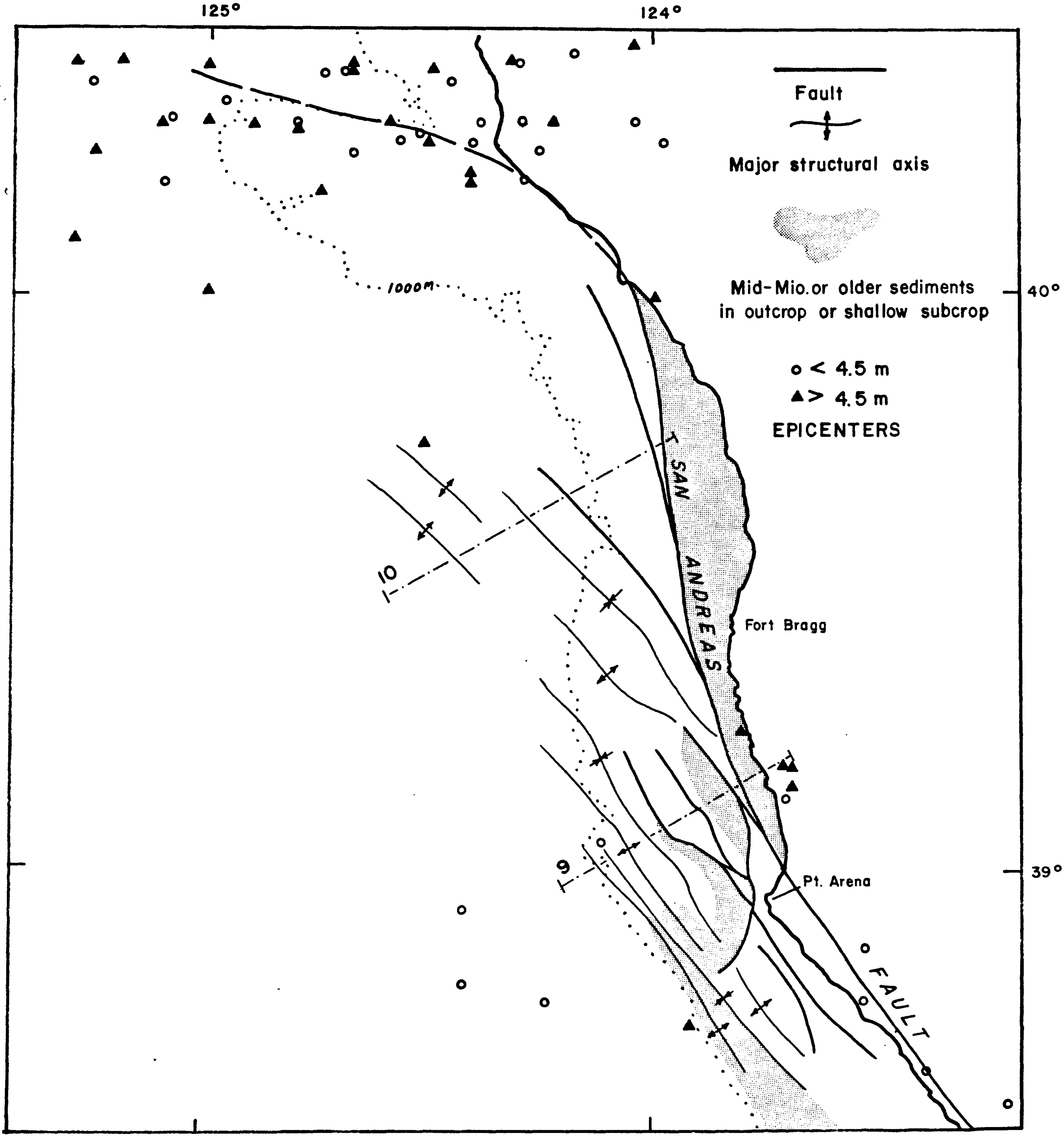


Figure 10. Generalized map of geologic structure and faults in Point Arena Basin (from Hoskins and Griffiths, 1971). Geologic sections in figure 12.

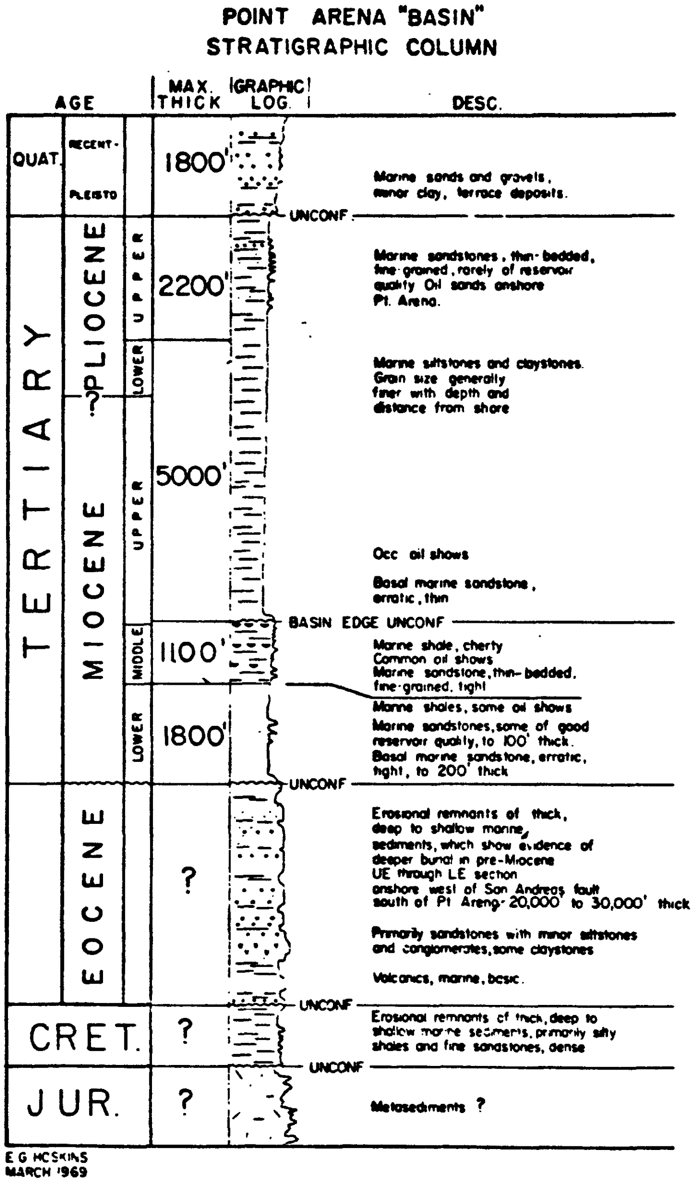


Figure 11.

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

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.

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 lower Eocene sediments, a considerable thickness of overlying rocks may have been

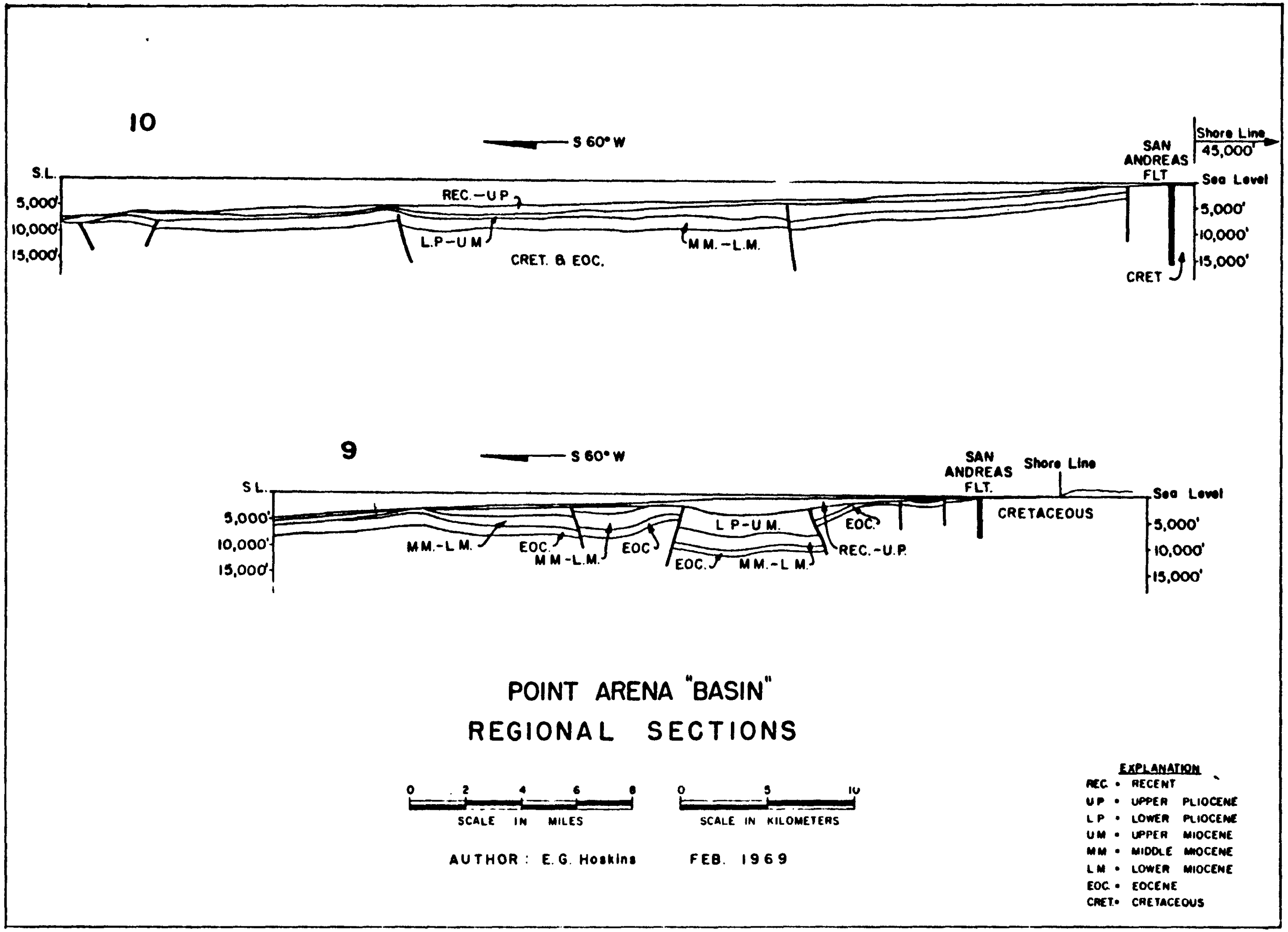


Figure 12. Geologic cross sections in Point Arena Basin (Hoskins and Griffiths, 1971). Sections located on figures 1 and 10.

removed. Likewise little is known of the history of the western boundary ridge. Seismic reflection profiles (Silver, 1971; Kulm and von Huene, 1973) 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 vertical displacements of about 2000 m and the fold axes that lie parallel to the elongate basin were largely formed in late Pliocene time. These faults and folds trend northwest, and diverge northward from the San Andreas fault.

Eel River Basin.--The basin extends from Cape Mendocino (40°30'N) on the northern California coast northward for 200 km 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 (Fig. 13). The south end of the basin extends inland for about 50 km in the lower Eel River-Arcata Bay area. The geology of the on-land portion of the basin has been 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 Field and others (1980), and the regional structure is discussed by Silver (1969, 1971a, 1971b).

The onshore Eel River basin is a syncline that trends nearly west and is bounded on the north and east by anticlinal folds and steeply dipping faults. The basin contains a thick sequence of upper Miocene and younger rocks that unconformably overlie and are in fault contact with Eocene and older units (Fig. 14). Basement rocks along the eastern margin of the basin are assigned to the central belt of the Franciscan Complex, a late Jurassic-

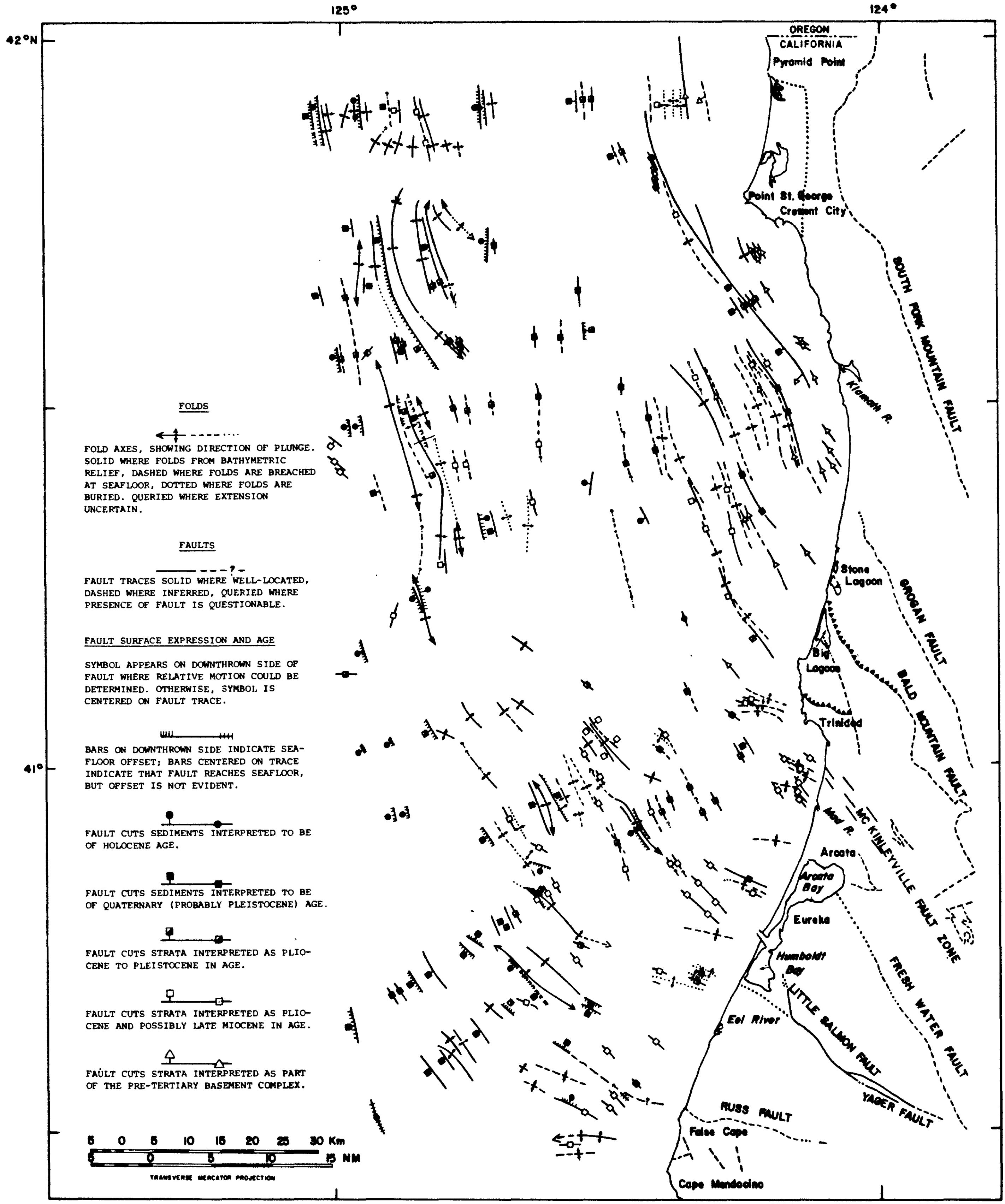


Figure 13. Generalized map of geologic structure and faults in Eel River Basin, from Field and others, 1980.

Cretaceous melange of graywacke, chert, basalt-greenstone and schist in a sheared matrix of shale and sandstone. Elsewhere, the coastal belt of the Franciscan Complex and the partly coeval Yager Formation underlie the onshore Eel River basin and probably form basement for most of the offshore basin as well. The coastal belt is Late Cretaceous to latest Eocene in age, and consists principally of interbedded fine-to coarse-grained clastic rocks (slightly metamorphosed zeolite facies) and, locally, of volcanic rock(of spilitic composition),limestone and chert. It is thought to represent a subduction complex comprising accretionary prism and trench slope basin deposits (Bachman, 1978). The Yager Formation, Eocene in age (Evitt and Pierce, 1975), is in fault contact with central belt rocks in the lower Eel River area, but lies in depositional contact with coastal belt strata 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 well indurated marine shale, mudstone and siltstone, with lesser graywacke and conglomerate containing locally-derived Franciscan detritus (Ogle, 1953).

Regional deformation occurred between Eocene and middle Miocene time and strata of the Wildcat Group overlie older rocks in the Eel River basin with angular unconformity (Ogle, 1953; Hoskins and Griffiths, 1971). The Wildcat Group comprises an essentially conformable sequence more than 3600 m thick of fine to coarsely clastic, principally marine strata of late Miocene to Pleistocene age (Ogle, 1953; Ingle, 1976). Predominant lithologies are weakly consolidated mudstone, siltstone and claystone, with subordinate sandstone and conglomerate, and minor lignite and tuff. Units of this group appear to record an eastward transgression over basement during late Miocene and early

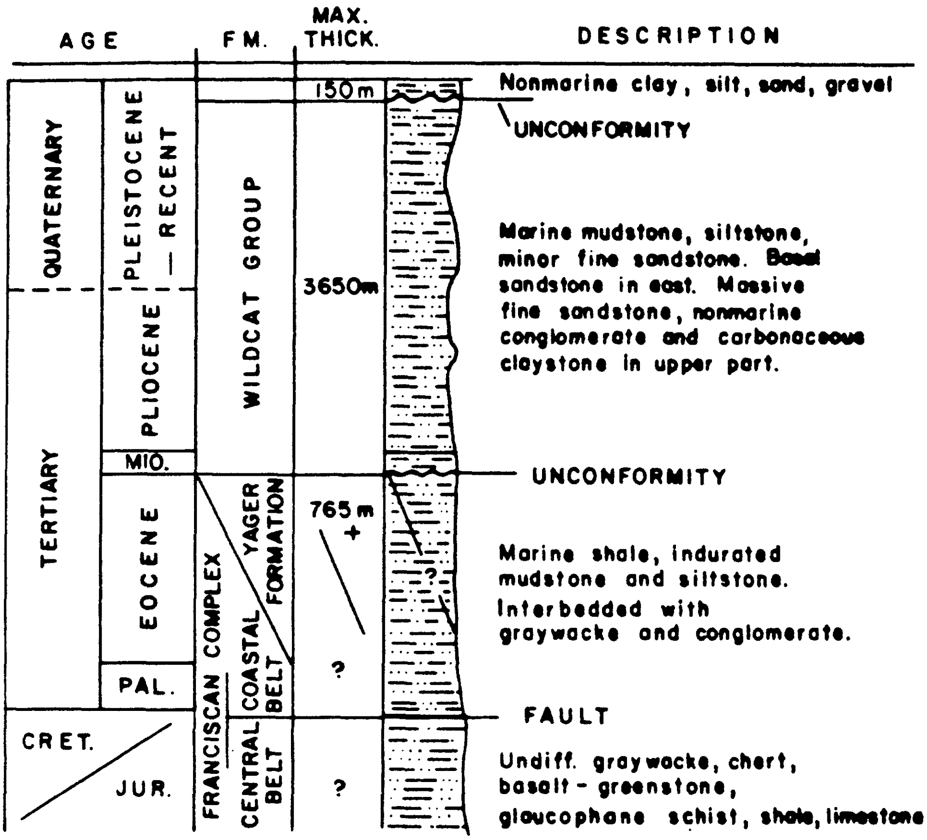


Figure 14.

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

Pliocene, deepening of the basin to bathyal-abyssal depths with basin plain, submarine fan and basin slope deposition during Pliocene and early Pleistocene, followed by shoaling to shelf depths and ultimately by emergence and marginal marine and non-marine depositon in Pleistocene time (Ogle, 1953; Ingle, 1976; Piper and others, 1976). The section coarsens upward, reflecting Pleistocene regression, and eastward, reflecting the presence of a landmass. Similar, predominantly shallow-marine, strata 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).

Wildcat deposition closed with basin margin warping and uplift, culminating in basin-wide deformation that followed established 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 represent 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 N80°W onshore (Ogle, 1953), but swings to a near northerly orientation offshore. Folds onshore parallel the basin margin and associated faults are thrusts and high-angle reverse faults, apparently reflecting northeast-southwest to north-south 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 trend of the basin axis. Folds involving Pliocene and younger strata on the marginal plateaus and adjacent continental slope 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). The folds are characteristically broadly symmetrical or asymmetrical with east dipping axial planes, reflecting a principal compressive stress from the west. This east to northeast directed compression presumably results from Quaternary underthrusting of the Gorda plate. This margin segment has been interpreted as a forearc basin-ridge-slope accretionary prism with dominantly landward dipping thrusts, and the uplifted marginal plateaus forming the western margin of the offshore Eel River basin as stacked, imbricated wedges of Gorda basin sediment. Numerous unconformities in the sedimentary fill of the restricted basins on the marginal plateaus attest to an episodic history of deformation throughout deposition of the Neogene section. Some folds of the marginal plateaus appear to be associated with shale flowage and diapirism, and some of the marginal

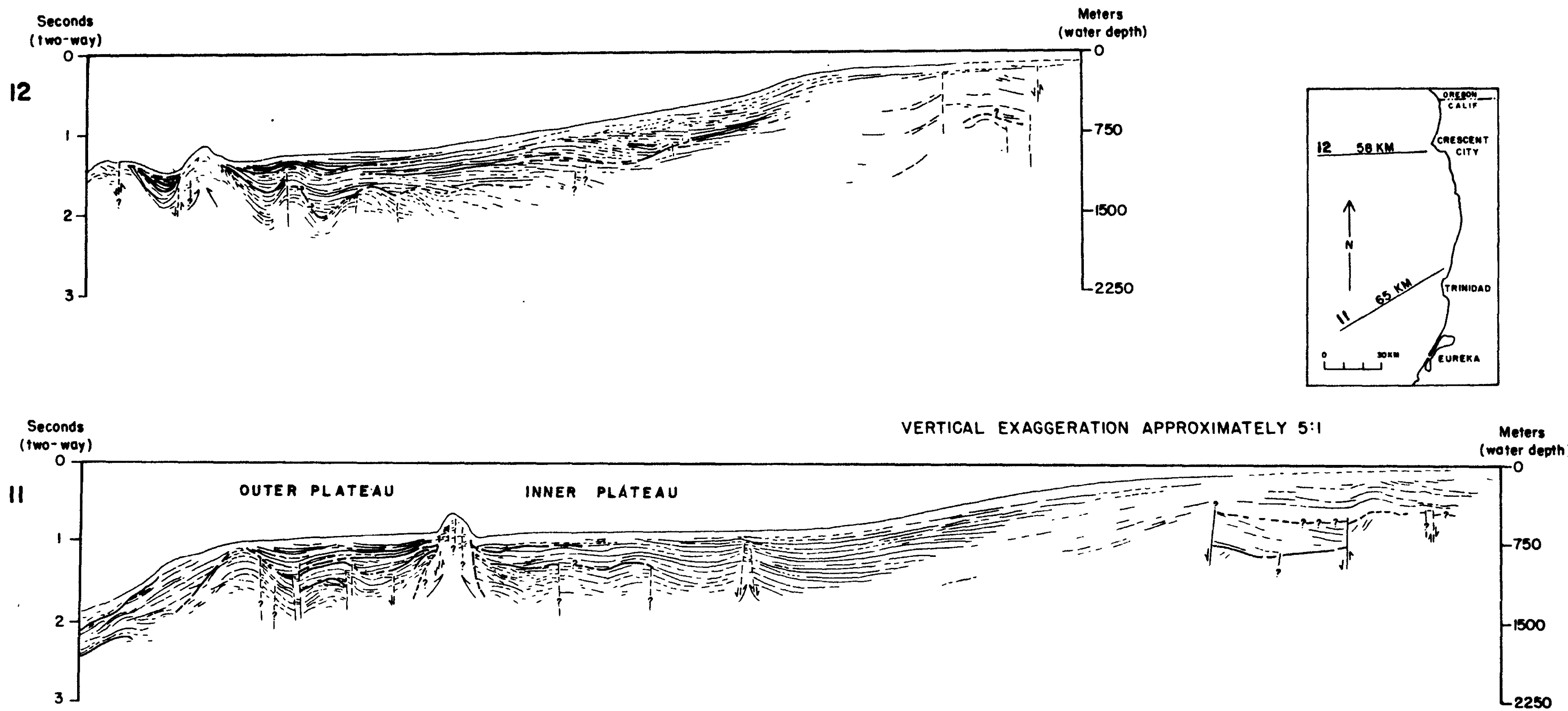


Figure 15. Line drawings of acoustic profiles across Eel River Basin. Sections located on figure 1.

ridges are piercement structures (Fig. 15). The deep structural depression landward of the uplifted marginal plateaus is filled by a thick section of upper Tertiary and Quaternary hemipelagic sediment and turbidites. Several northwest-trending roughly en-echelon faults, some showing evidence of Quaternary displacement, cut basement and the overlying Cenozoic sedimentary section on the inner shelf south and west of Crescent City. Associated with these faults are en-echelon folds that are stepped to the right (Silver, 1971a). Fault plane solutions by Bolt and others (1968) from three shallow-focus earthquakes in this area during 1961-1965 are consistent with right-lateral motion, interpreted by Silver (1971a) as the result of shear interaction between the Pacific and North American lithospheric plates.

PETROLEUM GEOLOGY

Previous Petroleum Exploration in Proposed OCS Lease Sale 73

Exploration of the proposed OCS Lease Sale 73 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 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 that 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 73 lies adjacent to three onshore basins (Fig. 1). Santa Maria basin onshore and basins in the adjacent Salinian province may be quasi-equivalent 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 onshore as 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 constituted 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; however, as McCulloh has noted (1979), changing economics and evolving technologies both may convert marginal or submarginal resources of immature, shallow, viscous and dense asphaltic crude oil into productive reservoirs. Per well recoveries in the

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	

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 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 Halfmoon 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 (California

TABLE 2. EXPLORATORY WELLS DRILLED ON OCS LANDS

(after 1963 Federal OCS Lease Sale)

Company and Well Name	Basin	Total Depth Meters	Total Depth Feet	Spudded	Abandoned
Humble P-012-1	Eel River	903	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	7-07-65
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	12-02-64	12-26-64
Shell P-055-1ET	Bodega	2279	7477	10-12-64	11-06-64
Shell P-055-2ET	Bodega	2213	7261	1-03-65	1-23-65
Shell P-055-2AET	Bodega	2224	7297	1-25-65	2-15-65
Shell P-051-2ET	Bodega	3190	10,466	8-02-64	10-03-64
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

Division of Oil and Gas, 1975; California Division of Oil and Gas, 1960). Humboldt basin (the onshore Eel River basin) has had no significant oil production. The small, now abandoned, 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 grained sands of the Pliocene Rio Dell Formation in anticlinal traps (California Division of Oil and Gas, 1976; California Division of 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. As shown on Figure 1, there are only two relatively small areas where burial is as great as 3050 meters (10,000 feet), a depth usually believed necessary for a thermal regime sufficiently high to generate hydrocarbons. However, 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. In addition, a higher than normal temperature gradient exists onshore and an exceptionally high geothermal gradient was encountered in the deep stratigraphic test well (OCS-CAL 78-164 No. 1) drilled in 1978 at the extreme south end of the offshore basin (McCulloh and Beyer, 1979; Fig. 1). If a similar high geothermal gradient extends to the entire offshore basin it may significantly increase the possibility for the generation of hydrocarbons. Unfortunately there has been essentially no measurement of the heat flow that occurs on the central and northern California shelves that could be used as a basis for examining this possibility.

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 1965 test well (Humble P-060-1) 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.

There is some evidence for source rocks in the basin as shown by McCulloh's (1979) analysis of the 1978 stratigraphic test well. He says,

"The shallowest "show" recorded on the mud log occurred at a depth of about 2900 ft. The show was of gas without indications of crude oil or heavier hydrocarbons and originated from a clayey interval. The shallowest indication of migratory hydrocarbons heavier than methane occurred at about 3355 ft. These hydrocarbons consisted of chromatographically analyzed ethane, propane and butane accompanied by traces of petroliferous sands in the drill cuttings. Shows of both gas and more-or-less tarry oil are abundant to general from 3410 ft to about 5850 ft. Minor indications of tarry oil and heavy paraffin homologs were recorded throughout the deeper Miocene strata to a depth of about 9400 ft.

"Compositional details about the oil shows are lacking. No production tests were conducted and samples were not collected for analysis. Many of the shows of both gas and oil were from siltstone, mudstone, or calcareous shale as determined from induction electric log, the mud-log lithologic notes, and sample lithologies. The hydrocarbons which occur in such fine-grained strata are either indigenous products or have migrated from deeper sources. These fine-grained sediments would be regarded by most petroleum geologists as lacking the permeability to serve as petroleum reservoirs.

"In any event, the shows of oil and gas that occurred during drilling of this well attest eloquently to the presence of effective petroleum source rocks at or near the well site."

A more recent well (Mobil P-0321-1) drilled in Lease area 68 near the stratigraphic test well reached a depth of approximately 3500 m. This newer well must have penetrated essentially the same Neogene rocks, and its target may have been an unconformity on the top of an Upper Cretaceous or Lower Jurassic bedded sequence (Espada equivalent?) also found in the vicinity of the stratigraphic test well (McCulloch and others, 1979). This well was not announced as a discovery, and was abandoned; however, there is no information available as to whether or not it encountered producible hydrocarbons.

Outer Santa Cruz Basin.--The most probable source beds are tar-impregnated middle Miocene cherty shales that are found throughout the basin. Cretaceous rocks below the early 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 attactive 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 lower 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 unproductive holes.

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 Upper 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. A 1.6 m-long core taken recently from Quaternary sediment ponded near the crest of a piercement structure on the marginal plateaus west of Eureka contained gasoline-range hydrocarbons and gas in the methane to butane range (Field and others, 1979). These hydrocarbons are thought to have formed within Tertiary strata and migrated upward along fractures into the overlying unconsolidated sediment. Otherwise, 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 Miocene-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 possibility 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.

ENVIRONMENTAL HAZARDS

Geologic hazards in parts of the central and northern California shelf basins that were previously included as prospective lease blocks in sale 53 have been described by McCulloch and others (1980) and Field and others (1980). Although these hazard studies were of limited areas they help to describe the kinds of hazards that may occur elsewhere in Lease Sale 73. However, geologic hazards in the remaining areas of Lease Sale 73 that may become prospective lease blocks cannot be adequately defined without additional fieldwork.

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 sediments (< 11,000 years old), as well as those associated with historic earthquakes, are considered active and therefore potentially hazardous to petroleum 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.

The occurrence of gas increases chances for blowouts, which are considered to be the most costly and feared operational hazards related to oil and gas operations (Danenberger, 1980). Gas also decreases soil strength, and careful consideration must be given to gas content when designing foundations for seabed structures. As shown in the following discussion of the shelf basins in central and northern California, all lie adjacent to one or more long seismically active faults, and they can be expected to experience seismically induced ground motion. Slumps and slides have been mapped in the Point Arena and offshore Santa Maria basins, and evidence for shallow gas exists in, or adjacent to, all the basins.

Santa Maria Basin.--Geological hazards in offshore Santa Maria basin are of several kinds; gas charged sediment, shallow soil failures, deep-seated lateral displacement landslides, potential fault offset of the sea floor, and relatively strong seismic shaking (Fig. 16).

High amplitude seismic reflections ("bright spots") indicate that there may be accumulations of gas in the tops of anticlines in the Neogene rocks beneath the basin (Figures 17, 18). The gas appears to be moving upward from these structures, and migrating up dip toward the shore throughout the upper Tertiary and Quaternary strata. This gas may be thermogenic in part (McCulloch and others, 1980).

Shallow soil failures (the largest has an area of 125 sq. km.) that involve the upper several tens of meters of unconsolidated sediment have occurred on gentle slopes (less than 2°) at water depths greater than 300 m. The gentle slopes on which the failures occur indicates that gravitational contribution to initial slide movement was minimal, and the water depths are sufficiently great to isolate the slides from cyclical storm-wave loading. When coupled with evidence for several episodes of sliding at the same sites,

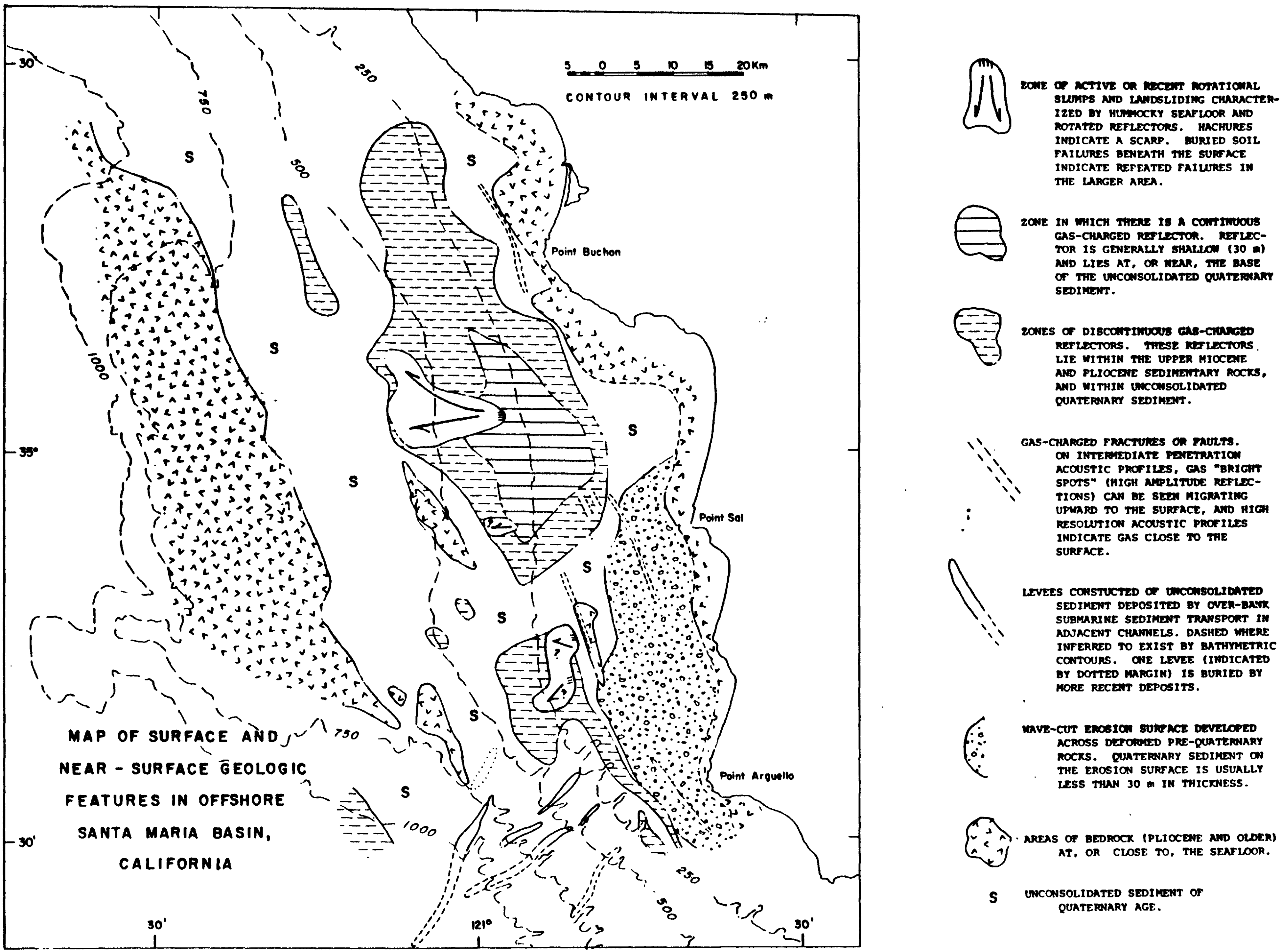

MAP OF SURFACE AND NEAR - SURFACE GEOLOGIC FEATURES IN OFFSHORE SANTA MARIA BASIN, CALIFORNIA
5 0 5 10 15 20 Km
CONTOUR INTERVAL 250 m
Point Buchon
Point Sal
Point Arguello
S
250
500
750
1000
30'
35°
30'
30'
121°
30'
ZONE OF ACTIVE OR RECENT ROTATIONAL SLUMPS AND LANDSLIDING CHARACTERIZED BY HUMMOCKY SEAFLOOR AND ROTATED REFLECTORS. HACHURES INDICATE A SCARP. BURIED SOIL FAILURES BENEATH THE SURFACE INDICATE REPEATED FAILURES IN THE LARGER AREA.
ZONE IN WHICH THERE IS A CONTINUOUS GAS-CHARGED REFLECTOR. REFLECTOR IS GENERALLY SHALLOW (30 m) AND LIES AT, OR NEAR, THE BASE OF THE UNCONSOLIDATED QUATERNARY SEDIMENT.
ZONES OF DISCONTINUOUS GAS-CHARGED REFLECTORS. THESE REFLECTORS LIE WITHIN THE UPPER MIOCENE AND PLIOCENE SEDIMENTARY ROCKS, AND WITHIN UNCONSOLIDATED QUATERNARY SEDIMENT.
GAS-CHARGED FRACTURES OR FAULTS. ON INTERMEDIATE PENETRATION ACOUSTIC PROFILES, GAS "BRIGHT SPOTS" (HIGH AMPLITUDE REFLECTIONS) CAN BE SEEN MIGRATING UPWARD TO THE SURFACE, AND HIGH RESOLUTION ACOUSTIC PROFILES INDICATE GAS CLOSE TO THE SURFACE.
LEVEES CONSTUCTED OF UNCONSOLIDATED SEDIMENT DEPOSITED BY OVER-BANK SUBMARINE SEDIMENT TRANSPORT IN ADJACENT CHANNELS. DASHED WHERE INFERRED TO EXIST BY BATHYMETRIC CONTOURS. ONE LEVEE (INDICATED BY DOTTED MARGIN) IS BURIED BY MORE RECENT DEPOSITS.
WAVE-CUT EROSION SURFACE DEVELOPED ACROSS DEFORMED PRE-QUATERNARY ROCKS. QUATERNARY SEDIMENT ON THE EROSION SURFACE IS USUALLY LESS THAN 30 m IN THICKNESS.
AREAS OF BEDROCK (PLIOCENE AND OLDER) AT, OR CLOSE TO, THE SEAFLOOR.
S UNCONSOLIDATED SEDIMENT OF QUATERNARY AGE.

Figure 16.

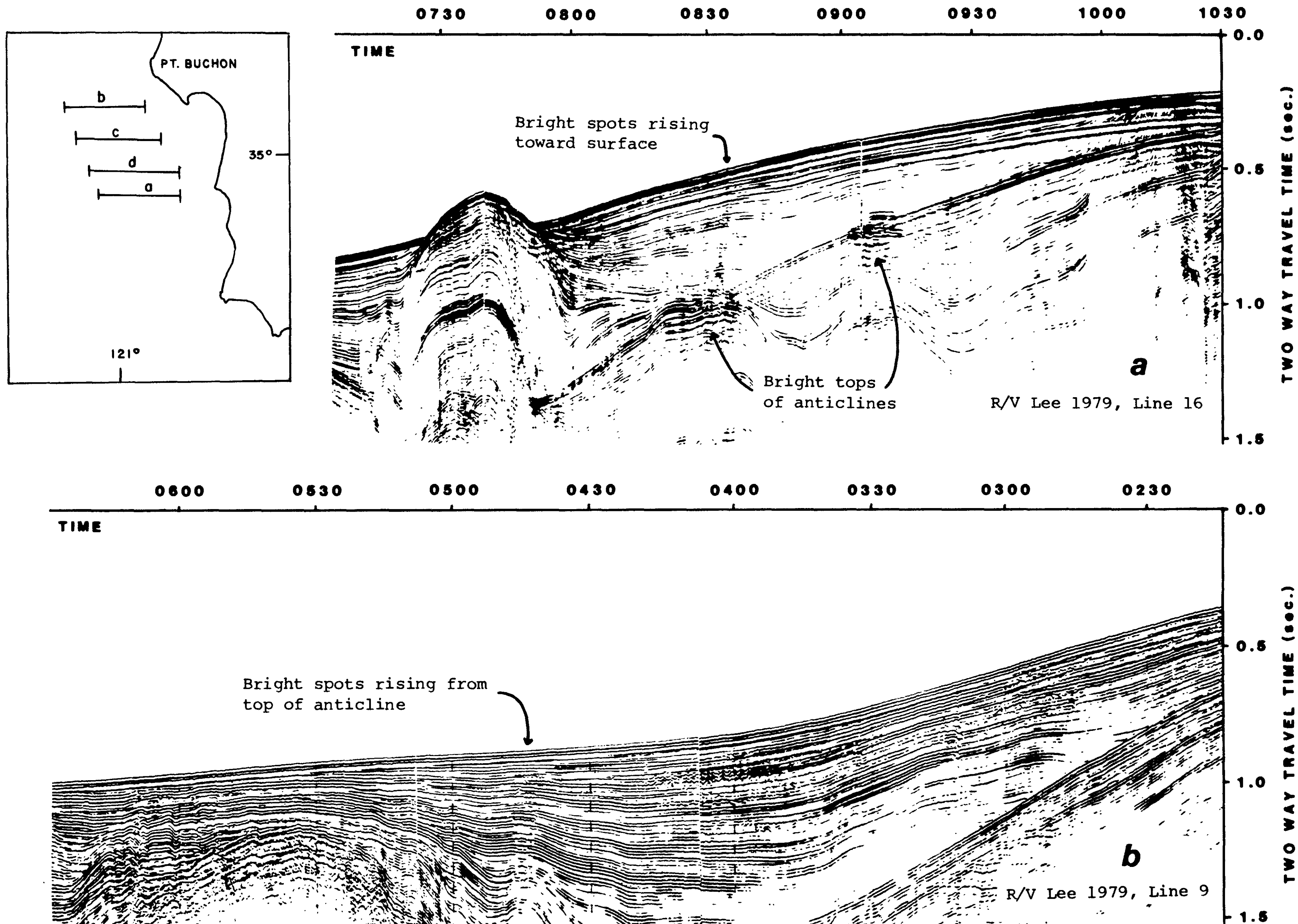
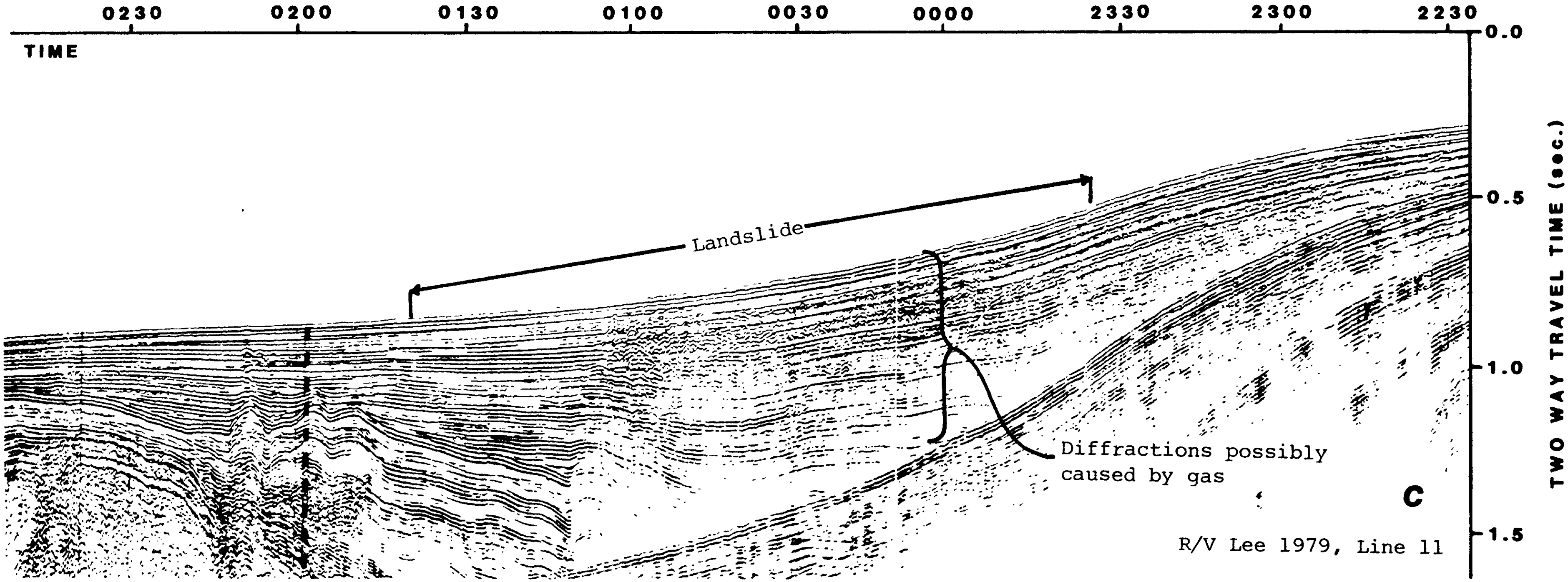


Figure 17. High amplitude "bright spot" reflectors and diffractions associated with subsurface gas in Outer Santa Maria Basin.



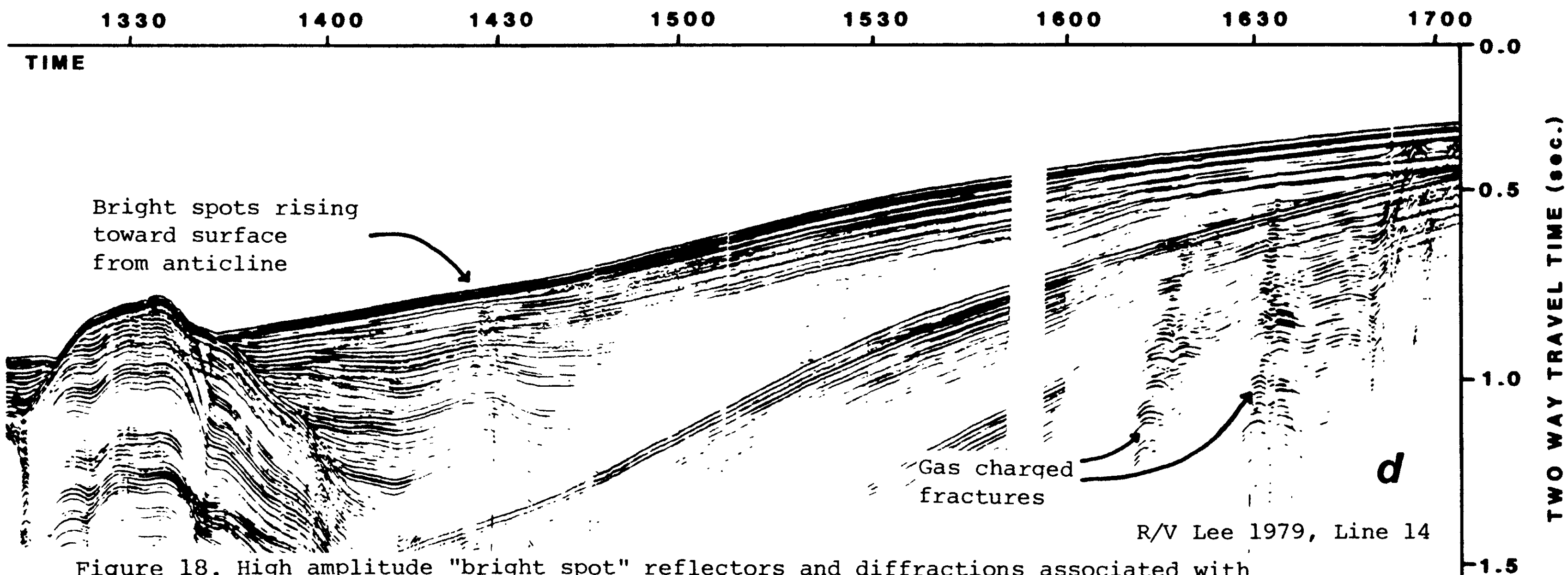


Figure 18. High amplitude "bright spot" reflectors and diffractions associated with subsurface gas in Outer Santa Maria Basin.

it is suggested that sliding may have resulted from a loss of soil strength due to seismic shaking. The slides occur in areas of gas charged sediment, and the presence of gas may have contributed to failure by decreasing soil strength (Fig. 16 and 18).

Deep-seated lateral displacements of rock masses and shallow slumps and slides occur in the northeastern end of the basin. The slides occur approximately 10-40 km south of Point Sur at the narrowest part of the continental shelf, and it is possible that sliding may have contributed to narrowing the shelf. The large slide blocks of Neogene rocks (uppermost Miocene, Pliocene and Quaternary) are found as discrete blocks of relatively coherent seismic reflectors that are underlain and laterally bounded 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.

The basin is bounded on the east and west by relatively long seismically active faults (Fig. 2). Profiles across the 3-5 km wide Hosgri Fault zone (Wagner, 1974) on the east show considerable east-side-up vertical separation on steep easterly dipping faults along which presumed Franciscan basement rocks have been elevated to near the surface (Fig. 4). The displacement history of this fault zone is controversial. Some (e.g. Graham and Dickinson, 1978) suggest that it has acted as part of the major coastal fault system that continues north, eventually joining or approaching the San Andreas fault in the Gulf of the Farallones and that it has undergone right-lateral strike slip displacement of as much as 115 km. Others (e.g. Hamilton and Willingham, 1977) prefer less than 20 km strike slip, and argue for no direct connection with a coastal fault system. On the basis of lithologic similarities, Hall (1975) suggested 80 km of right lateral slip on the Hosgri fault between Pt. Sal and San Simeon, and mapping (Leslie, 1981) has demonstrated a possible offshore connection between an eastern strand of the Hosgri fault zone and the San Simeon fault to the northwest. This recent mapping (Leslie, 1981) supports the possibility of a through-going fault system although the amount of motion cannot be demonstrated.

Earthquake epicenters indicate that the fault is seismically active, and first motion studies show that it is undergoing right lateral displacement with some north-south compression (Fig. 19). Although the fault has produced no unequivocal sea floor offsets in Holocene deposits, Wagner (1974) and Leslie (1981) show displacement of the base of the unconsolidated surface sediment of Quaternary and probable Holocene age. Thus, this seismically active fault must be considered as having the potential for producing surface displacement.

The Hosgri Fault has been mapped to about 10 km south of the latitude of Point Sal (Buchanan-Banks and others, 1978), and at the south end of the basin faulting steps seaward and changes in strike fron NNW to NW. To the west the faults turn and parallel the northwest trend of the faults associated with the Santa Lucia Bank. The Santa Lucia Bank fault comprises two or more strands that approach but do not break the surface. The large topographic expression of the fault (as much as 40 m) appears to be largely a fault line scarp, rather than a fault scarp. As shown by the offset of unit Tp along the fault (Fig. 4) there has been considerable relatively young displacement on the fault, and within the basin, sediment of probable Pleistocene age has been folded against the edge of the block, indicating young relative displacement between the Santa Lucia high and the basin. West of the Santa Lucia Bank fault there are numerous steeply dipping faults, most of which show vertical separation, and some of which have displaced the seafloor to lengths of 30 to 40 km. Adjustment to the motion between the North American and Pacific plates appears to be taking place across this basin. In this part of California movement between the plates is thought to be approximately 5.5 cm/yr (Atwater, 1970) and only about 2.5 cm/yr is occurring on the San Andreas. Thus, more than half the displacement may be involved in deformation and faulting west of the San Andreas fault (Gawthrop, 1975).

Earthquake history prior to instrumentally located epicenters that date from the late 1920's must be drawn from historic accounts (Townley and Allen, 1939). During this pre-instrumental period of 124 years more than 116 earthquakes were reported, most since 1900 (Fig. 6, in McCulloch and others, 1980). The post-1900 increase appears to have been greater than the demographic change (Donley and others, 1979) and probably represents a real increase in seismic activity. Rossi-Forel shaking intensities assigned to 57 of these 116 earthquakes have the following distribution:

Rossi-Forel Intensity	Number of Earthquakes
X	3
VIII-IX	8
VII-VIII	5
VI-VII	4
V-VI	12
IV-V	8
III-IV	11
II-III	6

The most severe earthquake during this time, and as yet the most severe in this area, was the magnitude 7.3 Lompoc earthquake of November 4, 1927.

Byerly (1930) located the epicenter 75 km west of Point Arguello. Reanalysis of seismographic data by Smith (1978), Hanks (1979), Gawthrop and Engdahl (1975) and Gawthrop (1975, 1978a) moved the epicenter progressively eastward (Fig. 2), and the Gawthrop location places it very nearly on the Hosgri Fault. Evernden (oral commun., 1980) modeled the observed onshore distribution of shaking intensity (Fig. 19) and concluded that the epicenter was close to the mapped location of the Hosgri fault. The earthquake generated a tsunami that locally reached a height of 6 feet. The tsunami was also recorded on tide gauges at San Francisco and San Diego, and was sufficiently large to cross the Pacific and to be recorded at Hawaii and Japan. Because of its possible location on the Hosgri fault that passes several kilometers west of the Diablo Canyon nuclear reactor at Point Buchon, this earthquake has received considerable scrutiny. It is the basis for the maximum credible earthquake that the reactor must be designed to withstand.

Strong seismic shaking can be expected in the eastern part of the basin in the event of a repeat of a 1927 earthquake on the Hosgri fault zone. Design spectra for maximum ground motion of the Diablo Canyon reactor facility at Point Buchon (Newmark, 1976) specify:

Acceleration (g)	Velocity (inches/sec.)	Displacement (inches)
0.75	24	8

Although this ground motion is strong, it is presently under review, in part because unexpectedly high vertical accelerations recorded during the m 6.7 Imperial Valley earthquake of October 15, 1974 (Porcella and Matthesen, 1979) suggest the possibility for still stronger ground motion.

Strong ground motion could also be expected in the western part of the basin as the result of faulting on Santa Lucia Bank. The largest events on the Santa Lucia Bank are m 5.4 and 5.6, and, as relocated by Gawthrop (1975),

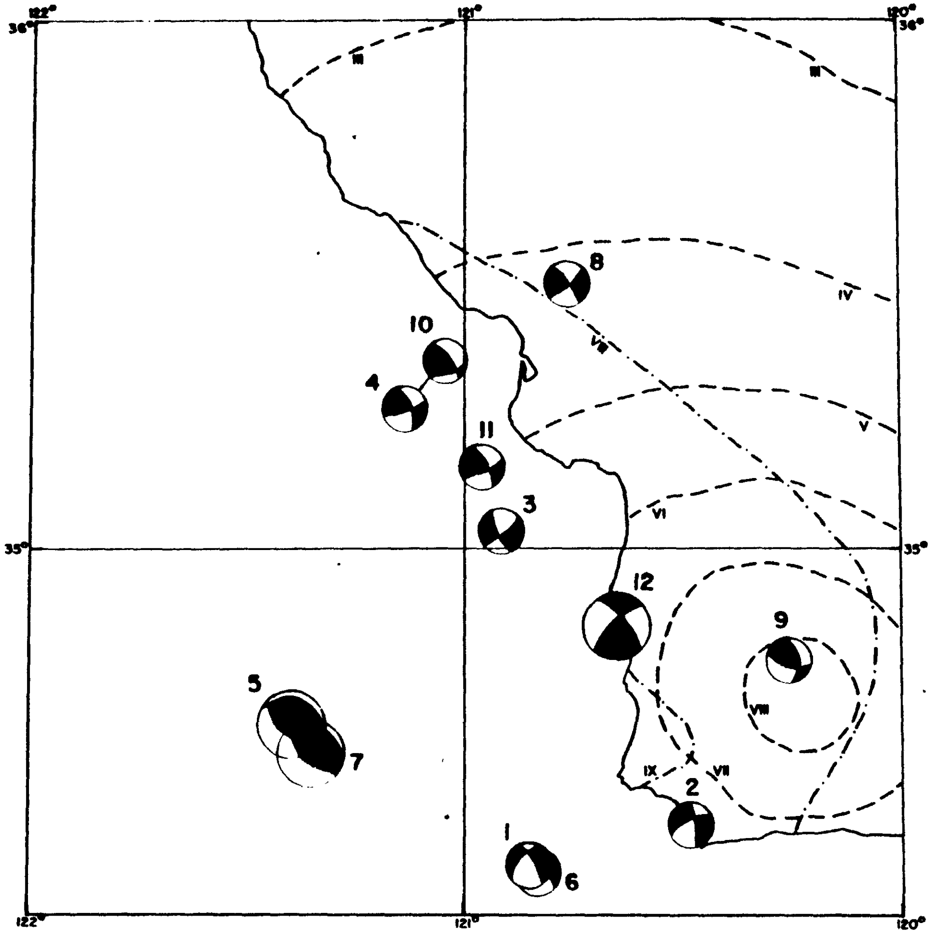


Figure 19. First motions and Rossi-Forel shaking intensities in the Santa Maria Basin area. The first motion diagrams are lower hemisphere plots, the white indicating dilation, the black, compression. Large diagrams indicate well-constrained events.

– – – – – – – – 1915 Los Alamos earthquake
–·–·–·–·–·– 1927 Lompoc earthquake

	DATE	MAGNITUDE
1	49/06/27	4.5
2	59/10/01	4.5
3	62/02/01	3.7
4	69/09/01	3.7
5	69/10/22	5.4
6	69/10/30	3.7
7	69/11/05	5.6
8	71/01/26	3.1
9	72/09/23	3.0
10	74/06/19	2.8
11	74/09/24	3.0
12	80/05/28	4.8

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-all focal mechanisms except events 1, 6, and 12 ffrom Gawthrop, W. H., 1978b, Seismicity and tectonics of the central California coastal zone: California Division Mines and Geology, Special Report 137, p. 45-56.

-events 1 and 6 from Gawthrop, W. H., 1975, Seismicity of the central California coastal region: U.S. Geological Survey Open-File Report 75-134, 90p.

-event 12 from Robert S. Cockerham (written commun., 1980).

-1915 Los Alamos isoseismals from Beal, C. H., 1915, The earthquake of Los Alamos, Santa Barbara, California, Jan. 11, 1915: Seismological Society of America Bulletin, v. 5, p. 14-25.

-1927 Lompoc isoseismals from Byerly, P., 1930, The California earthquake of November 4, 1927: Seismological Society of America Bulletin, v. 20, p. 53-66.

they lie in the area where faults break the seafloor. However, if one of the several approximately 40 km long seafloor fault offsets on the bank resulted from a single displacement event, the associated earthquake would have had a magnitude of approximately 7 as estimated from comparisons of observed fault rupture length vs. earthquake magnitude (e.g. Tocher, 1958; Iida, 1965; Albee and Smith, 1967; Bonilla, 1967, 1970).

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 seafloor (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 seafloor, but the redistribution of seafloor sediment is so rapid that displacement of the seafloor is minimal. These faults occur in a wide zone between the San Andreas and the possible northwestern extension of the San Gregorio-Palo Colorado 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. Strong seismic shaking could occur in outer Santa Cruz basin in the event of a large earthquake on the San Gregorio-Palo Colorado fault. Based on the assumption that this fault is part of a coastal fault system that extends at least from the south shore of Monterey Bay northward to the Golden Gate, it has been suggested that this fault may have the potential of producing a magnitude 7.5 earthquake (Greene and others, 1973). Strong seismic shaking could also occur in Bodega basin from such an event, or be caused by a large earthquake on the San Andreas fault.

Shallow gas, herein called shelf-edge gas, has been mapped along the upper edge of the continental slope of the outer Santa Cruz basin. The gas appears to be migrating up the slope and accumulating along bedding surfaces in a prograded sediment wedge that forms the edge of the continental shelf (McCulloch and others, 1980). Associated with this shelf-edge gas is irregular bottom topography that suggests downslope movement of unconsolidated surface sediment on the continental slope. In the northern part of Bodega basin (Fig. 20) much of the continental slope west of the 250 m isobath is in landslide. Landslides may extend further south than the latitude of Point Reyes, but there are insufficient data to define this distribution.

Shallow gas a few meters to tens of meters below the seafloor has been mapped along the eastern edge of the northern Bodega basin (Fig. 20) where it occurs in a band as much as 12 km wide and 90 km long. A small accumulation of shallow gas on the edge of the shelf approximately 50 km northwest of Point Reyes has surface pits thought to be craters eroded by escaping gas.

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 tsunami at Crescent City to the north had only a minor effect along the shore of Bodega basin and produced 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 the northern two-thirds of this basin (see Appendix). 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 activity 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. Shallow gas accompanied by gas craters and a possible gas plume in the water column have been mapped along the shelf edge in the southern third of the basin (Fig. 20), and slides have been identified seaward of the 500 meter isobath on the adjacent continental slope. The combined potential for strong ground motion, the possible presence of shallow gas and the fine-grained muds on the basin floor (Welday and Williams, 1975) suggest that slumps and slides may exist in the northern two-thirds of the basin.

Eel River Basin.-- Subduction of the Gorda lithospheric plate beneath Eel River Basin results in considerable seismic activity. Within the general area of the basin, 1182 earthquakes (detected without instruments or > m2) during the last 12 decades have had the following distribution (Couch and others, 1974; Real and others, 1978):

MAGNITUDE

DECADE	3	3.0-3.9	4.0-4.9	5.0-5.9	6.0-6.9	> 7	UNKNOWN	TOTAL
1850's							12	12
1860's							5	5
1870's							6	6
1880's							12	12
1890's							49	49
1900's							106	106
1910's					1		50	51
1920's				1	1	2	73	77
1930's			5	12	2		78	97
1940's		8	29	13	4		41	95
1950's	38	138	50	6	3		25	260
1960's	11	178	56	10	0		27	282
1970-3	4	75	42	4	0		4	129
TOTALS	53	399	182	46	11	2	488	1181

This table indicates that on the average the area should experience one> M5 earthquake per year and one > M6 earthquake per decade. Major earthquakes of M7 - 7.5 have also occurred, and should be expected in the future (Smith, 1975).

The shelf and plateau areas are cut by numerous faults, many of which displace the seafloor or Quaternary age sediments (Fig. 13, Field and others, 1980). First motion studies by Bolt and others (1968) have shown a right-lateral strike slip component along northwest-trending structures southwest of Crescent City. Normal and thrust faulting, as well as strike-slip faulting are also found within the basin. The large number of faults that displace the seafloor or very young sediments, coupled with the high seismicity of the area, suggest, that there exists a high potential for repeated movement along

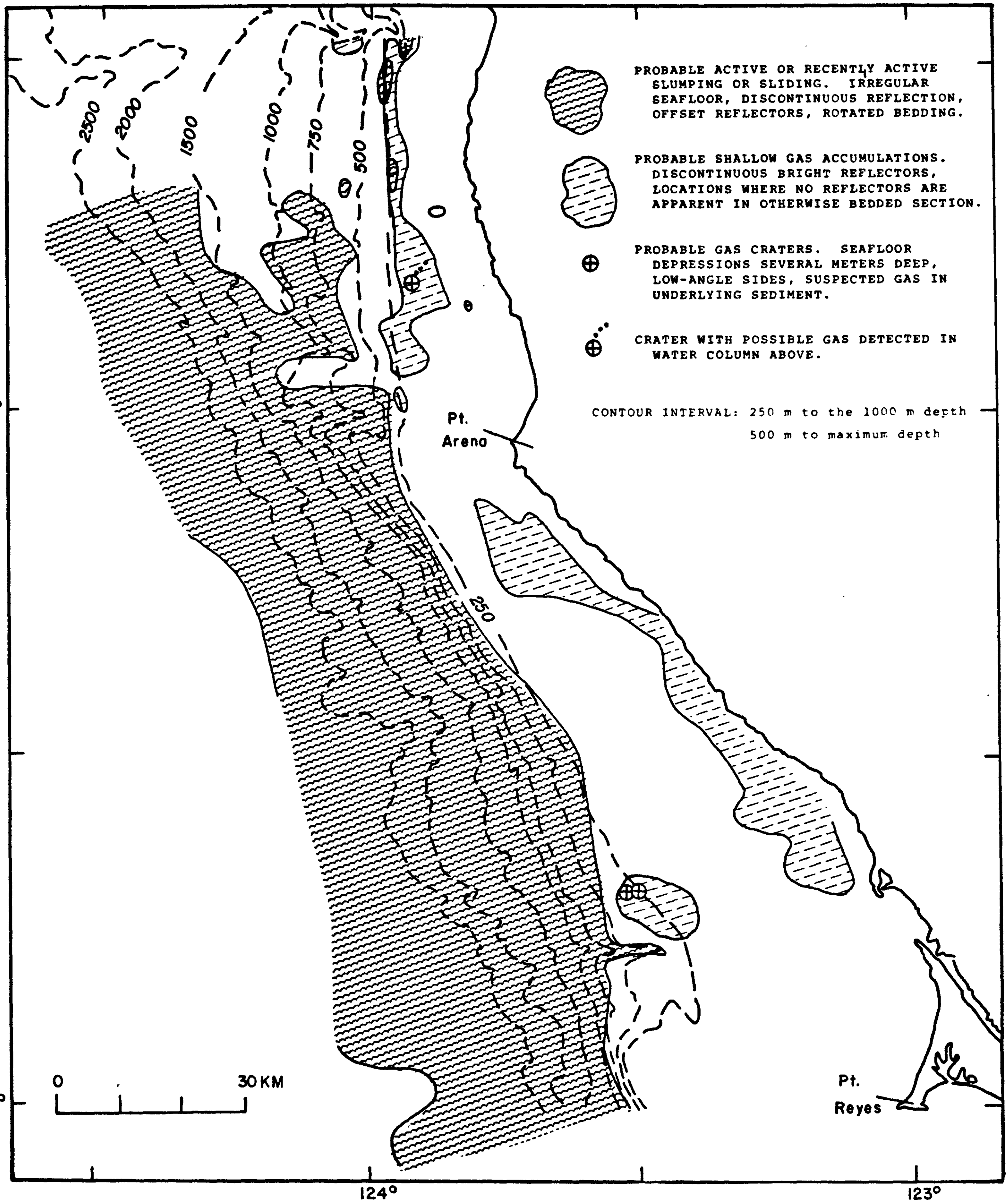

Figure 20. Surface and near surface features in Arena and Bodega basins, after Rubin, in McCulloch and others, 1980.

faults.

A series of discontinuous ridges on the central and outer plateaus are interpreted as being diapiric in origin. Ridge flanks and crests have irregular surface topography and contain little or no Quaternary sediment. Internal acoustic structure ranges from opaque to deformed, and sediment cores from the ridges contain Pliocene aged stiff clayey silt with mudstone clasts. Recent diapiric activity of these ridges is documented by large-scale slumping, upward bowing of the seafloor, and offsets in the seafloor from recent thrust faulting (Field and Gardner, 1980). The active uplift may produce concurrent ground shaking and abrupt changes in declivity.

Onto this seismically active shelf streams draining northern California discharge large loads of fine-grained organic-enriched potentially unstable sediment. Average deposition rates may be as high as 1.0 m/1000 yr throughout the area and much higher nearshore. Sediment exceeding 50 m in thickness collects in large depocenters offshore of Humboldt Bay and the Klamath River. Thick sequences of sediment are deposited on the slope and inner plateau. Associated with this young sediment are large zones, measuring 100's of km^2, of sediment slumps and slides. Many of the slumps extend to depths of 80 m or more below the seafloor and in some areas there is evidence for repeated failure at the same location. The hummocky nature of the slumps attests to their recency, and their widespread distribution demonstrates that sediment failure is the principal mechanism of downslope sediment movement in Eel River Basin. Large areas of unstable sediments, which appear to be incipient slumps, also occur throughout the area (Fig. 21). In addition, sediment cores from the plateau areas contain contorted and disturbed bedding, graded sand layers, and others indications of mass transport. On the shelf, shoreward of the failure zones, large areas show acoustic characteristics that

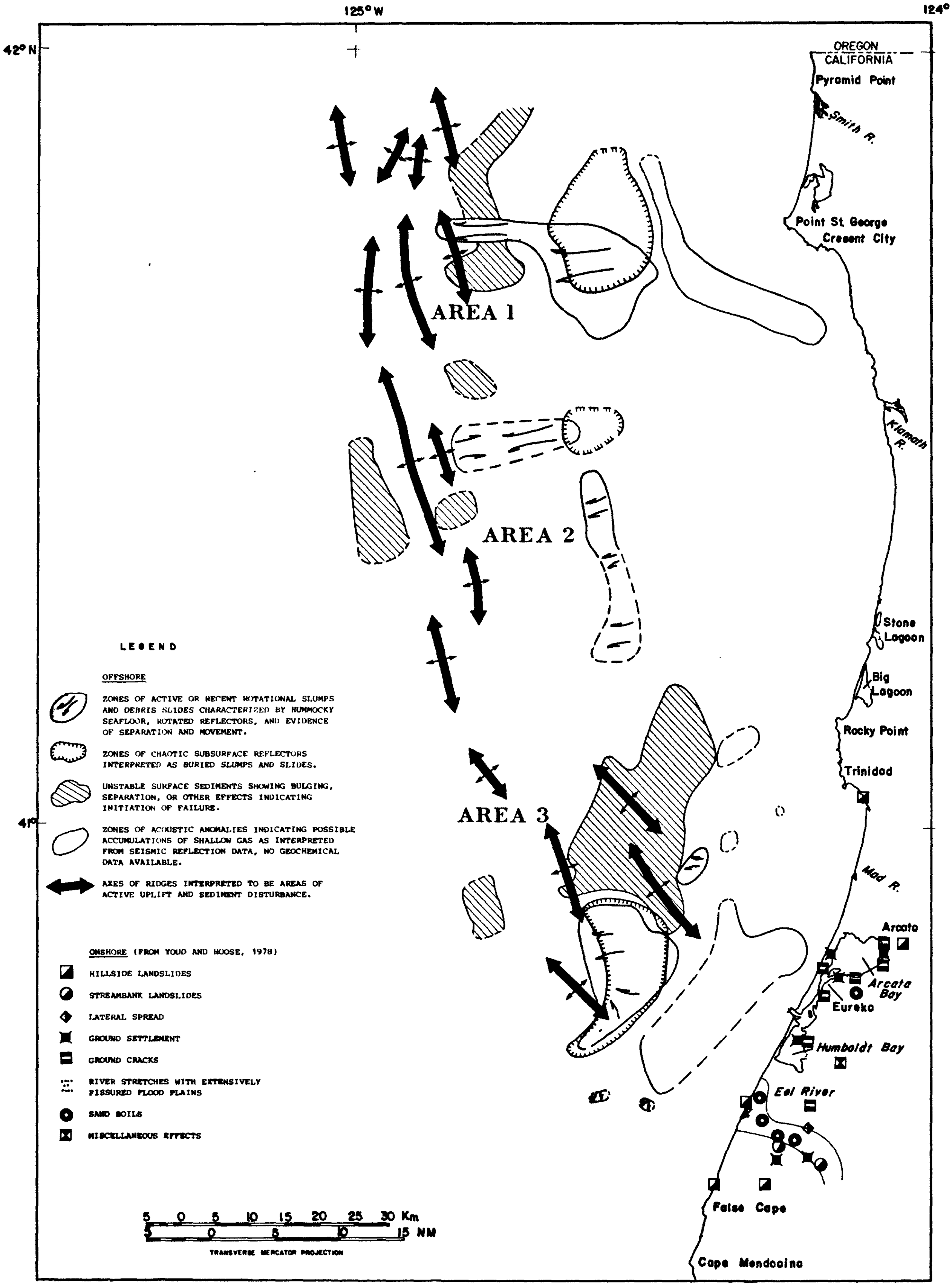

Figure 21. Surface and near surface features in Eel River Basin.

suggest the presence of shallow gas. The seafloor on the outer plateau is underlain by "Bottom Simulating Reflectors" (BSR) that may indicate the presence of gas hydrates. Dillon and others (1980) have suggested that hydrates may form seals that trap gas. Thus, there is a possibility for the existence of overpressured gas that may present problems during exploration.

The frequent large earthquakes generated along major structural features (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 damage (Iida and others, 1967).

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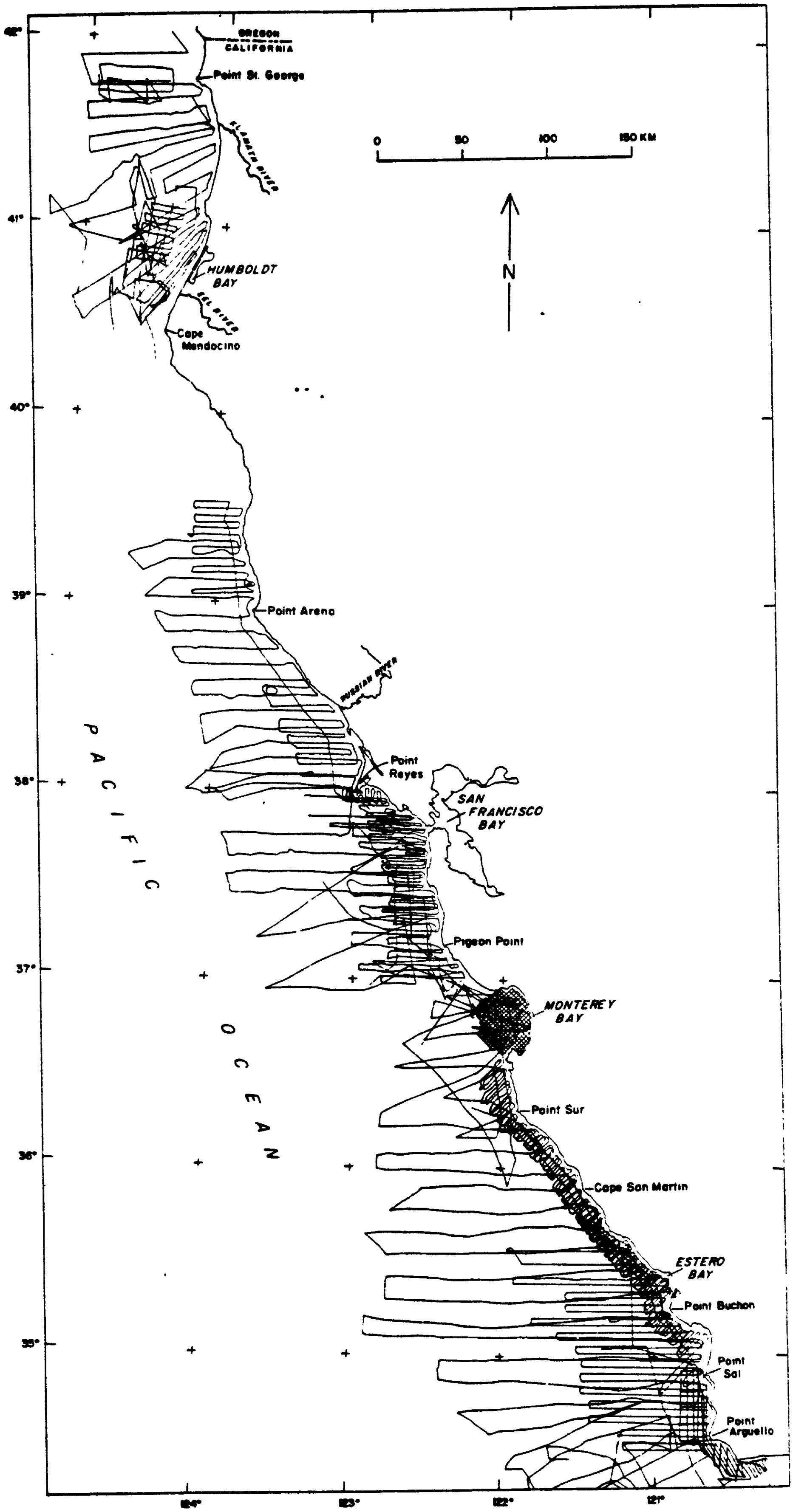

APPENDIX

U.S. Geological Survey tracklines in central and northern California Outer Continental Shelf.

PETROLEUM RESOURCE APPRAISAL

by

E. W. Scott and G. L. Dolton

The proposed oil and gas lease sale No. 73, offshore central and northern California, extends from Point Conception (approximately $34^{o}20'$ N latitude) on the south to the Oregon border (42^{o} N latitude) on the north. The area assessed for oil and gas resource potential lies within these boundaries and extends from the shoreline seaward to the 2500 meter isobath.

The assessed area involves a total of about 26,000 square miles and a sediment volume of 23,000 cubic miles. Approximately 6% (1,800 mi^2) of the total area lies within the three-mile limit and is under the jurisdiction of the state of California.

Five separate geologic basins or provinces are included in the total area. These provinces, from south to north, are:

<u>Central and Northern California</u>

Santa Maria

Santa Cruz

Bodega

Point Arena

Eel River

Geological estimates (unconditional) of the total amounts of undiscovered recoverable oil and gas resources for the aggregate of these provinces of this sale area, including State and Federal waters, are shown in Table 1.

TABLE 1. Unconditional Estimates of Total Undiscovered Recoverable Oil and Gas, Central and Northern California (0-2500 m)

	Probability		
	$F_{.95}$	$F_{.05}$	Mean
Oil (Billion BBLS)	0.4	4.6	2.0
Gas (TCF)	0.7	5.1	2.4

These resource estimates are based on individual basin geological analysis which includes volumetric yield and analog methods and structural analysis. It should be indicated that this aggregation represents a combination of basins from significantly different geologic settings and water depths along the Pacific margin.

Assessments have been made of these basins in separate parts by water depth of 0-200 meters, and 200-2500 meters (Table 2). Thus, 10 separate areas were assessed for undiscovered recoverable oil and gas, and these assessments have been aggregated by Monte Carlo methods for the proposed Sale 73, as shown in the following figures.

Aggregate estimates incorporate the risk of one or more of the basins not being productive. The complete probability distributions are shown in Figures 1 and 2.

For planning purposes, conditional estimates which assume no individual province risk for the occurence of oil and gas are sometimes employed. The conditional estimates of individual provinces which fall within this total sale area are included in Table 1, and show the complete distribution of resources, including State waters.

Conditional estimates exclusive of State waters for the aggregate sale area are derived through Monte Carlo techniques and are shown in Table 3.

TABLE 2. CONDITIONAL ESTIMATES AND MARGINAL PROBABILITIES OF UNDISCOVERED RECOVERABLE OIL AND GAS FOR BASINS INCLUDED WITHIN OCS SALE 73*

Region and province		Crude Oil: Estimated amounts (billion barrels) Low F_{95}	High F_5	Mean	M.P.	Assoc. Gas: Estimated amounts (trillion cubic feet) Low F_{95}	High F_5	Mean	M.P.	Non-associated Gas: Estimated amounts (trillion cubic feet) Low F_{95}	High F_5	Mean	M.P.
Santa Maria	0–200 m	0.1	2.0	0.7	1.00	0.1	1.8	0.6	1.0	---------none---------			
	200–2500 m	0.2	3.2	1.1	.73	0.2	2.8	1.0	.73	0.4	1.3	0.7	.14
Santa Cruz	0–200 m	0.1	.8	0.3	.38	0.1	0.7	0.3	.38	---------none---------			
	200–2500 m	<0.1	1.1	0.3	.28	<0.1	1.0	0.3	.28	---------none---------			
Bodega	0–200 m	<0.1	0.5	0.2	.26	<0.1	0.4	0.1	.26	---------none---------			
	200–2500 m	<0.1	0.4	0.1	.18	<0.1	0.3	0.1	.18	---------none---------			
Point Arena	0–200 m	<0.1	0.4	0.1	.27	<0.1	0.4	0.1	.27	---------none---------			
	200–2500 m	0.1	0.8	0.3	.21	0.1	0.7	0.3	.21	---------none---------			
Eel River (Calif. portion)	0–200 m	<0.1	0.7	0.2	.14	<0.1	0.5	0.2	.14	0.2	1.0	0.5	.25
	200–2500 m	<0.1	0.7	0.2	.11	0.1	1.0	0.3	.11	0.3	1.4	0.6	.26

* Conditional estimates of quantities of undiscovered hydrocarbons shown here are based in each case upon the condition that the given hydrocarbon is present; that is, if it is present, it will occur in the indicated quantity. The marginal probability (MP) states in each case the probability that the hydrocarbon is present.

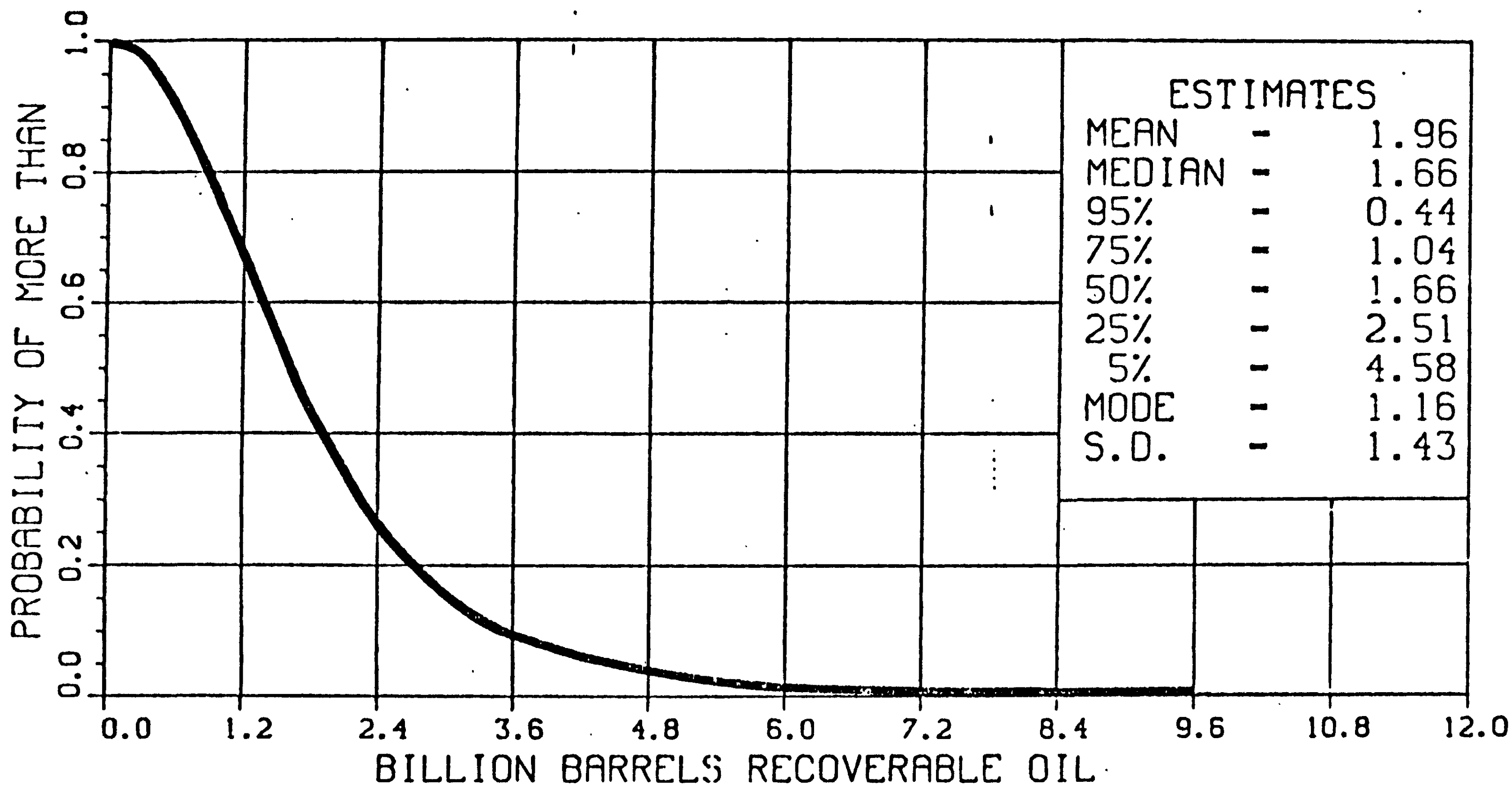

Fig. 1--Probability distribution for unconditional estimates of undiscovered recoverable oil for central and northern California (0-2500 m).

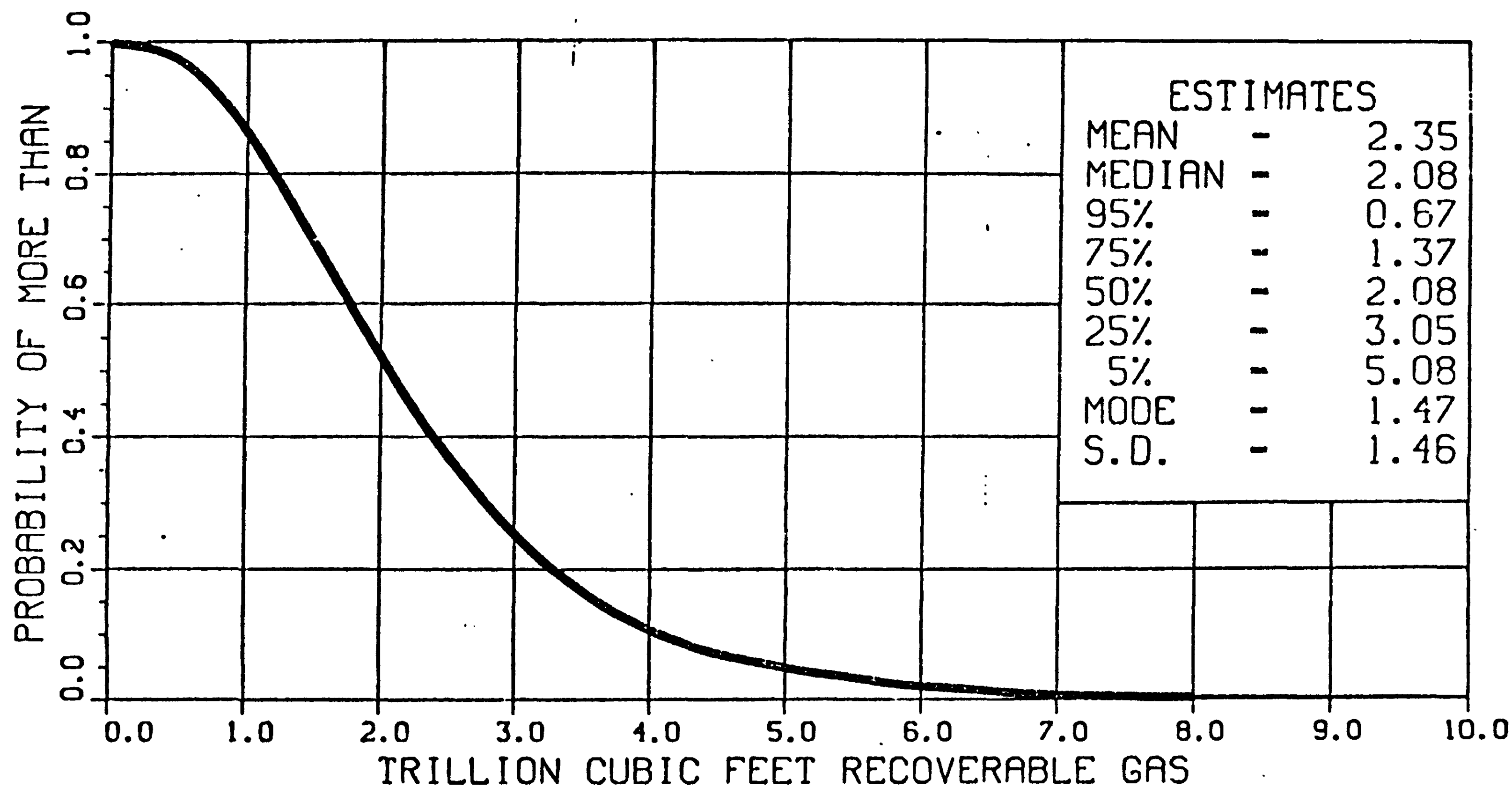

Fig. 2--Probability distribution for unconditional estimates of undiscovered recoverable gas for central and northern California (0-2500 m).

TABLE 3. Conditional Estimates of Total Undiscovered Recoverable Oil and Gas, OCS Sale 73, (0-2500 m), Federal waters only.*

	Probability			
	$F_{.95}$	$F_{.05}$	Mean	MF
Oil (Billion BBLS)	0.3	3.9	1.6	1.0
Gas (TCF)	0.5	4.5	2.0	1.0

*These estimates are an aggregation of the conditional estimates of the individual basins exclusive of State waters and assume that if oil (or gas) is present in all of these separate basins within the sale area, then the total indicated here would be reached.

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