UNITED STATES DEPARTMENT OF THE INTERIOR

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THE MARINE GEOLOGY OF THE EASTERN SANTA BARBARA CHANNEL WITH PARTICULAR EMPHASIS ON THE GROUND WATER BASINS OFFSHORE FROM THE OXNARD PLAIN, SOUTHERN CALIFORNIA

by

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ABSTRACT

Marine geophysical investigations provide new data concerning the stratigraphy, tectonic and sedimentary history, and the ground water geology of the southeastern Santa Barbara Channel region. The offshore stratigraphy identified in seismic reflection profiles includes a succession of Neogene to Quaternary strata. The middle Miocene Conejo volcanics form an acoustical basement and the overlying late Cenozoic sedimentary rocks attain a thickness greater than 2,500 m. These sedimentary deposits fill a structurally controlled, physiographic and depositional depression called the Ventura Basin.

Structure consists generally of a gently folded, east-trending, Tertiary synclinorium bordered on the north by a regional thrust fault and on the south by a steep asymmetrical anticlinal ridge. Most structures show evidence of north-south compression that occurred during early Pleistocene time. Three well-defined unconformities represent widespread erosion in late Miocene, early to middle Pleistocene, and late Pleistocene time. The boundaries of Miocene, Pliocene, and lower Pleistocene strata continue uninterrupted eastward along the southern part of Santa Barbara basin to Hueneme Canyon, where they turn northeast and can be traced to the coast near Port Hueneme. These limits probably represent the south edge of the Santa Barbara basin during Pliocene and Pleistocene time.

Fresh water-bearing materials of the Oxnard plain are unconsolidated Quaternary sediment laid down on more consolidated Tertiary rocks. Offshore, the total fresh water-bearing materials distinguished in the seismic reflection profiles attain a thickness of about 356 m and have an areal extent of over 760 km^2. Strata that contain the offshore continuation of the five major on-land aquifers (Grimes Canyon, Fox Canyon, Hueneme, Mugu, and Oxnard aquifers)

are identified in the seismic reflection profiles. These strata make up the two offshore ground-water basins, the Mound and Oxnard plain ground-water basins, which are separated by the east-west trending Oak Ridge fault.

Possible entrance areas for salt water intrusion into fresh water aquifers are found along the walls of the submarine canyons and along the northern slopes of Santa Barbara and Santa Monica basins. Hueneme and Mugu aquifers are probably exposed locally in all five submarine canyons of the Oxnard offshore area and may also crop out along the upper northern slope of Santa Monica basin. In all of these areas, salt water readily intrudes the aquifers. A salinity-temperature-depth study made in April, 1971, does not indicate any great dilution of surface ocean water by fresh water that could be "leaking" from the exposed aquifers along the walls of Hueneme Canyon and the landward slope of Santa Barbara Channel.

Earthquakes in the vicinity of the Oxnard plain suggest that the region is seismically active. Epicenters are widely dispersed over the region. No distinct trend or alignment of earthquake epicenters occurs near the trace of any of the faults, although many epicenters are scattered around the Oak Ridge zone of deformation in the northern part of the region. The largest magnitude earthquake recorded in the area was a magnitude 5.7 that occurred on February 21, 1973, offshore of Point Mugu, south of the Oxnard plain.

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The Marine Geology of the Eastern Santa Barbara Channel With Particular Emphasis on the Ground Water Basins Offshore from the Oxnard Plain, Southern California

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H. Gary Greene, S.C. Wolf, and K.G. Blom

INTRODUCTION

The eastern part of the Santa Barbara Channel is underlain by thick deposits of sediment that fill the Ventura Basin. This basin is a structurally controlled, physiographic and depositional depression approximately 80 km (50 mi) northeast of Los Angeles, California (Fig. 1). The Ventura Basin-Santa Barbara Channel region is bordered on the north by the Santa Ynez Mountains and on the south by the western Santa Monica Mountains and the northern Channel Islands. These features are part of the Transverse Range province, which is characterized by west-trending topographic and structural features that transect the regional, northwest, structural grain of California.

Within the Ventura Basin are west-trending folds and faults. The area is underlain by as much as 18,000 m (60,000 ft) of Cretaceous and Tertiary sedimentary deposits and is one of the largest and most prolific oil-producing districts in California (Bailey and Jahns, 1954; Vedder and others, 1969). Strata of the Ventura Basin unconformably overlie, and locally are faulted against, Mesozoic plutonic and metamorphic basement rocks (Plate 1).

The prograding delta of the Santa Clara River deposited the Quaternary sediments of the Oxnard plain and the nearshore parts of the eastern Santa Barbara Channel. These Pleistocene and younger strata are the major sources of fresh water for the towns of Ventura and Oxnard, for the U.S. Navy installations at Port Hueneme and Point Mugu, and for irrigation of crops in the Oxnard plain region. The Quaternary deposits associated with the plain thin

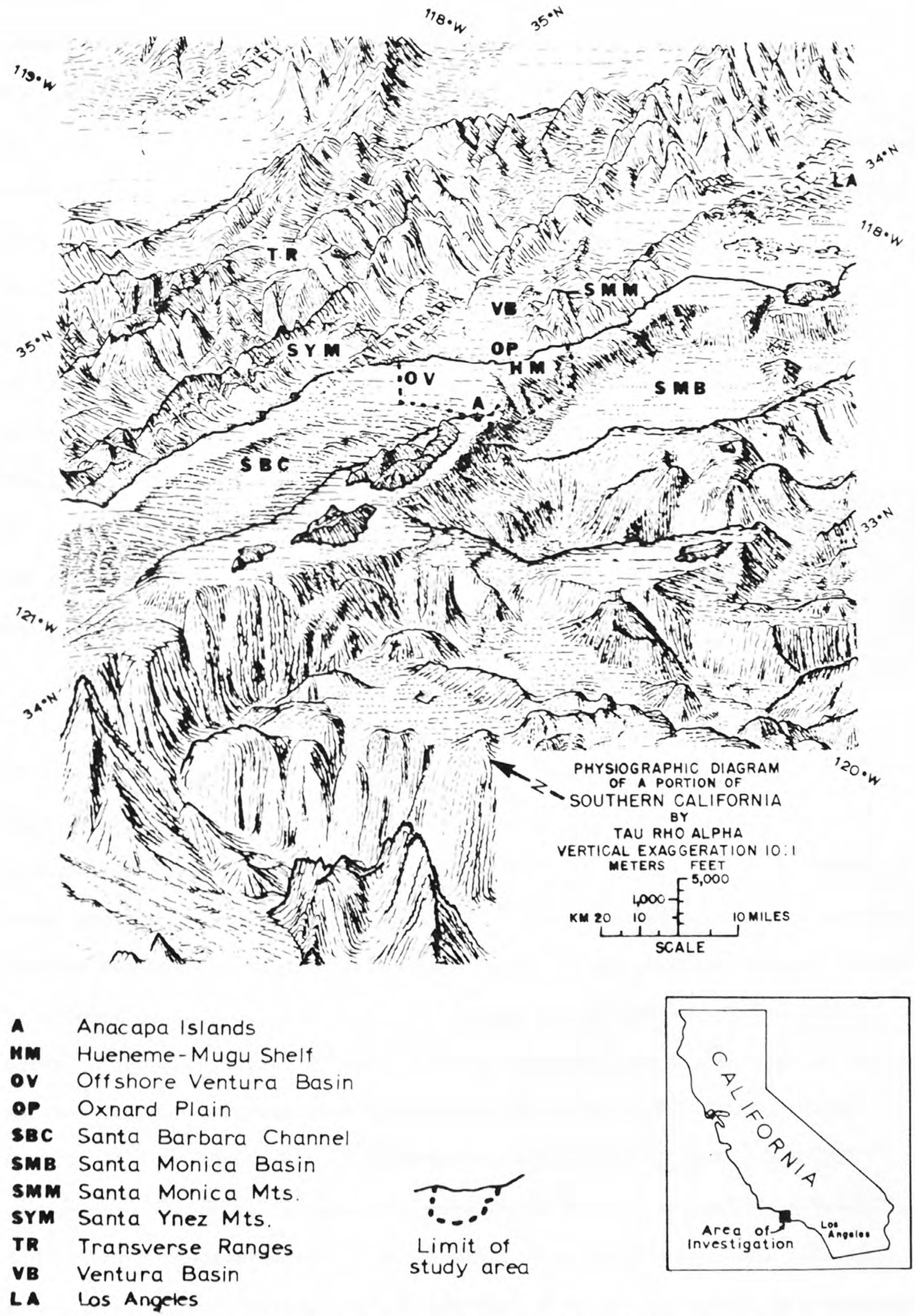

Figure 1. - Index map showing relationship of Oxnard plain region to part of southern California.

toward the south and contain six fresh water-bearing zones or aquifers. The aquifers on land are, in order of increasing depth beneath the ground surface: Semi-perched (10 m, 33 feet), Oxnard (-40 m, -130 ft), Mugu (-60 m, -200 ft), Hueneme (-76 m, -250 ft), Fox Canyon (-200 m, -660 ft), and Grimes Canyon (-451 m, -1500 ft). These aquifers make up several continuous hydraulic ground-water basins, two of which, the Oxnard plain and Mound ground-water basins, extend offshore (Fig. 2). The Oxnard plain ground-water basin is bounded on the north by the Santa Clara River and on the east by the Camarillo Hills and the Santa Monica Mountains at Point Mugu. The Mound ground-water basin is bounded on the north by the base of the foot-hills and upslope limits of alluvial fan surfaces of the Santa Ynez Mountains, on the southeast by the Oak Ridge fault, and on the south by the Santa Clara River.

A detailed marine geophysical survey was made in the Ventura-Oxnard plain offshore region of southern California (Fig. 3) in the summer of 1970 as a joint effort by the U.S. Geological Survey and the State of California Department of Water Resources. The survey was planned to determine the regional geologic setting and in particular to study the offshore ground water geology. Single channel high resolution, shallow penetration (0.6 kj) and low resolution, intermediate penetration (23 kj) sparker seismic reflection profiles were obtained using equipment aboard the U.S. Geological Survey's research vessel POLARIS. Single channel, deeper penetration (80 kj) sparker seismic reflection profiles obtained by the U.S.G.S. aboard the M/V OIL CITY in 1969 are also presented. Also gathered during the 1970 survey were magnetic, bathymetric, wide angle seismic refraction (sonobuoy), and salinity-temperature-depth (STD) data. The geophysical data were collected along approximately 720 km (450 mi) of track line by the R/V POLARIS

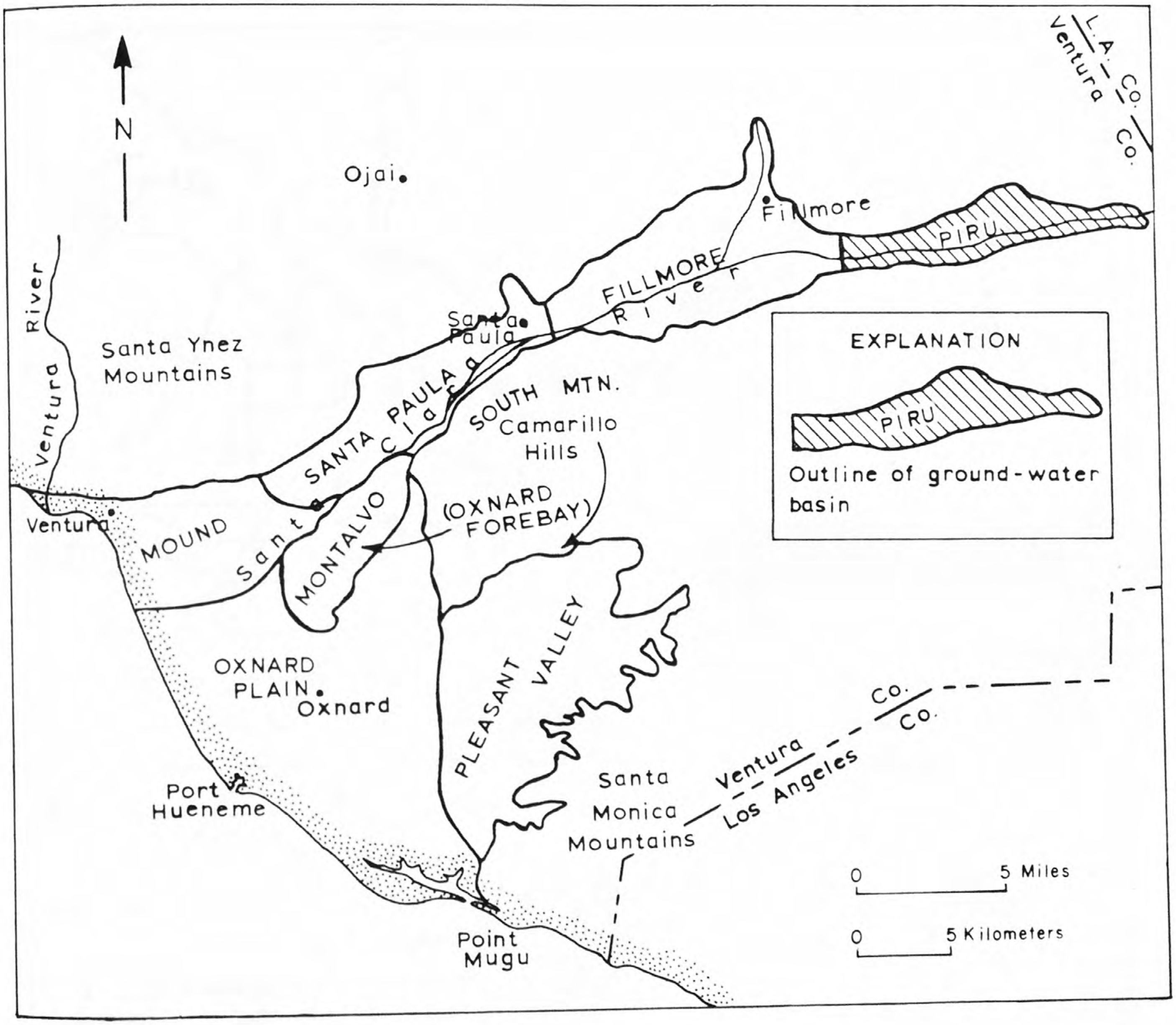

Figure 2. - Map showing ground-water basins in western Ventura County.

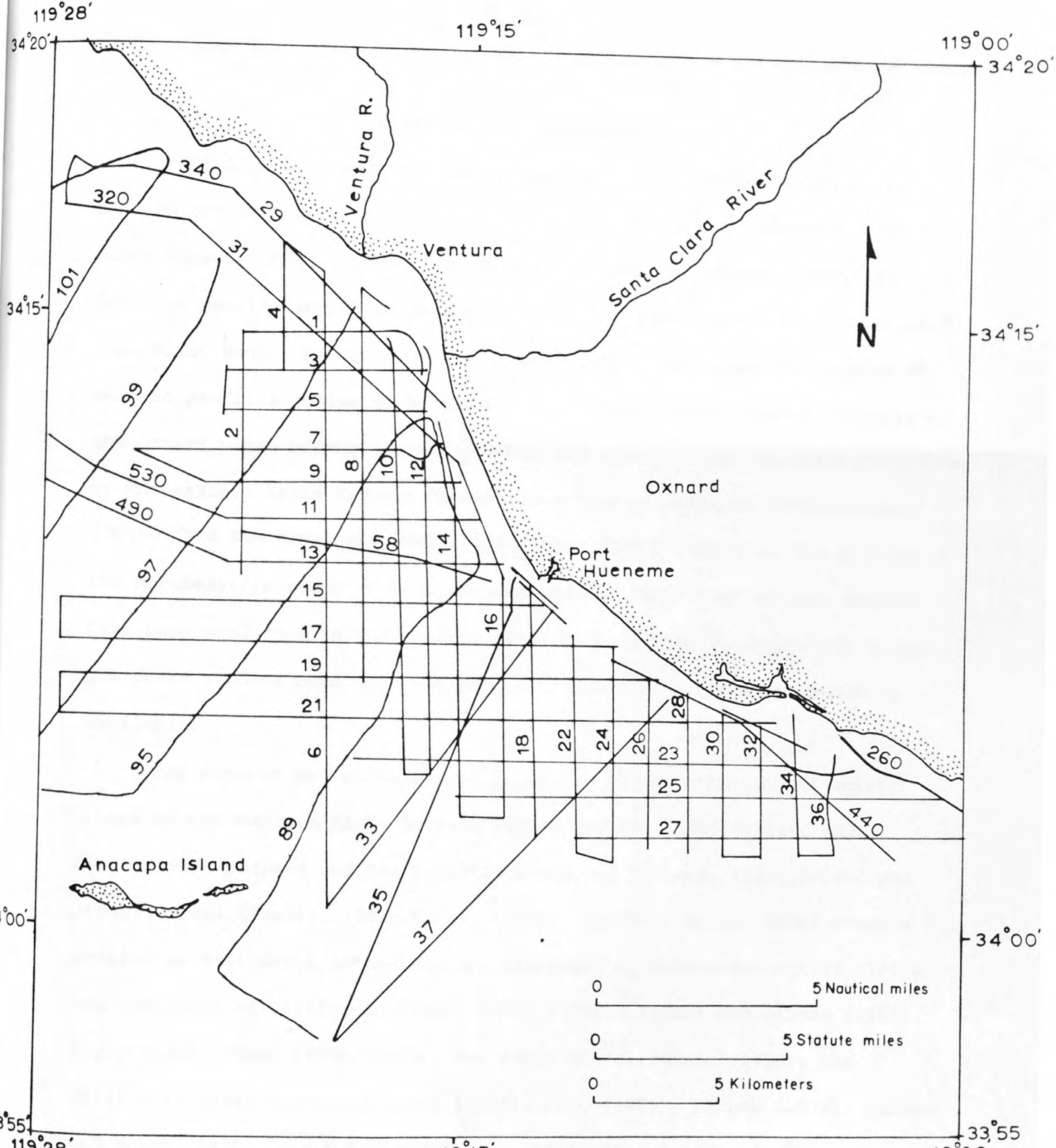

Figure 3. - Map showing seismic profile tracklines.

in 1970 and about 160 km (100 mi) of track line by the M/V OIL CITY in 1969.

Previous Investigations

Several reconnaissance, continuous, seismic reflection studies, both shallow and deep penetration types, have been made in the offshore Oxnard plain region. Moore (1960) discusses the results of a high resolution (shallow penetration) seismic survey around Anacapa Island and on the shelf near Point Mugu. Wagner (1975) and Moore (1975) have published copies of seismic profiles collected by the U.S. Geological Survey in the vicinity of the Oxnard plain offshore area. Vedder and others (1969) describe structure of the eastern Santa Barbara Channel from deep penetration profiles collected from the area, and Wagner and Junger (1977) report on the geology of the northeastern slope of Santa Monica Basin. Many other seismic surveys have been conducted in the eastern Santa Barbara Channel by private groups, but these studies have not been published and the data are not publicly available.

Many reports on sediments and lithology of the offshore and coastal areas of the eastern Santa Barbara region are available (Trask, 1931; Cohee, 1938; Shepard and Emery, 1941; Emery and Shepard, 1945; Poland and others, 1948; Crowell, 1952; Emery, 1960). Numerous ground water studies related to salt water intrusions are discussed by Poland and others (1948) and the State of California (1950, 1958, 1965). Thomas and others (1954), Price (1956), Mann (1959, 1968), the State of California (1950), the California Water Resources Board (1956), Page (1963), Turner (1975), Turner and Mukae (1975), and Mukae and Turner (1975) discuss ground water studies in the Oxnard plain region. An investigation on ground water leakage from submarine exposures of coastal aquifers along the Hueneme-Mugu shelf is reported by Gorsline (1970).

Environmental geology for the entire Santa Barbara Channel region is discussed in a U.S. Department of Interior Environmental Impact Statement (U.S. Geol. Survey, 1976) and for the entire Borderland, including the Santa Barbara Channel, by Vedder and others (1974, 1976).

Acknowledgments

We have benefited greatly from extensive conversations with, and the cordial cooperation of, John Turner of the Oxnard Water District, Richard Slade and Joseph Gonzalez of Geotechnical Consultants, Inc., of Ventura, and Ernie Weber, formerly of the California State Department of Water Resources. Jerry Nelson, formerly of the California State Department of Water Resources, aided in the collection of the data. Russ Campbell and Tom Dibblee of the U.S. Geological Survey kindly assisted the senior author in acquainting himself in the field with the on-land geology and spent a considerable amount of time in the discussion of regional geology. Jack Vedder, Russ Campbell, Holly Wagner, Mike Marlow, and Arne Junger of the U.S. Geological Survey critically read the manuscript.

Interpretations

The acoustical and structural criteria used to distinguish different lithologic units in the seismic reflection profiles are based on acoustical seismic signal characteristics and reflector types and on consistently identifiable structural and sedimentary characteristics such as truncated beds (unconformities) and prograded bedding. The line drawings in this report are representations of seismic profiles with added geological interpretations. Some of the structures hidden by the "bubble-pulse" 1/ (in approximately the upper 60 m or 200 ft) in the deeper penetration profiles were drawn from high resolution profiles without exaggeration to provide true perspective of the dips of faults and flanks of folded structures (Pl. 1).

Depths of reflectors were calculated using average interval velocities, obtained from sonobuoy records, of 1.5 km/sec (4,900 ft/sec) in water, 1.7 km/sec (5,600 ft/sec) for unconsolidated to semi-consolidated materials in the top 150 m (500 ft) of section, and 1.8 km/sec (5,900 ft/sec) for consolidated sediments below 150 m (500 ft).

High resolution, intermediate, and deep penetration profiles have average vertical exaggerations of 14:1, 6:1, and 6:1, respectively. Apparent and true dips of recognizable sedimentary beds and volcanic surfaces observed in the seismic profiles were plotted on the geologic map (Pl. 2).

Onshore well data (Pl. 3) and various published geologic cross sections (Paschall and others, 1956; Mann, 1959; State of California, 1965; and Ogle, 1969) (Pl. 4) are used to correlate known lithologic data in the eastern Santa Barbara Channel region with the seismic units established from the marine seismic profiles. The marine units are correlated partly on their acoustical, structural, and depositional characteristics and partly on their position within the stratigraphic section. Also, stratigraphic positions of the onshore aquifers are extrapolated into the offshore subsurface area (Pl. 1). Approximate limits of the salt water-fresh water interfaces were

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1/ A "bubble-pulse" consists of attenuating reverberations that continue in the water column for 5 to 10 milliseconds after the primary pulse has been produced. These reverberations are reflected back from the ocean bottom and appear as pseudo-sea floor traces on the seismic record and effectively cancel any signals reflected from shallow structures immediately beneath the sea floor.

determined from limited offshore well data (Pl. 3).

Several major acoustic units are identified from the seismic profiles. These units probably range in age from Miocene to Holocene and represent a maximum stratigraphic thickness of nearly 2,700 m (9,000 ft). In the deep and intermediate penetration seismic records, lithologic boundaries between the various seismic units are locally difficult to define at depth except where distinct unconformities occur. In the other areas boundaries are approximately located and may be as much as ± 150 m (500 ft) in error. Boundaries between the shallow acoustic units, however, are generally readily identifiable and correlate well with the onshore water well data.

The nomenclature of the seismic marine stratigraphic units is equivalent to that for the stratigraphic units onshore. Stratigraphic terminology used in this report is after Kew (1924), Poland and others (1948), Paschall and others (1956), Gamble (1957), Mann (1959), Ogle (1969), State of California (1965), and Vedder and others (1969)1/.

Seismic Characteristics And General Stratigraphy

The stratigraphy in the onshore part of the Ventura basin includes a succession of Late Cretaceous to Holocene units (Pl. 5). In the offshore area, the middle Miocene Conejo Volcanics form an acoustical basement. Sedimentary strata overlying this basement range in age from middle Miocene to Holocene. The late Cenozoic strata observed in the seismic reflection records have been tentatively assigned formation names; from oldest to youngest, they are: lower Miocene Rincon shale and Topanga-Vaqueros undifferentiated units; middle to upper Miocene Monterey shales that may include the Santa Margarita

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

sandstones; Pliocene Pico Formation; upper Pliocene to lower Pleistocene Santa Barbara Formation; and the lower to middle Pleistocene San Pedro Formation. The latest deposited Quaternary sediments identified in the seismic profiles consist of unnamed Pliocene-Pleistocene terrace deposits (restricted to the northern insular shelf of Anacapa Islands), late Pleistocene marine deposits, Holocene basin, slope, and shelf deposits, and Holocene terrace deposits (also restricted to the northern insular shelf of Anacapa Island). Other sedimentary features identified include slumps, canyon fill, and areas of downslope creep, all of which are restricted to the submarine canyons and basin slopes.

Highly contrasting lithologic units within a stratigraphic section generally exhibit independent, distinct, acoustical signatures depending upon their density and structure. Through use of these characteristics, one may distinguish in a seismic profile such lithologic units as volcanic, crystalline, and metamorphic rocks or highly folded and lithified sedimentary rocks from well-bedded, consolidated sediments. The seismic and structural criteria used to identify the offshore acoustical units are described below in conjunction with lithologic descriptions and a general stratigraphic summary condensed and modified from Thomas and others (1954), Mann (1959), the State of California (1965), and Vedder and others (1969, p. 1-5).

Miocene volcanic rocks

Extrusive and intrusive sequences of volcanic rocks with basaltic, andesitic, and rhyolitic composition, and some volcanic breccias were formed during lower and middle Miocene time. These volcanic rocks are exposed on the Channel Islands, in the Santa Monica Mountains, and in the subsurface beneath the central and southeast Oxnard plain (Pls. 2 and 5).

They appear to thin rapidly northward from the Santa Monica Mountains. The name "Conejo volcanics" of Taliaferro and others (1924) has been applied to the basaltic and andesitic rocks of middle Miocene age in the western Santa Monica Mountains (Jenkins and others, 1949; Gamble, 1957) and on Anacapa Islands (Kennett, 1952; Scholl, 1960). On Anacapa Islands, the Miocene volcanic rocks consist of interbedded andesitic lavas and pyroclastics that contain two layers of San Onofre Breccia 11 to 12 m (35-40 ft) thick (Scholl, 1960, p. 129). Scholl (1960, p. 67) also reported that volcanic rocks crop out on the shelf surrounding Anacapa Islands; locations of these outcrops as mapped by Scholl are shown on Plate 2.

Acoustical criteria used to identify the volcanic rocks offshore are strong reflections beneath which there is little or no seismic coherency and where many acoustical hyperbolic and multiple reflections are found. The strong reflections represent acoustical basement and are readily correlated from one line to another and to onshore and nearshore areas where volcanic rocks are known to crop out.

Miocene strata

Onshore, near the mouth of the Ventura River, the lower Miocene strata consist of sandstone and conglomerate of the Vaqueros Formation. These deposits unconformably overlie nonmarine Oligocene strata and underlie and interfinger with concretionary claystone, mudstone, and siltstone beds of the Rincon Shale. The Rincon Shale is nearly 760 m (2,500 ft) thick near Ventura (Pl. 5). In the central and eastern part of the Oxnard plain, the lower to middle Miocene strata consist of coarse sandstone and conglomerate of the Topanga-Vaqueros undifferentiated unit (Campbell, 1971, oral commun.).

Uniform, hard, laminated, siliceous shales that contain diatomaceous and phosphatic beds as well as chert and limestone compose the middle Miocene Monterey Shale on land near the mouth of the Ventura River and in the central Oxnard plain. These strata grade downward into and locally conformably overlie Rincon Shale near Ventura and conformably overlie volcanics in the central part of the Oxnard plain. In the southeast part of the Oxnard plain, the Monterey Shale is absent and the coarse sandstone and conglomerate of the Topanga-Vaqueros undifferentiated unit underlie the middle Miocene strata.

Offshore, rocks of Miocene age are exposed near the heads of Mugu and Hueneme canyons (Cohee, 1938, p. 20; Emery and Shepard, 1945, p. 459-460). Dredge samples collected by Emery and Shepard (1945) contained calcite-cemented sandstone from an outcrop at the head of Mugu Canyon, cherty shale from an outcrop on a bank slope just east of Mugu Canyon, and transported Miocene cherty shale from Hueneme Canyon. Miocene strata crop out on the shelf around Anacapa Islands (Emery, 1960, p. 67, Fig. 62) and on the floor of Anacapa Passage, about 1.8 km (1 mi) west of Anacapa Islands (Scholl, 1960 p. 127, Fig. 4).

A poorly bedded unit, the "Santa Margarita" of Bailey (1952), is composed predominantly of diatomaceous mudstone, claystone, and siltstone. This unit crops out near Ventura and is found in the subsurface beneath the central part of the Oxnard plain where it disconformably overlies the Monterey Shale. Upper Miocene rocks are not present in the southeast part of the Oxnard plain (Pl. 2).

Acoustical criteria used to identify and separate strata of Miocene age are based mainly on seismic coherency. The Topanga-Vaqueros undifferentiated unit offshore consists of fairly strong reflectors with few hyperbolics and local seismic incoherency. The reflectors are discontinuous and widely spaced. Acoustical criteria used to identify the Rincon, Monterey, and "Santa Margarita" units consist of strong, coherent reflectors that are well defined, parallel to subparallel, and tightly spaced. The continuous, uniform, and repeating reflectors of this unit suggest rhythmic bedding characteristic of the Monterey Formation. Identical acoustical properties have been described for the Monterey Formation in Monterey Bay (Greene, 1970, p. 29).

The difference between the Rincon, Monterey, and the "Santa Margarita" units is very difficult to distinguish in the seismic records. The term Monterey Shale, as used in this report, is applied to all three. Separation of these units in the seismic profiles is not attempted.

Pliocene and lowermost Pleistocene deposits

Interbedded marine siltstone, sandstone, and thin lenticular conglomerate form the lower part of the Pliocene succession onshore. These strata, the Pico Formation, conformably overlie the marine Miocene rocks near Ventura and unconformably overlie Miocene rocks in the southeast part of the Oxnard plain. The upper part of the Pliocene strata form the lower part of the Santa Barbara Formation, whose upper section contains beds of lower Pleistocene age and the Grimes Canyon aquifer. The Santa Barbara Formation is composed of interlayered and intertongued mudstone, siltstone, sandstone, and conglomerate. A thin bed of vitric tuff occurs in the upper part of the Pliocene succession, in the Santa Barbara Formation, near Ventura; this is the only evidence of volcanism in or near the Santa Barbara Channel region during Pliocene or later time. Pliocene and lower Pleistocene rocks are exposed onshore near Ventura (Pl. 2) and form a thick sequence, 3350 m to 3960 m (11,000 to 13,000 ft) thick, beneath the Oxnard plain near the mouth of the Ventura River.

Pliocene strata are not exposed on the Channel Islands and the thick sequence near Ventura thins toward the southeast to less than 150 m (500 ft) near the western end of the Santa Monica Mountains (Pl. 5). It also thins westward under the Santa Barbara Channel (Pl. 5).

Acoustical criteria used to identify Pico strata offshore consist of strong reflections with little seismic incoherency. The reflectors are broad, continuous, and widely spaced, intercalated with thin, faintly discontinuous reflectors. Acoustical criteria used in identifying sediments of the Santa Barbara Formation offshore are weak reflections within a highly incoherent acoustical layer of noise and seismic scattering - i.e., poor reflectivity. Distinct reflectors are usually discontinuous or lacking completely.

Pliocene-Pleistocene terrace deposits

Underlying the northern insular shelf of Anacapa Islands is a terrace deposit that acoustically consists of strong reflectors with little acoustical incoherency. The reflectors are generally short but semi-continuous, and probably represent alternating layers of coarse- and fine-grained sediments characteristic of clastic marine terrace deposits. The internal reflectors of this unit dip gently away from the island and probably are progradational in origin.

Lower Pleistocene deposits

The lower Pleistocene deposits generally consist of marine and terrestrial clays, sands, silts, and small amounts of conglomerates, and contain the Fox Canyon and Hueneme aquifers. These deposits have been called the "San Pedro" and "Saugus" formations (Dibblee, oral commun., 1973). Deposits of the same age exposed north of Ventura are also called the "Saugus" Formation (Dibblee, oral commun., 1973). These Pleistocene deposits grade downward into the lowermost Pleistocene marine strata of the Santa Barbara Formation onshore near Ventura and in the northern Oxnard plain. However, in the central and southeast parts of the Oxnard plain, the "San Pedro" deposits unconformably overlie strata of the Santa Barbara Formation (State of California, 1965) (Pl.5).

Acoustical criteria used to identify the "San Pedro" deposits are almost identical to those used to identify the Santa Barbara Formation. Basically, these criteria consist of weak, random, incoherent reflections with much attenuation or scattering of the seismic signal. Fortunately, the unit contains a structural or sedimentary criterion that can be used to distinguish it from the underlying, lithologically similar, Santa Barbara Formation. "San Pedro" reflectors have a persistent south to southwest dip and are underlain by flat-lying strata of the Santa Barbara Formation and overlain by flat-lying strata of late Pleistocene and Holocene age (Pl. 1, line 33; Figs. 4 & 5). This apparent depositional discontinuity between the lower and upper Pleistocene deposits is shown on the seismic records as a fairly continuous, strong reflector that correlates with an unconformity in water wells near the coastline.

Upper Pleistocene deposits

Upper Pleistocene deposits are unnamed and are composed of marine and terrestrial sands, gravel, clay, and alluvial flood plain deposits that contain the Mugu aquifer. These deposits are separated from the underlying "San Pedro" Formation by an angular unconformity.

These deposits on land can be divided into two lithologically dissimilar units, an upper clay zone, 60 m to 120 m (200 to 400 ft) thick, and a lower sand and gravel zone, 30 m to 70 m (100 to 230 ft) thick. The lower unit

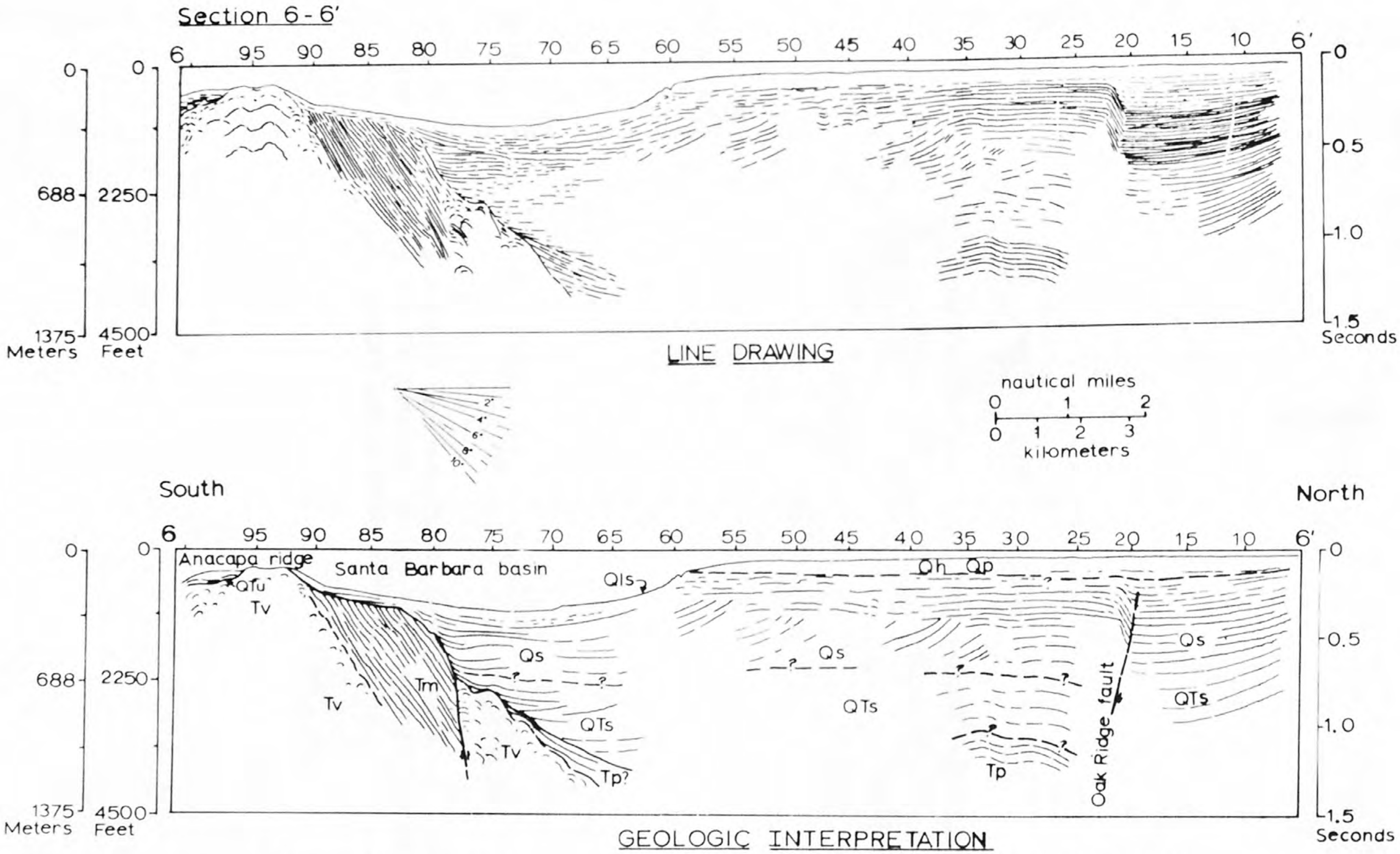

Figure 4. - Line drawing and geologic interpretation of intermediate penetration reflection profile 6 showing Miocene volcanics and strata of Anacapa ridge and Pliocene to Holocene sediments beneath the Ventura shelf. Symbol explanation same as Plate 2.

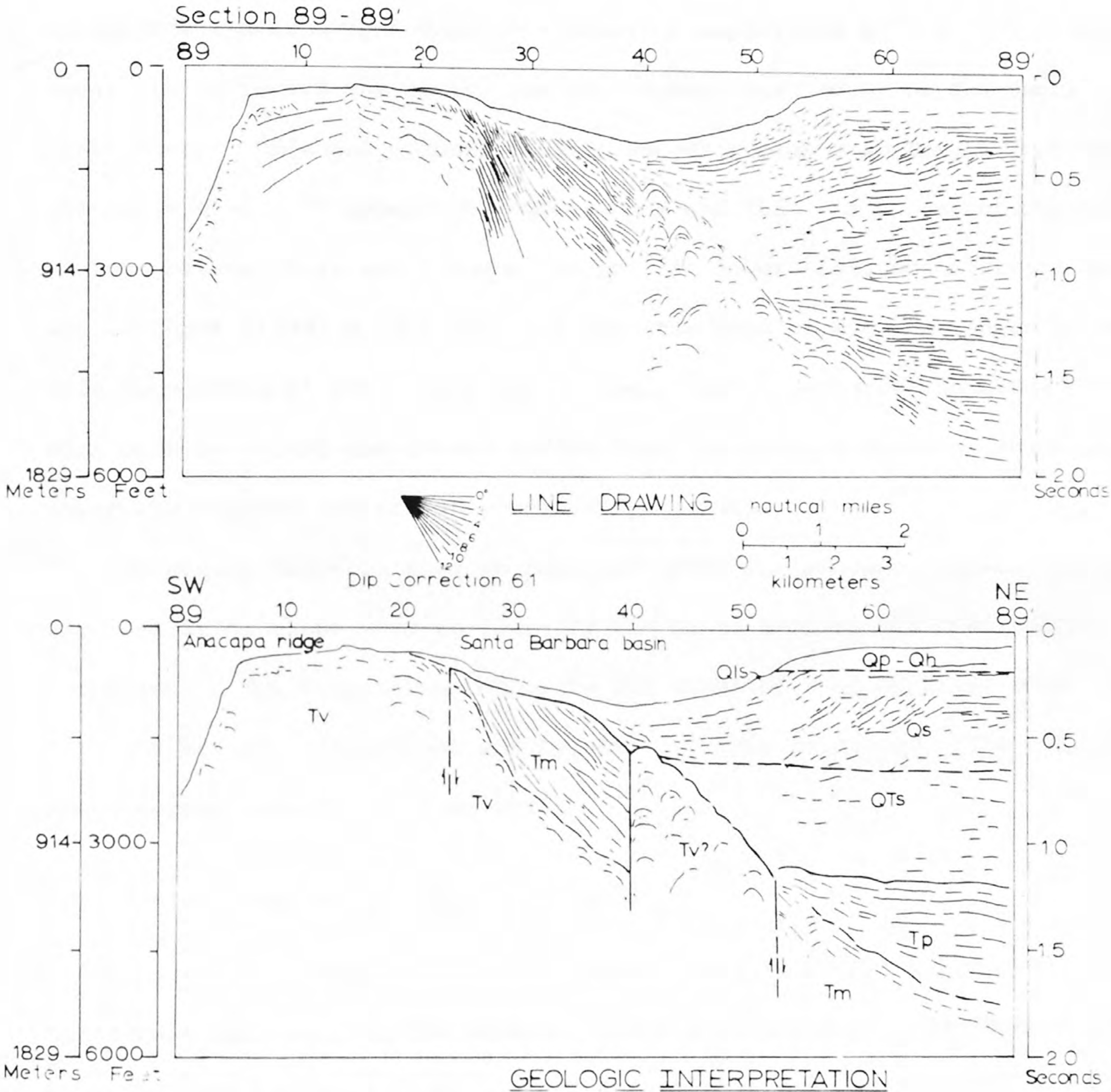

Figure 5. - Line drawing and geologic interpretation of deep penetration reflection profile 89 showing Miocene horst and graben beneath Santa Barbara basin. Symbol explanation same as Plate 2.

represents a distinct, independent phase of deposition by the Santa Clara River, thins toward the north, and is thickest just north of the Santa Clara River. Offshore, Crowell (1952) suggests that Mugu Canyon truncates the seaward edge of upper Pleistocene beds and that the three intervening canyons between Mugu and Hueneme canyons cut lower Pleistocene strata as well. Cohee (1938, p. 20) reported that the head of Hueneme Canyon is cut into formations of Quaternary age; Crowell (1952, p. 64-66) concluded from work done by Poland and others (1948) that the head of Hueneme Canyon cuts upper Pleistocene and probably Holocene deposits.

Acoustical criteria used to identify upper Pleistocene deposits offshore are similar to those used to identify the Santa Barbara and "San Pedro" formations. The Pleistocene deposits are distinguished by their more coherent seismic reflections and by stratigraphic relations. The reflectors are numerous, short, and flat-lying.

Late Pleistocene to Holocene deposits

Nonmarine terrace sands of late Pleistocene to Holocene age overlie the summit terrace atop the central island of Anacapa Islands (Scholl, 1960, p. 131). Marine terrace deposits of late Pleistocene to Holocene age are found in the foothills of the Santa Ynez Mountains around Ventura and in the western part of the Santa Monica Mountains.

Immediately underlying surficial sediments or cropping out on the sea floor of the northern insular shelf of Anacapa Islands is a Holocene terrace deposit. This deposit is identified principally from its topographic configuration and cross-sectional profile. It is acoustically transparent with a few, weak, northward-dipping reflectors.

Alluvial deposits of clay, silt, sand, and gravel fill most of the coastal valleys and flood plains of the Oxnard plain region (Pl. 2) and contain within them the Oxnard aquifer. The alluvium is mainly terrestrial material composed of fluvial deposits and aeolian sands. Throughout the Oxnard plain the alluvium unconformably overlies the upper Pleistocene deposits.

Holocene deposits offshore have acoustical criteria that consist of poorly bedded reflections with little or no seismic coherency. The unit appears to be acoustically transparent with a few flat-lying discontinuous reflectors.

Slumps and Sediment Creep

Many slumps and areas of sediment creep exist along the northern slopes of Santa Barbara and Santa Monica basins (Pl. 2). Slumps have been identified in the seismic records mainly from their geomorphic profiles, characterized by flat tops and hummocky topography (Figs. 6 and 7). Often acoustical hyperbolic reflections will be returned from the distorted material at the base of the slump, and truncated and displaced reflectors may be seen near the top of the slump. Areas of downslope sediment creep have been identified in the seismic profiles by hummocky slope topography and shallow internal reflectors that show intraformational folding (Fig. 6).

Buried Channels

Shallowly buried beneath the offshore Oxnard plain are several discontinuous stream channels and possibly an ancestral submarine (?) canyon (Figs. 7 and 8). An erosional surface appears to lie beneath unconsolidated material of late Pleistocene (?) and Holocene age and contains many cut and fill structures. Some of these structures exhibit sinuous patterns in

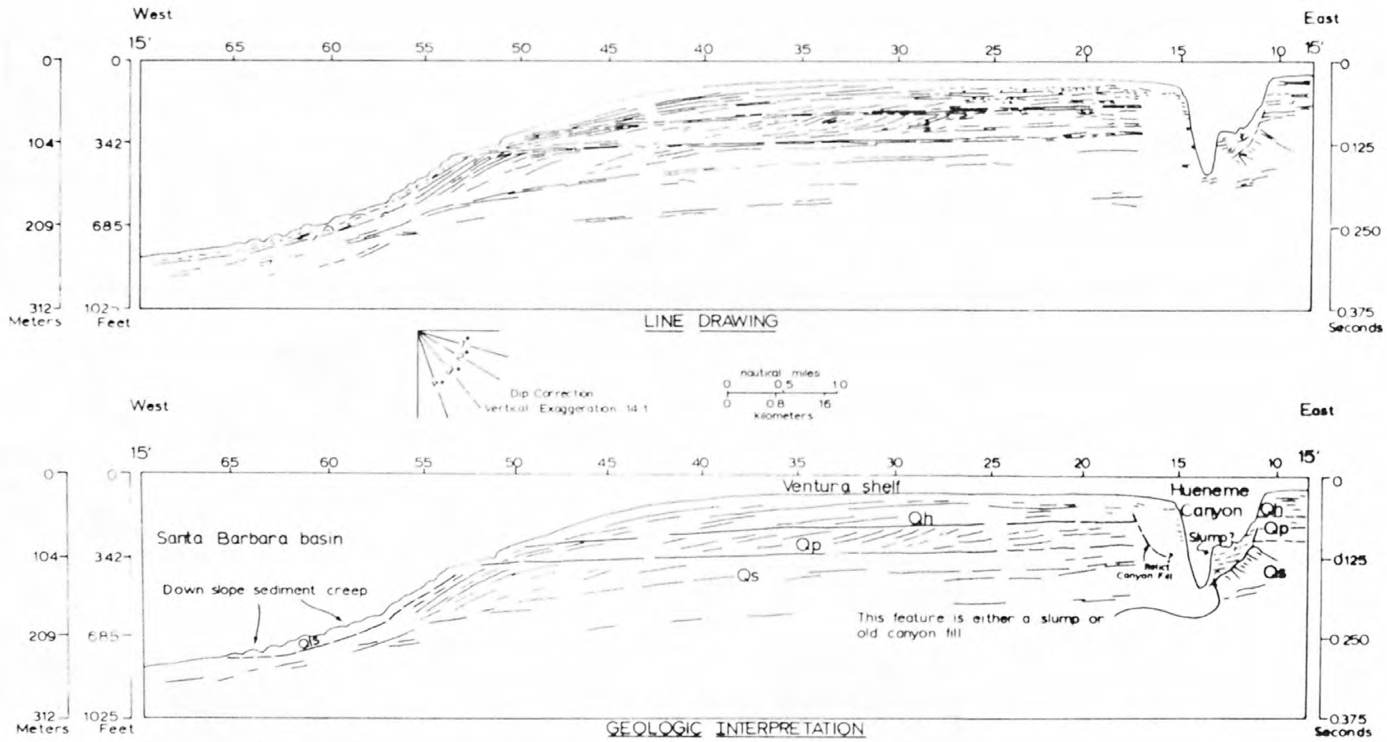

Figure 6. - Line drawing and geologic interpretation of high resolution profile 15 showing Pleistocene unconformities and sediment creep. Symbol explanation same as Plate 2.

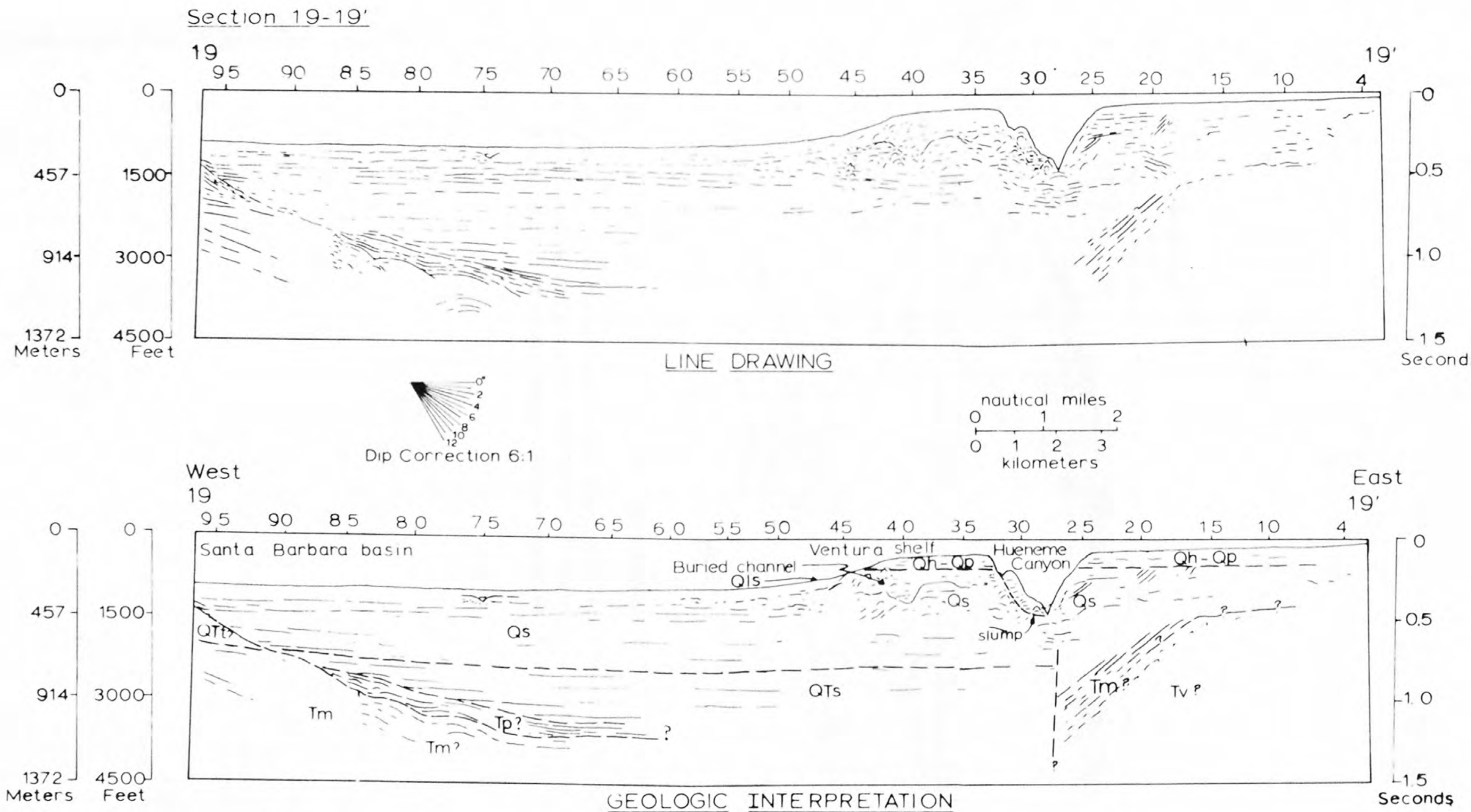

Figure 7. - Line drawing and geologic interpretation of intermediate penetration reflection profile 19. Symbol explanation same as Plate 2.

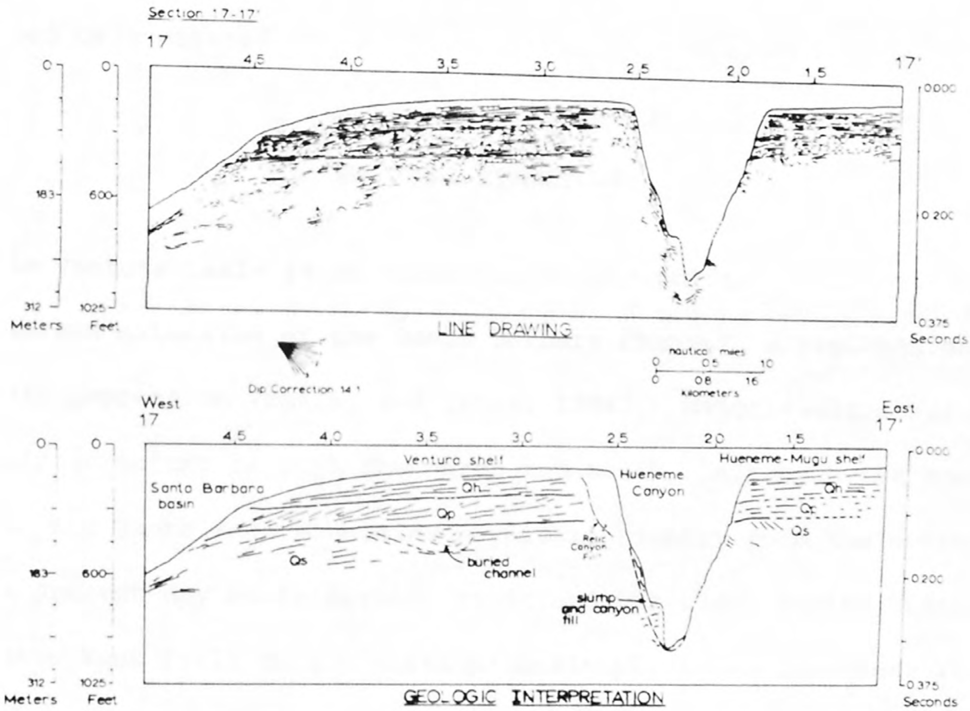

Figure 8. - Line drawing and geologic interpretation of high resolution reflection profile 17 showing Pleistocene unconformities. Symbol explanation same as Plate 2.

plan and overlie truncated strata. These features have been identified principally by their morphology and by acoustical properties characteristic of clastic channel fill material composed of sand and gravel. Acoustically, buried channels are areas of weak or no seismic signal return with acoustic opacity, which suggests that most of the seismic energy is absorbed or scattered.

REGIONAL STRUCTURE

The Ventura basin is an elongate, highly folded synclinorium that forms the eastern extension of the Santa Barbara Channel, a regional east-west tectonic depression (Bailey and Jahns, 1954). Major fault zones bound this tectonic structure on both the north and south. Although the homoclinal beds of the Santa Ynez Mountains physiographically form the northern boundary of the present-day Santa Barbara Basin and the older buried Ventura basin, the Santa Ynez fault to the north probably played an important role in the pre-Cenozoic tectonics of the region and has been defined as the northern structural boundary (Vedder and others, 1969). The Santa Ynez fault is thought to be a major active fault zone with left-lateral oblique slip (Page and others, 1951; Dibblee, 1966). Generally, this fault dips steeply to the south with the south side upthrown approximately 1,500 m to 3,000 m (5,000 to 10,000 ft) relative to the north side (Vedder and others, 1969, p. 8).

The Santa Monica fault system bounds the Santa Monica Mountains on the south, and may extend westward beneath the ocean floor south of Anacapa and Santa Cruz Islands, thus forming the southern structural boundary. The Santa Monica fault system consists of many northeast-trending faults, bounded by the Malibu Coast fault on the north and the Santa Monica fault on the south. Within this system, the Malibu Coast fault, a north-dipping reverse fault, juxtaposes completely dissimilar basement and younger rocks (Vedder and others, 1969).

Beneath the alluvial cover of the Oxnard plain, gently folded Cenozoic strata are broken by numerous faults. In the central part of Ventura basin, north-south compression has produced overturned beds, thrusts, and reverse faults along the flanks of anticlinal ridges. The Ventura Avenue anticline, for example, was formed by north-south compression (Pl. 2) and has fairly uniform limbs that dip at angles from 40° to 50°. The anticline is a petroleum trap and forms the Ventura Avenue oil field.

The Santa Clara and Oxnard synclines and Montalvo anticline are also significant structural features that resulted from north-south compression (Pl. 2). The Santa Clara syncline extends at least 25 km (15.6 mi) westward and eastward from the shoreline. Strata of the "San Pedro" formation of Thomas and others (1954) crop out on the north flank of the syncline; the south flank is covered by alluvium of the Santa Clara River and is partly concealed by older formations thrust over the "San Pedro" beds along the Oak Ridge fault. The Montalvo anticline trends generally west and is structurally complex. Onshore the anticline lies beneath the south side of the Santa Clara Valley, where it is composed of folded strata of the Santa Barbara and "San Pedro" Formations. The crest of the anticline in this area has been eroded and covered by alluvial gravels of the Montalvo (Oxnard Forebay) ground-water basin (Fig. 3; Thomas and others, 1954, p. 20). Offshore, the Montalvo anticline extends into the eastern part of the Santa Barbara Channel and is bounded on the north by north-dipping normal faults (e.g., Pitas Point fault). The Oxnard syncline trends east-west and is a broad seaward-plunging structure extending offshore from between South Mountain and the Camarillo Hills.

Three major faults cut the late Cenozoic strata of the Oxnard plain (Pl. 2). The Oak Ridge fault is a high angle, south-dipping, thrust (?) fault well defined in the subsurface. Onshore, the Oak Ridge fault trends northeastward along the northern flank of the Montalvo anticline and extends from the coast eastward through the Santa Clara River Valley (Mann, 1959). The McGrath fault is not so well located or well defined in the subsurface as the Oak Ridge fault; it is approximately 1 km (.5 mi) south of, and trends parallel to, the Oak Ridge fault. Subsurface data indicate that the McGrath fault extends inland for only about 2 km (1 mi), along the south side of the Montalvo anticline (Mann, 1959; Paschall and others, 1956). The Pitas Point fault is not well defined or well located onshore; water well data suggest that it lies north of Ventura, where it appears to extend eastward from the coast near the mouth of the Ventura River, along the base of the foothills of the Santa Ynez Mountains, and up along the north side of the Santa Clara River Valley (Gonzalez and Slade, 1972). The small hills or "mounds" protruding above the northwest part of the Oxnard coastal plain are the result of folding associated with the faulting in the eastern Santa Barbara Channel.

The Santa Monica Mountains in general are a broad, asymmetrical westward-plunging, anticlinal structure of middle Miocene age. Structural relief of the anticline was increased by diastrophism in late middle Miocene, late Pliocene, and Pleistocene times. Marine and terrestrial (?) strata along the western axis of the anticline have been severely ruptured and segmented by oblique faults and obscured by intrusive rocks (Bailey and Jahns, 1954, p. 95-96; Gamble, 1957). A predominantly north-east fault system has broken the central and western Santa Monica Mountains into a number of large fault blocks (Gamble, 1957). One such fault is the left-slip Sycamore fault (Pl. 2).

The northern Channel Islands form a complexly folded and faulted anticlinal uplift that appears to be a seaward extension of the Santa Monica Mountains (Weaver and others, 1969). However, the geology of the north and south parts of Santa Cruz Island differs markedly, suggesting major displacement of the Santa Cruz Island fault (McLean and others, 1976). Rocks in the southern part of Santa Cruz and Santa Rosa Islands do not seem to be western facies of rocks in the Santa Monica Mountains nor the southern facies of rocks in the Santa Ynez Mountains (Howell and others, 1976).

The eastern part of the Santa Barbara Channel floor has been divided by Vedder, Wagner, and Schoellhamer (1969, p. 9) into subparallel structural segments. The boundaries of these segments are formed by large east-west trending faults, and each segment contains numerous smaller, discontinuous faults and folds that are aligned with the overall structural trend of the region. From information based on seismic reflection profiles, Vedder, Wagner, and Schoellhamer (1969, p.9) were able to show that a zone of faults follows the 200 m (660 ft) contour along the south margin of the deep trough of the Santa Barbara Channel. Most of these faults dip steeply to the north. Another zone of faults exists along the 200 m (660 ft) contour on the north side of the trough; most of these faults dip to the south (Vedder and others, 1969). These workers concluded that these segments are elongate, graben-like features formed in the deeper part of the Santa Barbara Channel. Seismic reflection data indicate that Holocene deposits in the deep central part of the Santa Barbara Channel are locally deformed into small discontinuous folds, in contrast to shelf deposits that are intensely faulted (Vedder and others, 1969, p. 10).

Offshore Geology

The geologic map (Pl. 2) and the idealized stratigraphic cross sections constructed from the seismic reflection data (Pl. 6) show that the eastern Santa Barbara Channel is extensively covered with Quaternary sediments and underlain with possible fresh water-bearing deposits. Stratigraphic units identified in the seismic reflection profiles are described for the three geographic areas that make up the eastern Santa Barbara Channel region: (1) Santa Barbara Basin, including the insular shelves of Anacapa Islands, (2) Ventura shelf, and (3) Hueneme-Mugu shelf (Pl. 2).

Santa Barbara Basin

Beneath the Santa Barbara Basin, over 1,200 m (4,000 ft) of post-Pliocene sediments have been deposited. The total thickness of sediments in the basin is unknown because the maximum depth of seismic penetration in Santa Barbara Basin, about 1,220 m (4,000 ft) beneath sea level, is less than the thickness of the basin sediments. Miocene volcanics and strata are shown in the seismic reflection profiles to exist beneath the insular shelves of Anacapa Islands and dip beneath the post-Miocene sediments of the basin. The southern and southeastern limits of the upper surfaces of middle Miocene Monterey, Pliocene Pico, and uppermost Pliocene-lowermost Pleistocene Santa Barbara formations appear to continue uninterrupted east along the southern subsurface wall of Santa Barbara Basin to Hueneme Canyon, where they swing north and extend across the Hueneme-Mugu shelf to intercept the coast line about 3 km (2 mi) southeast of Port Hueneme (Pl. 3).

Conejo volcanics

Volcanic rocks of the Santa Barbara Basin appear to be offshore extensions of the middle Miocene Conejo volcanics exposed on Anacapa Islands (Pl. 2). They are most readily identified where they crop out on the sea floor of the insular shelves of the Anacapa Islands, and around the eastern tip of the islands where they extend offshore for 2 or 3 km (1 or 2 mi) along a northeast-trending topographic ridge. In the seismic records, the gently undulating surface of the volcanics can be seen underlying stratified Miocene rocks that dip away from the ridge (Figs. 4 and 9). The surface of the volcanic rocks is seen in the high-resolution profiles to crop out along the ridge, where it is very irregular and locally contains small pockets of Quaternary (?) sediments. The volcanic rocks are the acoustical core of the ridge (Channel Islands anticline) that supports the Anacapa Islands. The volcanic surface dips away from the island and ridge crest at an inclination between 10° and 20° on the northeast side (which agrees with attitudes measured by Scholl (1960, p. 129) on Anacapa Islands), and between 2° and 4° on the south side. Juxtaposition of the volcanic rocks with the Miocene Monterey marine sediments appears to be the result of normal faulting along the northeastern limit of the volcanic rocks (Pl. 2).

South of Anacapa Islands, Conejo volcanics seem to form the flat surfaces of wave-cut terraces that are covered with little or no sediment. However, several small sedimentary basins have formed in the volcanics by faulting and erosion. Under the east-central part of the Santa Barbara Basin a volcanic horst has been uplifted to within 152 m (500 ft) of the ocean bottom. The volcanics are overlain by Pleistocene (?) sediments that appear to lap onto the horst (Fig. 5). To the south the volcanics are faulted against Miocene marine sediments and to the north the Pliocene Pico Formation

Section 99-99'

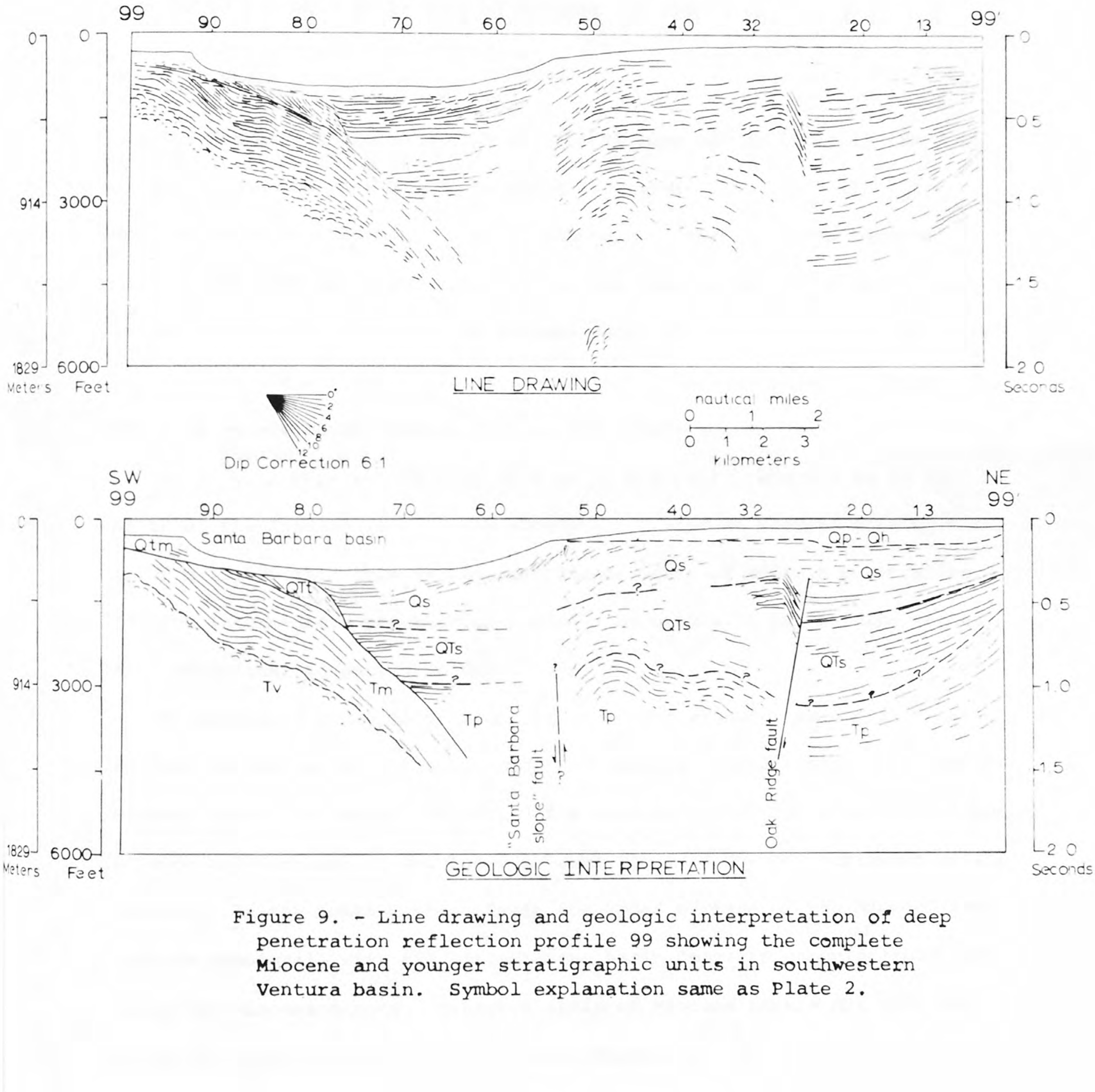

Figure 9. - Line drawing and geologic interpretation of deep penetration reflection profile 99 showing the complete Miocene and younger stratigraphic units in southwestern Ventura basin. Symbol explanation same as Plate 2.

appears to lap onto or is faulted against the horst.

Monterey Shale

The Monterey Shale of middle to late Miocene age is probably the most extensive Miocene unit mapped in the survey area (Pls. 2 and 5). It appears to exist throughout most of the eastern part of Santa Barbara Basin. The best seismic reflection profile example of the Monterey Shale is seen in the lines that cross Anacapa Ridge (Figs. 4,5, and 9) where the strata form the northern limb of the Channel Islands anticline. Here the Monterey strata unconformably overlie the Conejo Volcanics and dip northeast 15° to 20°, an apparent rate of 80 m/km (420 ft/mi). About 5 km (3 mi) north of the Anacapa Islands the Miocene unit lies at a depth greater than 1,100 m (3,600 ft); this is the approximate limit of seismic penetration for the intermediate penetration system. Structure in the bedding varies from monoclinal to gently folded.

Moderately dipping Miocene strata have been eroded into a flat terrace surface on the northern insular shelf of Anacapa Islands (Figs. 4,5, and 9). Miocene strata are about 245 m to 365 m (800 to 1, 200 ft) thick near Anacapa Islands and increase in thickness to over 760 m (2,500 ft) northwest of the islands. In the Santa Barbara Basin the upper surface of the Miocene beds appears erosional, with the post-Miocene basin deposits unconformably overlying the Miocene strata. A narrow strip of Miocene strata may crop out along the lower western wall of Hueneme Canyon (Pl. 2).

Pico Formation

The Pico Formation of Pliocene age is tentatively identified in some of the seismic profiles that cross the Santa Barbara Basin. In these profiles the top of Pico is interpreted to lie 1,220 m (4,000 ft) beneath sea level. The base of the Pico is not observed in the seismic profiles. However, since the maximum seismic penetration in the Santa Barbara Channel region was between 1,830 m and 2,740 m (6,000 and 9,000 ft), the shallowest depth for the base of Pico is probably deeper than 1,830 m (6,000 ft) below sea level.

From beneath the Ventura shelf the Pico dips slightly to the southwest under the Santa Barbara Basin and wedges out against the stratified Miocene of Anacapa ridge. Pico strata are generally flat-lying under the Santa Barbara Basin and unconformably overlie the stratified Miocene sediments (Figs. 4, 5, and 9). The Pico lies well below the sill of the Santa Barbara-Santa Monica basins, and apparently has a conformable or gradational upper surface; therefore, Pico sediments probably did not spill over from the Santa Barbara Basin into the Santa Monica Basin during the time of Pico deposition.

Santa Barbara Formation

Santa Barbara sediments conformably overlie the Pico Formation and unconformably overlie Miocene strata and volcanic rocks near the Anacapa Islands (Pl. 1, Profiles 33 and 35; Figs. 4, 5, and 9). The base of the Santa Barbara Formation can be easily identified as the top of a prominent set of well defined acoustic reflections and may be conformable with the underlying Pico everywhere in the survey area. In the entire eastern Santa Barbara Channel region, a conformable or gradational contact probably occurs between the Santa Barbara Formation and the overlying "San Pedro" formation; however, because of the transitional change in seismic characteristics, this contact is difficult to identify.

The Santa Barbara strata are flat-lying north of Anacapa Islands, under the Santa Barbara Basin, and have a maximum thickness of 700 m (2,300 ft) beneath the northeastern slope of the basin. They thin toward the south and east and wedge out or lap onto the Miocene strata and volcanic rocks of Anacapa ridge.

Pliocene-Pleistocene buried terrace deposit

A buried terrace deposit underlies the northern insular shelf of the Anacapa Islands (Pl. 2). The terrace sediments compose a 115 m (375 ft) thick prism of prograded strata dipping 4° to 13° to the north. The upper surface of this deposit also dips north at an angle of approximately 2° and is buried beneath about 50 m (160 ft) of younger basin deposits. This unit unconformably overlies Miocene strata and is overlain along its distal part by Pleistocene (?) "San Pedro" equivalent deposits that lap onto and wedge out against its frontal surface (Fig. 9). The terrace deposit is therefore presumed to have been laid down sometime in late Pliocene or early Pleistocene time.

"San Pedro" formation

Beneath the Santa Barbara Basin, beds of probable equivalent "San Pedro" age are flat-lying, indicating deposition in a flat-floored basin. Here the "San Pedro" (?) is approximately 120 m to 180 m (400 to 600 ft) thick, but thins and wedges out on Miocene strata and volcanic rocks on the north flank of Anacapa ridge (Fig. 4, 5, and 9). These beds crop out, or are thinly covered by Holocene (?) sediment, along the northeastern slope of the Santa Barbara Basin in water depths greater than 120 m (400 ft).

The basal part of the "San Pedro" unit that lies beneath the Santa Barbara Basin is difficult to identify, probably because it conformably overlies the Santa Barbara Formation. Resolution is poor in the upper 60 m (200 ft) of the deep and intermediate penetration seismic reflection records;

therefore, the upper surface of the "San Pedro" equivalent sediments in the basin is difficult to define, since it may be overlain by 60 m to 100 m (200 to 330 ft) of younger basin fill materials of probable late Pleistocene to Holocene age.

Holocene (?) terrace deposit

Immediately underlying the northern insular shelf of Anacapa Islands is a Holocene (?) terrace deposit (Pl. 2). It is a 100 m (330 ft) thick prism of sediment with gently northward-dipping beds. The deposit unconformably overlies the Monterey Shale. Its distal part appears to grade laterally into the deeper offshore Holocene (?) basin deposits.

VENTURA SHELF

Beneath the Ventura shelf an indeterminate amount of post-Miocene strata is thought to conformably overlie strata of the Miocene Monterey Shale. A maximum depth of penetration for the Ventura shelf area is in the northeastern nearshore region where the top of Miocene (?) rocks is identified at a depth of 2,285 m (7,500 ft) beneath sea level, 8 km (5 mi) west of Port Hueneme and just south of the Oak Ridge fault (Pl. 2; Fig. 9).

Monterey Shale

From the seismic reflection profiles, Monterey Shale is difficult to identify in the Ventura shelf area. The great thickness of overlying post-Miocene sediments in this region tends to attenuate and scatter the seismic energy, and the shallowness of the water creates multiple reflections that interfere with the interpretation of legitimate reflections. However, just south of the Oak Ridge fault, where the Monterey Shale can be seen in the profiles, Monterey strata dip about 15° toward the northeast. North of the fault, Monterey strata probably dip south about 5° to 10°. The offshore projections of onshore well data result in a good correlation with the top of the Monterey. For example, the offshore location where the 2,285 m (7,500 ft) depth to Monterey was calculated is less than 5 km (3 mi) offshore of where E.L. Doheny's well Laubacher #1 (Paschall and others, 1956) gives a 2,438 m (8,000 ft) depth to the top of Monterey (Pl. 3 and 4).

Pico Formation

Beneath the Ventura shelf, just offshore of the western part of the Oxnard plain, the top of the Pico lies at a depth of about 1,220 m (4,000 ft) beneath sea level and can only be seen in the deep penetration, and in the deepest part of the intermediate penetration, seismic records. South of the Oak Ridge fault, about 6.5 km (4 mi) due south of Ventura, Pico strata are over 1,370 m (4,500 ft) thick and are more disturbed from folding than the overlying younger strata (Fig. 9). Here the Pico beds are disrupted by folds and faults, but generally dip south to southwest about 2° to 4° (Pl. 1, Profiles 29 and 31). Just north of the Oak Ridge fault, about 11 km (7 mi) offshore, the Pico is over 760 m (2,500 ft) thick and dips between 6° and 7° toward the south. Depths to the top of the Pico shown in the Cenozoic correlation section of Paschall and others (1956) and determined from unpublished offshore well data are compatible with those depths calculated for the top of Pico from the seismic reflection profiles.

Santa Barbara Formation

The Santa Barbara Formation is over 760 m (2,500 ft) thick in the Ventura shelf area and conformably or disconformably overlies the Pico Formation. It thins to approximately 305 m (1,000 ft) at the southwestern and western limit of the shelf.

Along the north side of the Oak Ridge fault, Santa Barbara deposits are about 460 m (1,500 ft) thick and dip at an angle of 2^{0} to 3^{0} toward the south. These sediments thin toward the north and may crop out on the sea floor near the northern limit of the investigation area (Pls. 1 and 2). Along the south side of the Oak Ridge fault the sediments are tilted, folded, and faulted and dip away from the fault, toward the south, at an angle of 1^{0} to 2^{0}.

"San Pedro" formation

The "San Pedro" formation is very extensive in the Ventura-Oxnard plain offshore region. Beneath the Ventura shelf, north of the Oak Ridge fault, "San Pedro" deposits average approximately 120 m to 180 m (400 to 600 ft) thick, dip 1^{0} to 2^{0} south, and thin toward the north where they may crop out on the sea floor (Pl. 1, profiles 29 and 31, Pl. 2). South of the Oak Ridge fault the "San Pedro" sediments attain a maximum thickness of about 460 m (1,500 ft) and dip south about 1^{0} to 2^{0}.

The basal part of the "San Pedro" formation, beneath both the Ventura and Hueneme-Mugu shelves, is difficult to identify since it lies conformably upon Santa Barbara strata. Strata at the base of the "San Pedro" formation, along the southeastern extent of the unit, appear as "bottomset beds" where the predominantly south-dipping beds flatten out. Near the top of the "San Pedro" unit, reflections in the high-resolution profiles with apparent southerly dips of 10^{0} to 20^{0} are beveled and overlain by flat-lying reflections and appear as "topset beds" (Fig. 6). Generally, the unit may be characterized by prominent, south-dipping reflections that are truncated and covered by "topset beds" and flatten to nearly horizontal "bottomset beds" near the base. Locally, discordant reflections suggest later reworking of the sediments by streams (cut and fill). "San Pedro" sediments crop out, or are thinly covered with Holocene (?) sediment, along the eastern slope of the Santa Barbara Basin and along the southwestern edge of the Ventura shelf at a water depth of about 120 m (400 ft) (Pl. 2).

Unconsolidated deposits of probable late Pleistocene age

Late Pleistocene (?) alluvial deposits of the Oxnard plain are unnamed and the offshore equivalents are referred to in this report as unconsolidated deposits of probable late Pleistocene age or just "upper Pleistocene deposits". Most of the following descriptions of "upper Pleistocene" and "Holocene" deposits are based mainly on data obtained with the high resolution seismic system.

The upper Pleistocene deposits seem to be mostly restricted to the Ventura and Hueneme-Mugu shelves. A depositional angular discordance separates the upper Pleistocene deposits and the underlying "San Pedro" strata. The discordance is well defined in the seismic profiles as a distinct continuous reflection (Fig. 6) that is correlatable with onshore well depths to the discordance (Pls. 4 and 6).

Thicknesses of the upper Pleistocene deposits within the Ventura shelf area are quite uniform, ranging from 50 m to 55 m (160 to 180 ft) thick. The thickest part of the unit is found about 8 km to 9.5 km (5 to 6 mi) west of Port Hueneme where it attains a thickness of about 55 m (180 ft), and then thins toward the north to a thickness of 40 m (130 ft) along the south side of the Oak Ridge fault (Pl. 1). Generally, the strata dip southwest less than 1^{o}.

On the north side of the Oak Ridge fault the upper Pleistocene unit averages about 40 to 45 m (130 to 150 ft) thick and thins to the north. Upper Pleistocene strata here dip about 1^{o} or less to the south.

The upper Pleistocene deposits may be partially responsible for a seismically incoherent zone located near the Ventura shelf margin 8.0 km to 9.5 km (5 to 6 mi) west of Port Hueneme (Pl. 2). The outer seaward limit of this zone, mapped along the Ventura shelf between Hueneme Canyon and the Oak Ridge fault, roughly parallels the coastline and may represent coarse, unconsolidated materials laid down along an ancient strandline (Pls. 2 and 7).

Unconsolidated deposits of probable Holocene age

Offshore Holocene (?) deposits cover most of the ocean floor throughout the entire survey area. They consist of marine, flood plain, and alluvial clastic materials in the nearshore areas where they unconformably overlie upper Pleistocene (?) sediment, and of fine-grained marine materials in the deeper part of the region where they are laid down in the offshore basins and draped over the basins' slopes. Thickness of the nearshore marine and alluvial deposits on the Ventura shelf is quite uniform, averaging about 30 m (100 ft). The thickest parts of these deposits are found along the north side of the Oak Ridge fault and on the shelf between 8.0 km and 9.5 km (5 and 6 mi) due west of Port Hueneme where they increase in thickness to about 45 m (150 ft) (Pl. 7).

On the north side of the Oak Ridge fault, Holocene materials are about 40 m to 45 m (130 to 150 ft) thick, and thin to the north where they wedge out against the upper Pleistocene deposits (Pls. 1 and 2). The southern and western extent of the alluvial material is along the Santa Barbara Basin's landward slope where the deposits crop out or are covered with a thin veneer of Holocene marine sediments at a water depth of 67 m to 73 m (220 to 240 ft). The Holocene deposits thin to the north and are less than 40 m (130 ft) thick along the south side of the Oak Ridge fault.

The erosional surface that separates the upper Pleistocene unit from the overlying Holocene (?) deposits beneath both the Ventura and Hueneme-Mugu shelves is shown on the high-resolution profiles as a distinct, but locally discontinuous, reflection that may be easily correlated with onshore water well data and from one seismic track line to another (Pl. 1; Fig. 6). The boundary between the clastic Holocene alluvial deposits and the more recent Holocene marine deposits is difficult to determine from the seismic data; therefore, no attempt has been made to map the Holocene marine deposits separately.

HUENEME-MUGU SHELF

Subsurface stratigraphy in the Hueneme-Mugu shelf region is seismically more complex and difficult to interpret than in the Santa Barbara Basin and Ventura shelf regions. Near Mugu Canyon, the seismic reflection data indicate that the middle Miocene Conejo volcanics or the Topanga-Vaqueros undifferentiated deposits may be unconformably overlain by a thin wedge of post-Miocene sediments; most strata in this area are of upper Pliocene and lower Pleistocene age. Near the head of Hueneme Canyon, the Topanga-Vaqueros unit and volcanic rocks (?) are thought to be conformably overlain by less than 150 m (500 ft) of post-Miocene strata. About 885 m (2,900 ft) of post-Pliocene strata are thought to conformably overlie the Pico in the central to northwestern part of the Hueneme-Mugu shelf.

Conejo volcanics

The Conejo volcanics beneath the Hueneme-Mugu shelf are difficult to detect in the seismic reflection profiles. In this area a zone of seismic incoherency exists (Pls. 7, 8, 9, 10). The shallowness of the water and a hard ocean bottom create many multiple reflections, and unconsolidated sediments in the shallow subsurface produce random incoherent seismic reflections. A strong reflector between 305 m and 365 m (1,000 and 1,200 ft) below sea level indicates that a hard surface exists at this depth. This reflector could represent a high density bed within the Topanga-Vaqueros undifferentiated unit or the top of the volcanic rocks. Well data obtained from Western Gulf's Laubacher #1 (Paschall and others, 1956) onshore suggest that this surface is on volcanic rocks; this well shows the top of Conejo volcanic rocks about 396 m (1,300 ft) beneath sea level (Pls. 3 and 4). A depth of about 365 m (1,200 ft) to the volcanic rocks just offshore of the western tip of Mugu Lagoon is compatible with this data. Magnetic anomalies within the shelf also indicate the existence of volcanics in this area (Pl. 11). Offshore, the surface appears fairly regular and near Mugu Canyon dips about 5^{0} southwest.

In most parts of the western Santa Monica Mountains a well defined unconformity lies at the base of the Conejo volcanics, where these rocks overlie older sedimentary rocks. In a few areas, however, this unconformity is obscure and the basal Conejo above it contains interbedded sedimentary rocks, some of which are similar in lithology to the underlying beds; this suggests that the volcanics intertongue with the sediments (R.H. Campbell, written commun., 1972). Although intertonguing or interbedding of volcanics and sedimentary strata may occur onshore, this relationship has not been clearly seen offshore in the seismic profiles.

Topanga-Vaqueros undifferentiated unit

Topanga-Vaqueros undifferentiated strata appear to underlie late Pliocene or younger material in the extreme eastern part of the Hueneme-Mugu shelf and in the nearshore shelf area east of Mugu Canyon (Pl. 6). This unit probably also underlies the Conejo volcanics in the northwestern part of the shelf, although this relationship is not visible in the seismic profiles. Beneath the Hueneme-Mugu shelf, strata of the Topanga-Vaqueros undifferentiated unit appear to dip about 3° south and may be over 395 m (1,300 ft) thick. Near Mugu Canyon, and beneath the shelf east of the canyon, the Topanga-Vaqueros undifferentiated unit dips about 1° to the southwest. The unit appears to crop out on this shelf and along the walls of Mugu Canyon about 90 m to 120 m (300 to 400 ft) beneath sea level (Pl. 2). Sandstone samples taken at the head of Mugu Canyon by Emery and Shepard (1945) are probably lithologically similar to the stratified Miocene rocks mapped onshore in the western tip of the Santa Monica Mountains, and support the seismic interpretations. Also, outcrops of the older parts of the Topanga and the top of the Vaqueros formations, along the western tip of the Santa Monica Mountains, are thought to project offshore where they crop out on the sea floor in the vicinity of Point Mugu (R.H. Campbell, written commun., 1972).

A relatively strong, gently dipping reflector underlies the nearshore Mugu area, near the head of Mugu Canyon, at a depth of 30 m (100 ft) below the sea bottom and increases in depth away from land to about 90 m (300 ft) beneath the sea floor on each side of the canyon. This reflector generally dips 2° to 3° west from the western tip of the Santa Monica Mountains at Point Mugu and appears to crop out and form the flat headward floor of Mugu Canyon (Pl. 2). The rock type producing this reflector is unknown but is probably a hard shale member within the Miocene strata.

Monterey Shale

The Monterey Shale was not identified in seismic profiles that cross the Hueneme-Mugu shelf. However, extrapolation of onshore subsurface geology offshore and projection of the subsurface Monterey strata identified in the seismic profiles west and north of the shelf suggest that the Monterey Shale underlies Pliocene and younger strata beneath the northern part of the shelf.

Pico Formation

Pico strata are questionably identified in the seismic reflection profiles across the northwestern part of the Hueneme-Mugu shelf. Between 6.5 km and 8 km (4 and 5 mi) south of Port Hueneme and about 3 km (2 mi) east of Hueneme Canyon, Pico appears to wedge out against Miocene strata and possibly against the volcanic rocks (Pl. 3).

Santa Barbara Formation

Beneath the Hueneme-Mugu shelf, near Hueneme Canyon, the Santa Barbara deposits may range in thickness from 305 m to 455 m (1,000 to 1,500 ft) and probably wedge out to the east. Based on seismic reflection evidence, the Santa Barbara Formation is thought to thin very rapidly toward the south and west where it may unconformably overlie Conejo volcanics and possibly Topanga-Vaqueros undifferentiated strata in the extreme eastern part of the shelf (Pl. 6). The top of the unit lies between 120 m and 150 m (400 and 500 ft) beneath the floor of Hueneme Canyon. No evidence shows the unit cropping out on the sea floor east of Hueneme Canyon.

"San Pedro" formation

Seismic data in the Hueneme-Mugu shelf area suggest that the "San Pedro" deposits dip gently to the south from Hueneme Canyon and thin eastward toward Point Mugu where they probably wedge out against Miocene strata and volcanic rocks (?). This unit is approximately 245 m to 305 m (800 to 1,000 ft) thick around Hueneme Canyon, where it crops out along the walls of the canyon (Pl. 6). Extending southwest from the coastline, "San Pedro" strata thin considerably and probably crop out locally as thin beds along the walls of the intermediate and Mugu submarine canyons and along the slope of Santa Monica Basin (Pl. 2). Criteria used to identify "San Pedro" strata beneath the Hueneme-Mugu shelf are the same as for the "San Pedro" beneath the Ventura shelf, i.e., predominantly south-dipping reflections. The offshore stratigraphic position, thickness, and depth of the "San Pedro" correlates with the stratigraphic position, thickness, and depth established for the "San Pedro" from water well data on land (Pl. 1).

Unconsolidated deposits of probable late Pleistocene age

Beneath the Hueneme-Mugu shelf unconsolidated deposits of probable late Pleistocene age are about 45 m to 60 m (150 to 200 ft) thick, and thin toward Mugu Canyon where they discordantly overlie a very thin "San Pedro" unit and Topanga-Vaqueros undifferentiated unit (?) located on the west side of the canyon. This deposit appears to wedge out to the southwest into a thin zone that crops out along the Santa Monica Basin's northern slope and in the intermediate submarine canyons at water depths between 60 m and 120 m (200 and 400 ft) (Pl. 2). Near the head of Hueneme Canyon, and extending offshore along its eastern wall, probable late Pleistocene deposits are about 50 m to 55 m (165 to 180 ft) thick and can be traced 1.5 km to 3.0 km (1 to 2 mi) offshore until they are lost in the zone of seismic incoherency. Since the late Pleistocene deposits maintain a flat dip throughout most of the area, phantom horizons were constructed and used to continue the deposits through the zone of poor seismic reflectivity to areas on the sea floor where the deposits may crop out (Pl. 2). Criteria used in the interpretation of this unit were identical to those used to identify the upper Pleistocene beneath the Ventura shelf. This unit, like the underlying "San Pedro", also correlates with equivalent age deposits identified from onshore water well data (Pl. 1).

Unconsolidated deposits of probable Holocene age

On the Hueneme-Mugu shelf the marine and alluvial deposits of probable Holocene age are approximately 45 m to 60 m (150 to 200 ft) thick, and thin to the south where they are about 15 m to 20 m (50 to 65 ft) thick. They overlie upper Pleistocene (?), "San Pedro", and Miocene strata (Pl. 2). East of Mugu Canyon thickness of alluvium (?) appears to be between 18 m and 23 m (60 and 75 ft), and thins to the northeast where the material wedges out on an outcrop of Miocene strata (Pls. 2 and 9).

The erosional surface that separates the upper Pleistocene unit from the overlying Holocene deposits beneath the Ventura shelf is lost in the seismically incoherent zone of the Hueneme-Mugu shelf, but has been extrapolated offshore by the use of phantom horizons to areas where it is thought to crop out on the sea floor (Pl. 2).

Unconsolidated channel fill material of probable Holocene age has been identified on the floors of all the submarine canyons that cut the Hueneme-Mugu shelf and slope area. Acoustically the deposits are generally incoherent with few weak, flat-lying, internal, discontinuous reflectors (Pls. 1 and 2).

GROUND WATER GEOLOGY

Fresh water-bearing materials of the Oxnard plain consist of unconsolidated Quaternary sediments laid down on the more consolidated Tertiary rocks. Offshore, the total probable fresh water-bearing materials have been distinguished in the seismic reflection profiles by contrasting acoustical criteria. Unconsolidated water-bearing materials generally have acoustical characteristics of weak, discontinuous reflectors, and the units as a whole are acoustically incoherent. In contrast, the more consolidated Tertiary strata have acoustical characteristics of strong reflectors and are acoustically coherent with good reflectivity.

The base of the probable fresh water-bearing materials is not easily distinguishable everywhere. Where the materials overlie consolidated or crystalline rocks of high density, such as the Miocene strata and volcanics, the contact is easily identified. However, where the materials overlie poorly consolidated to semi-consolidated strata of low density, such as Pliocene sediments, the contrast of acoustical characteristics is poor and the base is more difficult to identify.

Three isopach maps have been constructed from the seismic reflection data obtained in the Ventura-Oxnard plain offshore area and represent thicknesses of various semi-consolidated to unconsolidated, possible fresh water-bearing sediments. One map shows the thickness of Holocene material above a late Pleistocene (?) to early Holocene unconformity (Pl. 7); another shows thickness of upper Pleistocene and Holocene material above a middle to late Pleistocene (?) depositional angular discordance (Pl. 9), and the third shows thickness of all Pleistocene and Holocene sediments that overlie Pliocene and older strata (Pl. 10). Contours on two of the isopach maps (Holocene and upper Pleistocene-Holocene sediment isopach maps) are in seconds, based on two-way seismic travel-time, with a 0.01 second contour interval (Pls. 7 and 9). The contours have also been converted to meters by using a seismic velocity of 1.7 km/sec (5,600 ft/sec), the velocity assumed in the unconsolidated sediments; this gives approximately a 10 m

(30 ft) contour interval. In order to facilitate correlation of the offshore, probable fresh water-bearing material with onshore, fresh water-bearing material as mapped by the State of California (1965), the post-Pliocene sediment isopach map contours are in feet with a 100 foot (30 m) contour interval (Pl. 10). Contours on all isopach maps are solid where depths to the base of the mappable unit are well established and dashed where depths are poorly located or inferred.

The offshore extension of the Mound ground-water basin is a long, linear trough restricted to the north side of the Oak Ridge fault, which it parallels (Pls. 7,9, and 10). Probable fresh water-bearing materials appear to be structurally blocked by, and lap onto, the upper plate of the fault (Pl. 1, Profile 31; Fig. 4). The basin extends offshore for over 22.5 km (14 mi) and the western limit is not within the investigation area. North and south boundaries of the basin are the sea floor where the Santa Barbara Formation appears to crop out, and the Oak Ridge fault, respectively. Width of the basin is about 8 km (5 mi) and the deepest part is located near the Oak Ridge fault, with the basin's deposits thinning and wedging out to the north.

The offshore extension of the Oxnard plain ground-water basin lies south of the Oak Ridge fault and west of Mugu Canyon. The deeper, fresh water-bearing materials of the Santa Barbara and "San Pedro" formations may extend southwest, west of Hueneme Canyon, to Anacapa ridge (Pls. 3 and 10). Shallower late Pleistocene and Holocene deposits in this area appear to extend offshore only to the northern slope of Santa Barbara Basin (Pls. 2 and 10). Beneath the Hueneme-Mugu shelf, the offshore limits of the ground- water basin are more difficult to determine because of the zone of seismic incoherency. The ground-water basin is probably limited by the northern slope of the Santa Monica Basin. The eastern limit of the ground-water basin appears to be about 3 km (2 mi) east of Mugu Canyon where the probable fresh water-bearing materials thin and wedge out against Miocene rocks that crop out on the sea floor (Pls. 2 and 3).

The total offshore ground-water basin has an areal extent of over 760 km^2 (290 mi^2) and consists of the offshore extension of both the Mound and Oxnard plain ground-water basins (Pl. 10). Average thicknesses of probable fresh water-bearing materials in the offshore ground-water basins range from 365 m (1,200 ft) on the shelf areas to about 245 m (800 ft) in Santa Barbara Basin. Potential fresh water-bearing sediments attain a thickness of over 580 m (1,900 ft) in offshore Mound basin and over 550 m (1,800 ft) in offshore Oxnard basin. The volume of post-Pliocene sediments deposited in the offshore southwestern part of the Ventura depositional basin (beneath the Hueneme-Mugu shelf, Ventura shelf, and the southeastern part of Santa Barbara Basin) is estimated at 268 km^3 (67 mi^3). Volumes of upper Pleistocene and Holocene sediments in the region are estimated at 19.3 km^3 (4.8 mi^3) and the volume of Holocene material only is estimated to be 7.8 km^3 (2.0 mi^3).

Thicknesses of the total offshore Quaternary (?) sediments that lie above Pliocene or older rocks agree fairly well with onshore depths to the effective base of fresh water, which is essentially the onshore thicknesses of water-bearing material, as mapped by John Turner (oral commun., 1971) and the State of California (written commun., 1971; Pl. 10). Therefore, the offshore post-Pliocene isopach contours have been connected with the onshore effective water base contours and may be considered as depths from an ocean bottom datum to the base of water-bearing sediments

(Pl. 10). Also, shallow offshore units in several seismic profiles (Pl. 1, profiles 29, 31, 33, and 35) were correlated readily with fresh water-bearing units shown in onshore geologic cross sections constructed by the State of California (1965).

Aquifer-bearing units have been identified from the seismic records and are discussed below. An attempt was made to delineate the offshore extensions of all five major aquifers identified on land: Grimes Canyon, Fox Canyon, Hueneme, Mugu, and Oxnard aquifers. However, only two aquifers, Mugu and Oxnard, could be mapped with any degree of confidence. The other aquifer-bearing formations have been crudely mapped; they were difficult, and locally impossible, to identify in the seismic records. Descriptions of the aquifers onshore are from the State of California (1965).

Grimes Canyon aquifer

The Grimes Canyon aquifer is located in the upper, late Pleistocene part of the Santa Barbara Formation. However, the aquifer could not be separately identified in the seismic profiles and only its approximate stratigraphic position within the Santa Barbara Formation was determined. As mentioned earlier, the base of the Santa Barbara can be easily identified in the eastern Santa Barbara Channel and seems to lie conformably on top of the Pliocene Pico Formation.

In the offshore extension of the Mound ground-water basin the Santa Barbara Formation is gently folded into an asymmetrical syncline and has a maximum thickness of about 460 m (1,500 ft) near the north side of the Oak Ridge fault, where the top of the unit, including the Grimes Canyon aquifer, is buried beneath about 520 m (1,700 ft) of overlying sediment (Pl. 1, Profile 31). Here the Santa Barbara Formation thins to the north, where it probably crops out on the sea floor (Pl. 2).

The Santa Barbara deposit found in the offshore extension of the Oxnard plain ground-water basin appears to extend west and south until it wedges out against Anacapa ridge. The deposit may be locally interrupted by faulting beneath the slope and floor of Santa Barbara Basin, but generally the beds are undisturbed and flat-lying. The deposit has a maximum thickness of about 760 m (2,500 ft) beneath the shelf break northwest of Hueneme Canyon, where the top of the formation, and possibly the Grimes Canyon aquifer, underlie about 365 m (1,200 ft) of younger sediment. Along the deposit's southwestern limit, along the northern flank of Anacapa ridge, the northwestern extent of Santa Barbara strata and aquifer (?) lies at a depth of 215 m (700 ft) below the sea floor (Figs. 4, 5 and 9). Beneath the floor of the Santa Barbara Basin, the Santa Barbara Formation is over 550 m (1,800 ft) thick and its top is buried at an average depth of about 150 m (500 ft).

The extent of the Santa Barbara Formation in the Hueneme-Mugu shelf area is difficult to determine , but the unit appears to thin rapidly toward the south and west, where it may unconformably overlie and wedge out against Miocene rocks. The Grimes Canyon aquifer and Santa Barbara strata probably do not crop out anywhere along the Hueneme-Mugu shelf area or along the landward slope of Santa Monica basin. The top of the Santa Barbara Formation appears to lie at a maximum depth of 365 m (1,200 ft) beneath the western floor of the Hueneme-Mugu shelf and 120 to 150 m (400 to 500 ft) beneath the floor of Hueneme Canyon.

Fox Canyon and Hueneme Aquifers

The Fox Canyon and Hueneme aquifers are located in the "San Pedro" formation. Onshore, the Fox Canyon aquifer is restricted to the lower part of the formation, composed of marine sand, silt, and gravel, and about 180 m (600 ft) thick. This aquifer is the second most extensive fresh water-bearing zone of the Oxnard plain. Separating the Fox Canyon aquifer from the underlying Grimes Canyon aquifer is an aquiclude of variable thickness that has a maximum thickness of about 12 m (40 ft). Beneath the Oxnard plain this aquiclude directly overlies the unconformity that separates the "San Pedro" strata from the Santa Barbara beds. In the southwestern part of the Oxnard plain, near Point Mugu, the strata containing the Fox Canyon aquifer and the aquiclude have been removed by erosion. Younger beds of lower Pleistocene age, northwest of Point Mugu, are similarly affected by this unconformity. From onshore subsurface data in the southwestern Oxnard plain area, the offshore extent of the Fox Canyon aquifer cannot be determined because of structural deformation and probable faulting. In this area the aquifer pinches out in a southerly direction along a bedrock high trending parallel to the coastline (Pl. 2).

The Hueneme aquifer onshore is restricted to uppermost early Pleistocene deposits, the upper part of "San Pedro" deposits of the Santa Clara River, which consist of irregularly interbedded sand, silt, and clay with continuous layers of gravel. The aquifer is separated from the underlying Fox Canyon aquifer by a continuous aquiclude of clay and silty clay about 65 m (215 ft) thick. The Hueneme aquifer has a maximum thickness of about 135 m (450 ft) approximately 4.8 km (3 mi) northeast of Port Hueneme, along the Saticoy-Oxnard-Port Hueneme axis (Pl. 2). The base of the aquifer slopes about 3 m/km (16 ft/mi) to the south and beneath Port Hueneme is buried about 75 m (250 ft) deep. Onshore subsurface data show that the aquifer continues seaward and northward from Port Hueneme. In directions extending away from the Saticoy-Oxnard-Port Hueneme axis, and seaward from Port Hueneme, the aquifer appears to thin. Erosion of upper Pleistocene beds has removed strata containing the Fox Canyon aquifer in the southwestern part of the Oxnard plain and has also removed strata containing the Hueneme aquifer, which appears to be missing near Point Mugu (Pl. 2).

Offshore the strata containing the Fox Canyon and Hueneme aquifers are easily identified. However, no distinct acoustical or structural characteristics are seen in the seismic profiles that could be used to delineate the two aquifers within the "San Pedro" deposits. "San Pedro" strata appear to underlie most of the survey area and lie conformably or disconformably over the Santa Barbara Formation and locally unconformably over stratified and volcanic (?) rocks of Miocene age.

In the offshore extension of the Mound ground-water basin, "San Pedro" deposits appear as an upper member of an asymmetrical syncline. The deposits have a maximum thickness of about 395 m (1,300 ft) just north of the Oak Ridge fault where the top of the formation, including the Hueneme aquifer, is buried beneath approximately 120 m (400 ft) of younger, probable fresh water-bearing material (Pl. 1, Profiles 29 and 31). Like the underlying Santa Barbara Formation, "San Pedro" strata thin to the north where they and the aquifers wedge out against the lower Pleistocene beds and crop out on the sea floor (Pl. 2).

"San Pedro" deposits in the offshore extension of the Oxnard plain ground-water basin appear to extend west and south, west of Hueneme Canyon, to where they wedge out against Miocene rocks along the north flank of Anacapa ridge (Figs. 4, 5 and 9). The top of the formation and the Hueneme aquifer in this area are buried beneath about 60 m (200 ft) of Holocene material. The "San Pedro" deposits have a maximum thickness of about 455 m (1,500 ft) beneath the shelf break west of Hueneme Canyon. Under the Ventura shelf, between the Oak Ridge fault and Hueneme Canyon, the top of

"San Pedro" and the Hueneme aquifer are buried beneath about 60 m (200 ft) of younger sediment. Thickness of the unit beneath the Santa Barbara Basin averages about 90 m (300 ft) and underlies a 60 m (200 ft) thick cover of Holocene (?) materials.

Identification of the "San Pedro" deposits beneath the Hueneme-Mugu shelf is difficult because of the seismically incoherent zone. In this area "San Pedro" strata average between 120 m and 180 m (400 to 600 ft) thick and underlie a 60 m (200 ft) thick cover of alluvial (?) material. The "San Pedro" and the aquifers within the deposit appear to thin considerably southwest and east of the coastline and may crop out along the 120 m (400 ft) contour on the northern slope of Santa Monica Basin (Pl.2). The upper part of the "San Pedro" formation and probably the Hueneme aquifer crop out or are covered by a thin veneer of Holocene sediment along the northern (landward) slopes of Santa Barbara and Santa Monica basins. About 215 m (700 ft) of "San Pedro" strata appear to crop out along the walls of Hueneme Canyon, below a water depth of 120 m (400 ft), and here both the Fox Canyon and Hueneme aquifers may be exposed. A thin upper section of "San Pedro" strata containing the Hueneme aquifer probably crops out in the intermediate canyons; part of this strata is also thought to crop out along the western wall and head of Mugu Canyon (Pl. 2).

The upper Pleistocene-Holocene sediment isopach map gives thicknesses of offshore late Pleistocene and Holocene materials that contain the Hueneme, Mugu, and Oxnard aquifers (Pl. 9). This map shows that the greatest thickness of upper Pleistocene-Holocene sediment in the offshore Oxnard plain ground-water basin is on the shelf immediately west of Hueneme Canyon, where it is over 90 m (300 ft) thick. In the offshore Mound ground-water basin, the map shows that the thickest section is north of, and parallel to, the Oak Ridge fault, where the sediments attain a thickness of over 100 m (330 ft) (Pl. 9).

Mugu aquifer

Onshore, the Mugu aquifer is in the lower part of the upper Pleistocene unit, which is composed of fine to coarse sands and gravels with interbedded silt and clay. This aquifer is relatively flat-lying and is about 80 m (260 ft) thick. The aquiclude of clay and silt separating the Mugu aquifer from the underlying Hueneme aquifer is thin and may even be absent near Port Hueneme. The late Pleistocene deposits that contain the Mugu aquifer lie above an angular unconformity and below a depositional angular discordance (Pl. 1 , Fig. 8).

Offshore, the Mugu aquifer can be delineated as a separate and distinct aquifer in the seismic reflection records. In the offshore extension of Mound ground-water basin the upper Pleistocene sediments attain a maximum thickness of over 45 m (150 ft) near the north edge of the Oak Ridge fault. These sediments thin northward where they wedge out against "San Pedro" strata and crop out on the sea floor (Pl. 1, Profiles 29 and 31; Pl. 2). Approximately 60 m (200 ft) of Holocene materials overlie the upper Pleistocene deposits in the deeper parts of the ground-water basin, and thin to the north.

Upper Pleistocene deposits of the offshore Oxnard plain ground-water basin are present beneath the Ventura and Hueneme-Mugu shelves. Beneath the Ventura shelf, strata containing the Mugu aquifer average about 50 m (160 ft) thick and appear to thin somewhat toward the west, where they crop out along the slope of Ventura shelf at a water depth of 120 m (400 ft). About 50 m (160 ft) of upper Pleistocene deposits crop out along the walls of Hueneme Canyon at a water depth of 75 m to 120 m (250 to 400 ft). The

Mugu aquifer is probably locally exposed here or covered by a thin veneer of Holocene material (Pl. 3).

Beneath the Hueneme-Mugu shelf the upper Pleistocene material thins from about 60 m (200 ft) near Hueneme Canyon to less than 30 m (100 ft) near Mugu Canyon, and is overlain with 45 m to 60 m (150 to 200 ft) of Holocene sediment. The Mugu aquifer appears to crop out along the headward walls of Mugu Canyon at a water depth less than 60 m (200 ft). It also appears to be locally exposed or covered by a thin veneer of Holocene material along the walls of the intermediate canyons and slope of the Hueneme-Mugu shelf, at a water depth between 60 m and 120 m (200 and 400 ft) (Pl. 1, Profiles 33 and 35; Pl. 2). The Mugu aquifer may also be present in a small area east of the Mugu Canyon.

Oxnard aquifer

Onshore, the Oxnard aquifer is composed of permeable strata within the Holocene deposits. These strata consist of fine to coarse sand and gravel separated by lenticular clay and silt beds that form localized aquicludes, especially in the Port Hueneme and Point Mugu areas. In the Oxnard plain ground-water basin, the Oxnard aquifer is about 70 m (230 ft) thick. The underlying Mugu aquifer is separated from the Oxnard aquifer by an impermeable aquiclude of 3 m to nearly 30 m (10 to nearly 100 ft) thick. This aquiclude consists of upper Pleistocene silt and clay and underlies the disconformity that separates the Holocene sediments from underlying upper Pleistocene strata. In the vicinity of Point Mugu the Oxnard aquifer is not everywhere overlain by a continuous aquiclude, and probably is in direct contact with ocean and lagoonal waters. Materials of the Oxnard aquifer were laid down after the latest structural disturbance and show no effects of diastrophism. The Oxnard aquifer is not present in the Mound ground-water basin.

Offshore, the Oxnard aquifer cannot be identified in the seismic reflection profiles as a distinct and separate unit, but the Holocene deposits, which contain the aquifer onshore, can be identified as a distinguishable acoustical unit. This unit unconformably overlies the upper Pleistocene deposits and correlates with the fresh water-bearing materials of Holocene age identified from onshore well data. The Holocene sediment isopach map gives thicknesses of the offshore, Holocene, probable fresh water-bearing materials that contain the Oxnard aquifer (Pl. 7). These materials are generally restricted to the shelf areas offshore of Oxnard plain, where they cover an area of about 608 km^2 (234 mi^2).

Holocene alluvial (?) materials in the offshore extension of the Mound ground-water basin are thickest, about 45 m (150 ft), near the Oak Ridge fault. They thin to the north, where they thinly cover most of the northern part of the survey area (Pl.1, Profiles 29 and 31; Pl.2). In the western part of the survey area, where older strata may crop out on the sea floor, the Oxnard aquifer is probably exposed or covered by a thin layer of Holocene (?) marine sediment (Pl. 2).

In the offshore extension of the Oxnard plain ground-water basin and beneath the Ventura shelf, west of Hueneme Canyon, Holocene alluvial (?) materials are about 45 m (150 ft) thick and extend to the slope, where they may crop out at a water depth of 65 m to 75 m (215 to 245 ft). The Oxnard aquifer may be exposed in this area, along the slope, and is most likely exposed along the walls of Hueneme Canyon. Beneath the Hueneme-Mugu shelf, Holocene sediment ranges in thickness from 60 m (200 ft) near Hueneme Canyon to 15 m (50 ft) near Mugu Canyon. The Oxnard aquifer is probably exposed between the 65 m and 75 m (215 and 245 ft) contours, especially along the walls of Mugu and intermediate canyons (Pl. 2).

In the seismic profiles no reflections could be identified and correlated with the "clay cap" or the semi-perched aquifer that are identified onshore in the shallow water wells that penetrate Holocene materials. The "clay cap" and semi-perched aquifer are probably restricted to only the on-land area of the Oxnard plain.

Areas of Possible Salt Water Encroachment

Possible entrance areas for salt water intrusion into the fresh water aquifers are generally found along the walls of the submarine canyons and along the northern slopes of Santa Barbara and Santa Monica basins (Pl. 3). Submarine canyons incised into the Hueneme-Mugu shelf and slope predominantly cut Pleistocene and Holocene, permeable, water-bearing deposits (Pls. 1, 2, and 6). The lower part of Hueneme Canyon, about 8 km (5 mi) south of its head, at a water depth between 180 m and 395 m (600 and 1300 ft), is cut into early Pleistocene "San Pedro" strata. Hueneme Canyon probably has cut through both the Fox Canyon (?) and Hueneme aquifers in this area and has exposed the aquifers to salt water. As previously indicated, all of the intermediate canyons are cut into upper "San Pedro" material and some may have cut into lower "San Pedro" strata (Pls. 2 and 3). Hueneme and Mugu aquifers may be exposed locally in all of these canyons and may also crop out along the upper northern slope of Santa Monica Basin. In all these areas, salt water probably readily intrudes the aquifers.

Generally, the shallow aquifers of the Oxnard plain offshore region are only locally exposed and many are covered by slump material or Holocene sediments that may act as impermeable barriers. However, slumps at the head of Hueneme Canyon may have opened aquifers to salt water encroachment by forming headward scarps that exposed the water-bearing materials. The future opening of the aquifers to sea water by slumping is possible, especially since the Santa Barbara Channel is a seismically active area.

A crude estimate for the location of the salt water-fresh water interfaces within the "San Pedro" formation (Fox Canyon and Hueneme aquifers) and the Santa Barbara Formation (Grimes Canyon aquifer) was made from a few unpublished offshore well logs of undisclosed sources. The interface within the "San Pedro" deposits is located approximately 6 to 7 km (3.8 to 4.4 mi) from, and is roughly parallel to, the Ventura-Port Hueneme coastline (Pl. 3). The eastern limit of the interface is about 2 km (1 mi) west of and parallel to the axis of Hueneme Canyon.

The interface in the Santa Barbara deposits appears to be located in the Santa Barbara Basin at a maximum distance of 21 km (13.2 mi) offshore, beneath the eastern part of the Hueneme-Mugu shelf (Pl. 3). It roughly parallels Anacapa ridge in the eastern Santa Barbara Basin. The Grimes Canyon aquifer appears not to be intruded by salt water along its eastern extent, since the salt water -fresh water interface is the eastern limit of the Santa Barbara Formation.

A salinity-temperature-depth (STD) study was made in Hueneme Canyon during the first part of April, 1971, by L.E. Schemel of the U.S. Geological Survey, to determine whether any fresh water was "leaking" from aquifers exposed along the walls of the canyon. This study was undertaken after the season's last major rains, and before pumping effectively drew down the recharged aquifers, in order to avoid dilution by fresh water discharge from the mouths of major rivers in the area, and to investigate the aquifers at the peak of recharge. Although the previous winter had been relatively dry, with below-normal precipitation, water wells near the coast producing from the Hueneme aquifer were reported to be exhibiting artesian flow (J.Turner, oral commun., 1971). Seventeen vertically continuous STD stations [1/] and three hydrocast stations were made (Fig. 10).

Every continuous STD profile was digitized at 2 m (6.5 ft), 5 m (16.5 ft), and at succeeding 5 m (16.5 ft) increments below the surface to a total depth of 100 m (328 ft), and then tabulated (Table I). The salinity range varied from 33.4 to 34.0. Five of 178 data points fall outside of this range. The most frequent salinity measurement in the upper 30 m (98.5 ft) was 33.8 ± 0.1. Gorsline (1970) reported a range of 33.5 to nearly 33.8 in the upper 50 m (164 ft) during his survey in early July, 1970. Our range is slightly higher, but since it was collected during early April rather than early July, the discrepancy could possibly be the result of seasonal climatic or current changes in the area, or a difference in measurement, method, and accuracy (L. E. Schemel, written commun., 1971).

Twelve deep samples taken at the hydrocast stations by Niskin bottles showed salinity generally increasing with depth. The salinity range of 34.0 to 34.2 ± 0.05 between 100 m (328 ft) and 250 m (820 ft) depth is the same as that measured by Gorsline (1970) (L.E. Schemel, written commun., 1971).

L.E. Schemel (written commun., 1971) reports that these data do not indicate any large dilution of surface ocean water by fresh water that could be "leaking" from the exposed aquifers along the walls of Hueneme Canyon and the landward slope of Santa Barbara channel.

1/ Vertically continuous STD stations are locations where STD data were gathered without interruption through a 100 m (328 ft) vertical column of water.

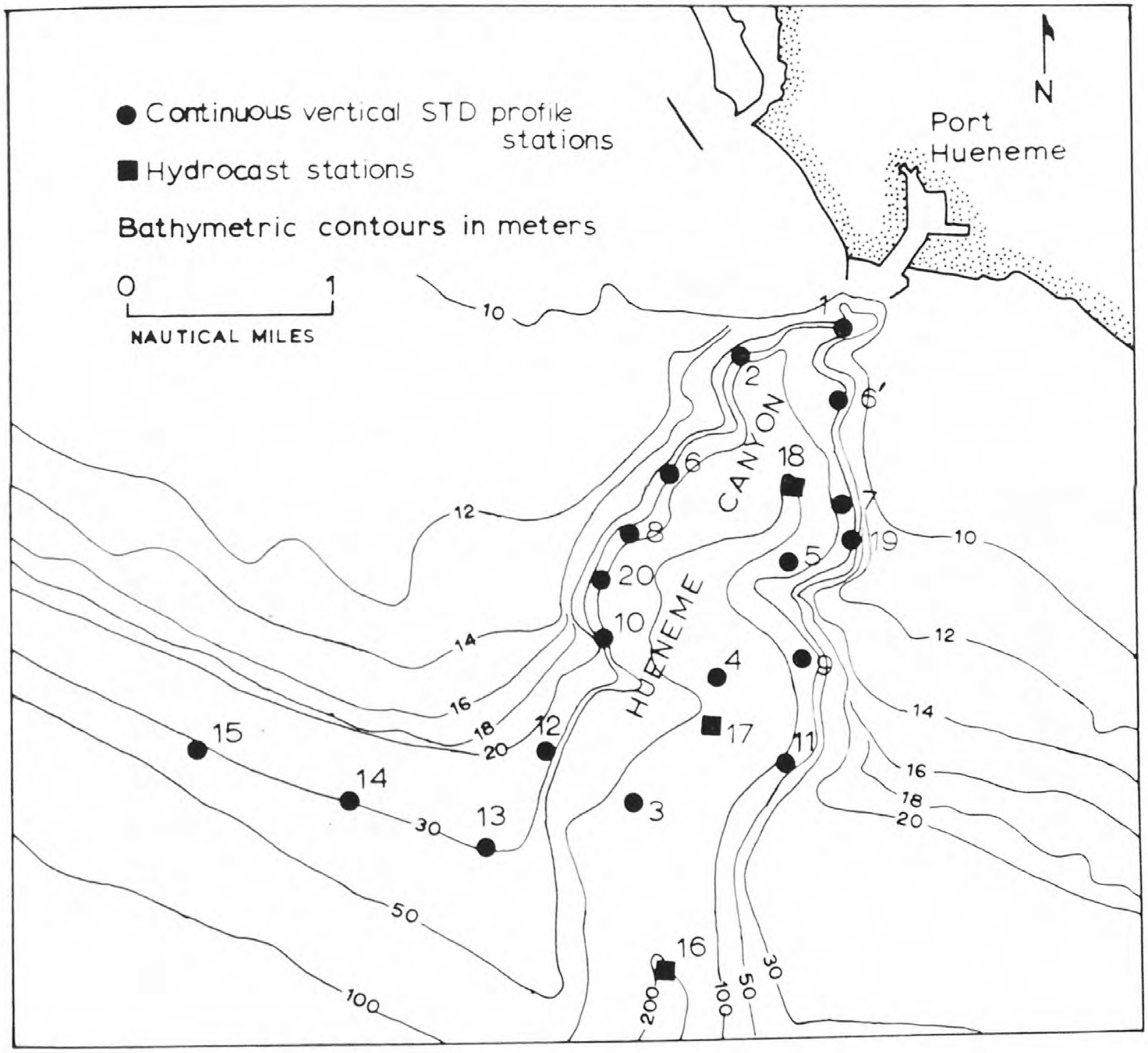

Figure 10. - Map showing locations of salinity-temperature-depth (STD) stations occupied in Hueneme Canyon.

TABLE I

Vertical STD Profiles - April 7, 1971
Hueneme Canyon, California

Station 1

Salinity	Temperature	Depth
33.8	12.5	2
33.8	12.5	5
33.8	12.0	10
33.6	11.5	15
33.6	11.0	20

Station 2

S	T	D
33.7	13.5	2
33.7	13.0	5
33.6	12.5	10
33.6	12.0	15
33.6	12.0	20

Station 3

S	T	D
33.7	13.0	2
33.7	13.0	5
33.7	12.5	10
33.8	12.0	15
33.8	11.5	20
33.7	11.5	25
33.7	11.0	30
33.5	10.5	35

Station 4

S	T	D
33.8	13.0	2
33.8	13.0	5
33.8	12.5	10
33.8	12.5	15
33.8	12.0	20
33.6	11.5	25
33.4	11.5	30

Station 5

S	T	D
33.6	13.5	2
33.8	13.5	5
33.8	13.0	10
33.8	12.5	15
33.6	11.5	20

TABLE I Continued

Vertical STD Profiles - April 8, 1971
Hueneme Canyon, California

Station 6

S	T	D
33.8	12.5	2m
33.8	12.0	5
34.0	11.0	10
33.8	10.5	15
33.8	10.5	20
33.6	10.5	25

Station 7

S	T	D
33.8	13.0	2m
33.8	12.5	5
33.8	12.0	10
34.0	11.5	15
34.0	10.5	20
33.9	10.0	25
33.8	9.5	30
33.8	9.5	35

Station 8

S	T	D
33.8	13.0	2m
33.8	12.5	5
33.8	12.0	10
33.8	11.5	15
33.6	10.5	20

Station 9

S	T	D
33.6	13.0	2m
33.6	13.0	5
33.7	12.5	10
33.7	12.5	15
33.7	11.5	20
33.8	10.0	25
33.8	10.0	30
33.6	10.0	35

TABLE I Continued

Vertical STD Profiles - April 8, 1971
Hueneme Canyon, California

Station 10

S	T	D
33.8	13.0	2
33.8	12.5	5
33.8	12.5	10
33.8	11.5	15
33.8	10.5	20
33.7	10.0	25
33.8	10.0	30
33.8	10.0	35
33.8	10.0	40
33.8	10.0	45

Station 11

S	T	D
33.8	12.5	2
33.8	12.5	5
33.8	12.0	10
33.8	11.5	15
33.9	10.5	20
33.9	10.5	25
33.8	10.0	30
33.8	10.0	35
33.7	9.5	40
33.7	9.5	45

Station 12

S	T	D
33.7	13.0	2
33.8	13.0	5
33.8	12.5	10
34.0	12.0	15
33.8	10.5	20
33.8	10.0	25
33.8	9.5	30
33.8	9.5	35
33.8	9.5	40
33.8	9.5	45
33.8	9.5	50

Station 13

S	T	D
33.7	13.0	2
33.7	12.5	5
33.7	12.5	10
33.8	12.0	15
33.9	11.0	20
33.7	10.0	25
33.7	10.0	30
33.7	9.5	35
33.7	9.5	40
33.7	9.5	45

TABLE I Continued

Vertical STD Profiles - April 8, 1971
Hueneme Canyon, California

Station 14

S	T	D
33.8	13.0	2
33.8	13.0	5
33.8	12.5	10
33.8	12.0	15
33.8	11.0	20
33.8	10.5	25
33.8	10.0	30
33.8	9.5	35
33.8	9.5	40
33.8	9.5	45
33.8	9.5	50
33.8	9.5	55

Station 15

S	T	D
33.8	13.0	2
33.8	13.0	5
33.8	12.5	10
33.9	12.0	15
33.7	10.5	20
33.6	10.5	25
33.6	10.5	30
33.7	10.0	35
33.7	10.0	40
33.7	9.5	45
33.7	9.5	50

Station 16

S	T	D
33.7	13.0	2
33.7	13.0	5
33.7	12.5	10
33.8	12.0	15
33.8	11.0	20
33.8	10.5	25
33.8	10.5	30
33.9	10.5	35
33.9	10.0	40
33.9	10.0	45
33.8	10.0	50

Station 17

S	T	D
33.8	13.0	2
33.8	12.5	5
33.8	12.0	10
33.8	11.5	15
33.8	10.5	20
33.7	10.0	25
33.7	10.0	30
33.7	10.0	35
33.7	10.0	40
33.7	10.0	45
33.7	10.0	50

TABLE I Continued

Vertical STD Profiles - April 8, 1971
Hueneme Canyon, California

Station 18

S	T	D
33.8	13.0	2
33.8	12.5	5
33.8	12.0	10
33.8	12.0	15
33.8	11.5	20
33.7	11.0	25
33.7	11.0	30
33.8	10.5	35
33.7	10.0	40
33.7	10.0	45
33.6	10.0	50

Station 19

S	T	D
33.8	13.0	2
33.8	12.5	5
33.8	12.0	10
33.8	11.5	15
33.8	11.0	20
33.8	10.5	25
33.8	10.0	30
33.7	10.0	35
33.7	10.0	40
33.7	10.0	45
33.7	10.0	50

Station 20

S	T	D
33.7	13.5	2
33.7	13.0	5
33.7	12.5	10
33.7	12.5	15
33.7	12.0	20
33.7	11.0	25
33.7	10.5	30
33.7	10.5	35
33.7	10.0	40
33.7	10.0	45
33.6	10.0	50

TABLE I Continued

Hydrocast samples of salinities April 8, 1971

Station 16		
16-1	250m	34.1
16-2	200m	34.2
16-3	150m	34.0
16-4	100m	34.0
Station 17		
17-1	250m	34.2
17-2	200m	34.2
17-3	150m	34.1
17-4	100m	34.0
Station 18		
18-1	150m	34.1
18-2	125m	34.1
18-3	100m	34.0
18-4	75m	33.9

OFFSHORE STRUCTURES

Structures that have been active from Pliocene (?) through Pleistocene time and that are suggestive of general north-south compression include: 1) the Pitas Point fault, 2) the east-west trending Oak Ridge foldbelt, which is composed of the Santa Clara and Oxnard synclines, the Montalvo anticline, and the Oak Ridge and McGrath faults, and 3) the western Santa Barbara slope fault (Pl. 2). Other subsurface faults mapped in the eastern Santa Barbara channel region include offshore extensions of the Sycamore fault and the Hueneme Canyon fault (Pl. 2).

FAULTS

Pitas Point fault

The Pitas Point fault appears to be a north-dipping reverse or thrust fault; however, the angle of the fault plane cannot be determined and probably has an inclination of 35° or more. Apparent vertical displacement of about 25 m (80 ft), north side up, has occurred along the upper part of the fault since late Pleistocene time, as shown by the displacement of the upper Pleistocene (?) erosional surface (Pl. 1, Profile 29). The fault appears to extend up into the Holocene deposits but does not displace the sea floor.

Based on the seismic reflection data, this fault can be extended west from its intersection of the coastline between the Ventura River and Pitas Point, for more than 20 km (12.5 mi) offshore, to its tie with the Pitas Point thrust of Weaver and others (1969) (Pl. 2). Onshore, the fault has been identified in the subsurface from water well data, and extends east along the base of the foothills of the Santa Ynez Mountains, beneath the alluvium and terrace deposits on the northern side of the Santa Clara river valley (Gonzalez and Slade, 1972) (Pl. 2).

Oak Ridge fault and zone of deformation

The Oak Ridge fault (also called the Montalvo "thrust" fault) is an east-west trending zone of deformation that is the most dominant major structural feature of the eastern Santa Barbara channel (Pl. 1, Profiles 29 and 31; Pl. 2). The most intense faulting and folding are along the more westerly part of the zone (Pl. 2; Figs. 4 and 9). To the west, Pleistocene strata ("San Pedro" formation) appear to be vertically displaced over 135 m (450 ft) with the upthrown block on the south (Pl. 1, Profiles 29 and 31; Pl. 2; Figs. 4 and 9). The fault plane appears to dip southward with an inclination over 35°. Faulting and breakage of the strata in the west change into isoclinal folding in the east; near the present coastline, flat-lying beds show no apparent deformation. Evidently, the latest or longer history of faulting along this feature is in the west, since more intense deformation occurs there. In the east, thrusting may have died out earlier and displacement of strata may exist only at depth.

No surface displacement is observed on the sea floor anywhere above the fault's trace. "San Pedro" strata appear to be the youngest sediments disturbed. Filling of a structural basin north of the fault with Holocene (?) sediments probably occurred after the southern upper block came to rest at its present location. Here the upbowed beds formed a barrier preventing sediments from the north from being transported farther south until filling was complete; this resulted in the accumulation of 45 to 60 m (150 to 200 ft) of sediment.

McGrath fault

Approximately 3 km (2 mi) south of the Oak Ridge fault, the McGrath fault extends offshore for a distance of only about 3 km (2 mi) (Pl. 2). In the seismic profiles the McGrath fault appears to be a south-dipping zone of faulting and folding similar to the Oak Ridge zone. The dip of the fault plane is thought to be greater than 35°. It probably connects on land with the McGrath thrust fault of Weaver and others (1969). The youngest strata disturbed by this fault are of late Pleistocene (?) age. Because the Oak Ridge and the McGrath faults are identical in their structural characteristics, they are probably en echelon faults related to the same tectonic zone. Therefore, the McGrath fault should be included in the Oak Ridge zone of deformation.

Faults in the Santa Barbara Basin

Interpretation of deep intermediate penetration seismic profiles across the Santa Barbara Basin show several faults beneath the floor of the basin (Pl. 2). One fault is located along the southern limit of the Oak Ridge foldbelt in the northern part of the survey area, and is here informally called the "western Santa Barbara slope fault". This fault trends generally east-west and is over 16 km (10 mi) long. The sense of displacement is not known. Another fault located between Anacapa Islands and the northern slope of the basin trends generally east-west for a distance of over 11 km (7 mi) (Fig. 5). The south side is downdropped, but the amount of displacement is difficult to measure; it appears to be over 300 m (1,000 ft). The fault is either a normal or high angle reverse fault with volcanic (?) rocks on the south faulted against Miocene strata (?) on the north.

Two other short faults, each less than 2 km (1 mi) long, were mapped beneath the floor of Santa Barbara Basin (Pl. 2). These faults also seem to have an east-west trend, and one has an apparent vertical offset of an unknown amount with the south side down.

All but one of the faults mapped in the Santa Barbara Basin seem to displace only Miocene and older rocks, since no younger sediments overlying the faults appear to be disturbed. Although the exact age of faulting is unknown, it probably occurred before the Miocene erosional surface was formed, or possibly shortly thereafter. The "western Santa Barbara slope fault" appears to have displaced Pliocene (?) strata.

Faults beneath the northern slope of Santa Barbara Basin

Several discontinuous subsurface faults along the northern slope of the Santa Barbara Basin appear to be tensional features developed along the periphery of the basin by subsidence or downbowing of the basin. Most of these faults, and also those beneath the northern insular shelf of the Anacapa Islands and the Ventura shelf west of Hueneme Canyon, indicate the basinward sides are down relative to the landward sides.

Three faults have been mapped beneath the northern slope of the Santa Barbara Basin (Pl. 2). The fault located just west of Hueneme Canyon has a nearly vertical fault plane separating volcanic rocks on the south from older Miocene (?) strata on the north (Fig. 5). Two shorter faults west of this fault are oriented approximately east-west. Both of these faults appear to have vertical offsets with the south sides down. All faults mapped beneath the northern slope of the Santa Barbara Basin displace Miocene and older rocks.

Faults of the insular shelves of Anacapa Islands

Two faults have been mapped on the insular shelves around the Anacapa Islands. One of these faults, the fault between fixes 20 and 30 in Profile 89 (Fig. 5), appears to be a normal fault (Pl. 2) that trends generally east-west for less than 3 km (2 mi), and brings Miocene strata on the north in contact with Miocene volcanic rocks on the south. Sense of movement is down on the north side and the amount of displacement is unknown. Miocene and older rocks are broken. The other fault trends northwestward and appears to be a normal fault downthrown on the east with probably over 120 m (394 ft) of displacement.

Hueneme Canyon fault

Miocene (?) sedimentary and volcanic rocks can be traced from the axis of Hueneme Canyon eastward beneath the Hueneme-Mugu shelf, but cannot be seen beneath the Ventura shelf west of the canyon (Pl. 1, Profile 33; Fig. 7). Deep penetration (90 kj) sparker profiles across the head of Hueneme Canyon show possible displacement of the acoustic basement, west side down, beneath the axis of the canyon. The truncation of strata and the displacement of the acoustic basement indicate that the Hueneme fault trends northwest-southeast for about 5 km (3 mi) down the canyon (Pl. 2). Displacement along and inclination of the fault plane could not be estimated. The age of faulting is difficult to determine because seismic resolution directly beneath the canyon is poor and deformation of the younger strata immediately above the fault is hard to detect. However, the fault appears not to displace any strata immediately beneath the canyon's floor.

Faults beneath the northern slope of Santa Monica Basin

Strong east-west lineation of the magnetic isoclines (Pl. 11) suggests that a fairly linear structural feature trends east-west beneath the northern slope of the Santa Monica Basin and extends for over 24 km (15 mi) into the Santa Barbara Basin. This may be an older trace of the Malibu Coast fault. However, the deep and intermediate seismic profiles do not indicate a fault in this area.

Sycamore fault

A fault has been mapped at the head of Mugu Canyon from geomorphic and seismic evidence in several high resolution profiles, and from bathymetric data. A block of strata appears to have been downdropped, either by slumping or faulting, along a plane that forms the steep, upper, western headwall of the canyon (Pl. 2). Strata within this block are truncated along the subsurface continuation of the plane, suggesting that this feature is probably a fault and not a stream-cut terrace.

The westward shift of the headward part of the Mugu Canyon axis may be due to resistant rock that locally retarded downcutting of the canyon. Erosion and downcutting migrated westward for a short distance, along a zone of weakened material created by the fault, before curving back downslope to recapture and continue downcutting of the canyon's lower axis (Pl. 2).

Bathymetry suggests that the trend of the fault is east-west, parallel to the headwall of Mugu Canyon; it therefore may be the offshore extension of the Sycamore fault. The Sycamore fault on land has been shown by Gamble (1957) to have left-lateral movement.

Folds

Most of the folding in the eastern Santa Barbara Channel is restricted to the Oak Ridge foldbelt. The foldbelt is about 6.5 km (4 mi) wide and lies mostly north of latitude 34°10'N and south of the Santa Clara syncline (Pl. 2). Fold trends are generally east-west, and the major folds appear to be the offshore extensions of the Santa Clara and Oxnard synclines and the Montalvo anticline. All folds are gentle structures that have flank dips less than 35° (the maximum resolvable dip from seismic data).

Santa Clara syncline

The asymmetrical Santa Clara syncline lies north of and parallel to the Oak Ridge fault and zone of deformation, and extends eastward to a point on shore where it apparently connects with the Santa Clara syncline mapped on land by Mann (1959, Pl. 17). This syncline extends at least 30 km (20 mi) seaward (Pl. 2). Dips on the flank of the syncline are gentle, ranging from 2° to 5°. The syncline appears to deform strata only as young as early Pleistocene, "San Pedro" age (Pl. 1, Profile 29).

Montalvo anticline

The Montalvo anticline offshore is named after its apparent counterpart onshore and is the major fold structure of the offshore region (Pl. 1, Profile 29; Pls. 2 and 6). It bisects the Oak Ridge foldbelt and extends from its presumed connection with the on-land Montalvo anticline at the shoreline in a general westerly direction for over 30 km (20 mi), continuing past the western limit of the survey area; it appears to tie in with the Montalvo trend as mapped by Vedder and others (1969, Pl. 1). All but the youngest (late Pleistocene to Holocene) strata have been folded. Flank dips are gentle on both sides of the anticline, ranging from 2° to 4°. In many places along the crest of the structure the beds flatten to almost horizontal and locally appear to have been beveled by erosion.

Oxnard syncline

The Oxnard syncline is a very gentle, broad fold that has been mapped near the southern boundary of the Oak Ridge foldbelt (Pl. 1, Profiles 29 and 31; Pl. 2). Because the syncline is so broad, the trace of the axis is approximately located. The axis appears to connect with the offshore extension of the axis of the Oxnard syncline as mapped onshore by Mann (1959, Pl. 17) (Pl. 2). It trends generally southwest-northeast, exhibiting dips of 1° or less on both flanks, and gently plunges to the west. Because of the low-angle dips, the oldest strata affected by the structure are difficult to determine from the seismic record.

Other Oak Ridge foldbelt anticlines and synclines

In the western part of the foldbelt an unnamed anticline and syncline lie between the Montalvo anticline and the "western Santa Barbara slope fault" (Pl. 2; Fig. 9). These structures, which exhibit flank dips between 2° and 5°, are identified in the deep and intermediate penetration profiles that cross the foldbelt.

Channel Islands anticline

The Channel Islands anticline, as mentioned by other workers (Gamble, 1957; Scholl, 1960; Vedder and others, 1969; Weaver and others, 1969), refers to the subsurface ridge extending between the west tip of the Santa Monica Mountains and Anacapa Islands. Steep north dips of 10° to 20° on the north side and generally gentle southwest dips of 2° to 4° on the south side typify this asymmetrical anticline. Miocene strata and volcanic rocks are truncated along the crest of the ridge, and the whole structure plunges toward the east (Pl. 2).

Unconformities and Discordances

Four unconformities and one depositional angular discordance have been identified in the seismic profiles and are diagrammatically illustrated on Plate 6. Two unconformities and the depositional angular discordance are shown at intermediate to shallow depths in the deep and intermediate penetration seismic records. The shallowest unconformity seen in the intermediate profiles and one other shallower unconformity are both seen in the high-resolution profiles. The three well-defined unconformities appear to represent hiatuses in middle Miocene, late Miocene, and late Pleistocene or early Holocene times. The angular discordance occurred sometime during middle to late Pleistocene time. A possible unconformity appears to exist at the base of the "San Pedro" deposits beneath the Hueneme-Mugu shelf that overlie the undifferentiated Topanga-Vaqueros formation; thus, this unconformity represents a hiatus between late Miocene to early Pleistocene time (Pl. 6).

Middle Miocene (?) unconformity

In middle Miocene (?) time an erosional surface appears to have developed on the surface of the Conejo volcanics in the eastern Santa Barbara Basin, especially along Anacapa ridge (Pl. 1, Profiles 33 and 35; Figs. 4, 5, and 9). It is an irregular surface unconformably in contact with the overlying Monterey Shale. However, on Santa Cruz Island, where the top surface of the volcanic rocks is exposed, it is an irregular, nonconformable surface with no evidence of erosional truncation (D.G. Howell, oral commun., 1976).

Late Miocene unconformity

In late Miocene time an erosional surface was developed on Miocene strata and possibly locally on the volcanic rocks; it is best developed in the vicinity of Anacapa ridge. Along the crest and shallowly buried flanks of the ridge, folded Miocene strata and, locally, volcanic rocks are truncated at the sea floor or are covered with a thin layer of Holocene (?) sediment. This suggests that the area has either remained emergent or was repeatedly uplifted since late Miocene time. Elsewhere, within the Santa Barbara Basin, an unconformity or disconformity (?) exists between upper Miocene strata and younger sediments. This is probably the result of subsidence of the basin, with renewed deposition producing an angular relationship on the flanks of the basin between upper Miocene and younger strata, and a disconformable relationship between these units in the center of the basin.

The topography of this Miocene surface, as identified in the seismic reflection profiles, is shown on Plate 8. Contours were established from the eroded volcanic surface and truncated Miocene strata around the northeast end of Anacapa Islands, along Anacapa ridge, and on a broad, flat, volcanic (?) rock surface or a high density bed within the Topanga-Vaqueros undifferentiated (?) strata beneath the nearshore area of the Hueneme-Mugu shelf (Plate 8).

The contour map indicates that the surface of the Miocene generally becomes deeper toward the north, reaching over 2,285 m (7,500 ft) just south of the McGrath fault. North of the Oak Ridge fault the Miocene is deeper than the penetration of the seismic records. A general east-west trend predominates except in the vicinity of Anacapa ridge, between the Anacapa Islands and the Santa Monica Mountains. Interruption of the general trend of the contours in this area indicates the presence of Mugu Canyon, which has eroded into and partially removed Miocene strata.

Beneath the easternmost extent of the present-day Santa Barbara Basin, the contours suggest an indiscrete low in the buried topography. This obscure "notch" has a general north-south orientation and lies approximately 640 m (2,100 ft) beneath the sea floor. It may represent a bedrock sill that existed during latest Pliocene-earliest Pleistocene time, when Santa Barbara strata were deposited. At that time the Santa Barbara Basin may have been filled to overflowing, allowing some sediment to spill over the sill into Santa Monica Basin.

Middle to late Pleistocene (?) depositional angular discordance

A depositional angular discordance exists between the "San Pedro" strata of early Pleistocene age and the overlying upper Pleistocene sediments. This discordance appears to be restricted to the shelf area and may grade into a disconformable (?) contact beneath the Santa Barbara Basin. The upper surface of the "San Pedro" formation does not appear to represent an erosional surface, but rather a surface that has been developed by a prograding shelf. Development of "topset beds" over earlier steep "foreset beds", rather than truncation by erosion, probably created the angular discordance. This discordance correlates with the offshore extension of a similar discordance reported in the onshore subsurface by the State of California (1965).

Late Pleistocene (?) to early Holocene unconformity

An angular unconformity exists between late Pleistocene (?) sediments and overlying Holocene (?) material. The unconformity appears to have been created by erosion of upper Pleistocene deposits and is restricted to the shelf areas. It is represented by a strong seismic reflector that is locally discontinuous (Pl. 1, Profiles 33 and 35; Fig. 6). Discontinuity of the reflector probably occurs where the lithologically similar deposits exist above and below the unconformity, a relationship known to occur locally onshore (State of California, 1965).

Buried Channels

Beneath the Ventura shelf just west of Hueneme Canyon, an erosional feature of probably fluvial origin has been identified in the seismic profiles and buried beneath about 120 m (400 ft) of late Pleistocene (?) and Holocene material (Pl. 2; Fig. 7). This feature appears to be a buried stream channel that developed in late Pleistocene and Holocene time. Several shallow, discontinuous, filled, stream channels suggest that a meandering stream or river, probably the Santa Clara River or related tributaries, moved back and forth across the shelf during this time.

Another feature that may represent an ancient buried canyon is closely related to the west edge of Hueneme Canyon (Pl. 2; Figs. 6, 7, and 8). A zone of poor seismic reflectivity characterizes this buried canyon. This feature is believed to be ancestral to Hueneme Canyon and to have formed during late Pleistocene time, because it appears to have cut early Pleistocene "San Pedro" and upper Pleistocene deposits. It probably was buried during latest Pleistocene time.

Submarine Slumps and Landslides

Submarine slumps and landslides in the eastern Santa Barbara Channel are restricted to the submarine canyons of the Hueneme-Mugu shelf (Pls. 1 and 2). The most active slumping appears to be taking place in Hueneme Canyon and the least active in Mugu Canyon. Hueneme Canyon cuts a thicker Pleistocene section than Mugu Canyon. Near its head, Mugu Canyon has eroded consolidated Miocene strata, which are more resistant to undercutting and slumping than the unconsolidated Pleistocene materials. The largest slump of the area is in Hueneme Canyon and is over 3 km (2 mi) wide (Pl. 2). Most slumps exhibit a fairly well-defined headward scarp.

Many of the slumps identified are assumed to represent a mature geomorphic age; only a few appear to be youthful. Generally, the youthful slumps are characterized by sharp profiles, flat tops, backward rotation, and hummocky distorted toes, and mature slumps by hummocky topography at the base of steep slopes. The sharp profiles and scarp-like features produced by slumping are assumed to be blunted and modified in time by current and wave action or sediment deposition. Aging of slumps is also accomplished by repeated sliding. Time required to mature a slump feature is unknown, but is assumed to vary depending upon sediment type and amount of undercutting by canyon-erosive processes. If these assumptions, subjective as they may be, are correct, then the predominance of mature slumps suggests that undercutting and generation of slumps are not particularly active in the canyons today. This lack of activity is also supported by the fact that all the canyons have locally flat floors and are partially filled with sediment. The indication is that the canyons are probably less active now than in the recent past, or that the supply of sediment to the canyons today is greater than the transport of material down the canyons (although locally V-shaped profiles of the canyons' floors suggest active removal of slump material in some places). Mugu Canyon seems to have less accumulated sediment along its floor than the other canyons. The three intermediate canyons may possibly be completely inactive today, as indicated by their relatively gentle topography and accumulated sediments (Pl. 2).

Slope areas between the canyons and along the northeastern slope of Santa Barbara Basin exhibit evidence of sediment creep. Seismic profiles across these areas show a hummocky or gently wrinkled surface topography (Fig. 6). Internal reflections of the first 30 m (100 ft) or less of subsurface section in these areas are distorted and the shallow internal beds appear intraformationally folded and compressed. This suggests that the northern slopes of Santa Barbara and Santa Monica basins are unstable and are experiencing active down-slope creep of surficial material. Creep in this region appears to be a general feature of slopes that average 30 m/km (160 ft/mi) or greater.

Terrace-like Platforms

At the head of Mugu Canyon two levels of terrace-like platforms have been identified (Pl. 2). The deepest platform appears to have formed on the surface of a dense and resistant sedimentary bed within the Topanga-Vaqueros undifferentiated unit. A strong reflector in the seismic profiles can be traced from beneath the shelf on either side of the canyon to the platform surface. This surface essentially produces a relatively flat floor at the headward part of the canyon that gently slopes down-canyon from the 50 m (165 ft) contour to the 100 m (330 ft) contour. Above the deeper platform lies a narrower, less pronounced platform that is restricted to a depth of about 30 m (100 ft).

RESIDUAL MAGNETIC INTENSITIES

The eastern Santa Barbara Channel has an overall east-west trending residual magnetic intensity pattern with local deviations (Pl. 11). This pattern correlates well with the structural grain of the area established from other geophysical data.

Significantly high magnetic anomalies over 200 gammas are located along the Anacapa ridge east of Anacapa Islands and on the Hueneme-Mugu shelf. These anomalies are probably produced from volcanic rocks known to lie close to the surface or to crop out on the sea floor along Anacapa ridge, and are suspected to lie at shallow depths beneath the Hueneme-Mugu shelf. A relatively steep magnetic isoclinal gradient of 50 to 100 gammas and a narrow, shallow magnetic trough are mapped in the northern part of the survey area. These features lie directly over the eastern trace of the Oak Ridge fault and trend in the same direction as the fault. They probably express the faults and folds associated with the Oak Ridge zone of deformation. A gentle isoclinal gradient of about 15 to 20 gammas with a distinct east-west trend exists in the southern part of the survey area. This feature could possibly represent a deeply buried fault that may be the western extension of, or related splay to, the Malibu Coast fault that has been mapped on land east of the survey area. The overall trend of the magnetic contours in the survey area agrees with the regional aeromagnetic data gathered across the Oxnard plain and contoured by Andreasen and others (1964).

SEISMICITY

Earthquakes in the vicinity of the Oxnard plain suggest that the region is seismically active. Sites of reliably located earthquakes compiled by W.H.K. Lee (written commun., 1973) that occurred from 1932 to 1976 are shown on Plate 12 and are listed in Table II.

Detection and determination of locations and focal depths of earthquakes in the eastern Santa Barbara Channel are difficult because the area lies near the edge, or outside of, the network of seismographic stations. Prior to 1969, epicenter locations were probably accurate to ± 10 km (6 mi). After the installation of additional seismographs since 1969, locations have probably been accurate to ± 5 km (3 mi). Focal depths are probably accurate to ± 10 km (6 mi); most appear to be shallow and to lie within 20 km (12 mi) of the surface.

Epicenters are widely dispersed over the region (Pl. 12). No distinct trend or alignment of earthquake epicenters occurs near the trace of any of the faults, although many epicenters are scattered around the Oak Ridge zone of deformation in the northern part of the region. The largest magnitude earthquake recorded in the area prior to 1971 occurred near the Hueneme Canyon fault on March 18, 1957, and had a magnitude of 4.7.

A moderate-sized earthquake of magnitude 5.7 occurred on February 21, 1973, offshore of the Oxnard plain. The earthquake damaged buildings in the town of Oxnard and was followed by several hundred aftershocks that ranged in magnitude from 1.0 to 4.0 and occurred for several days after the main event. The main event and aftershocks are located in a triangular area centered about 3 km (2 mi) offshore (south) of the mouth of Big Sycamore Canyon (Pl. 12). The focal depth of the main shock is about 15 km (9 mi) and focal depths for the aftershocks range from 10 to 11 km (6-7 mi).

Table 2. List of Earthquakes in the Eastern Santa Barbara Channel Region (1932 - 1971)

Origin Time (Greenwich Mean Time)								Focal					Recording
Year	Month	Day	Hour	Minute	Second	Latitude (N)	Longitude (W)	Depth	Magnitude	ERH	ERZ	Q	Station
1936	9	20	2	38	0.00	34°11.00	119° 2.00'	0.0	3.0	0.0	0.0	B	Cal. Tech.
1946	4	27	8	45	42.00	34° 1.00	119° 1.00'	0.0	3.1	0.0	0.0	C	
1949	5	11	21	13	22.00	34° 4.00	119° 3.00'	0.0	2.8	0.0	0.0	C	
1949	6	28	0	31	37.00	34° 4.00	119° 2.00'	0.0	2.7	0.0	0.0	C	
1951	9	9	8	5	7.00	34°10.00	119° 9.00'	0.0	2.6	0.0	0.0	C	
1951	12	24	10	38	46.00	34° 0.00	119° 5.00'	0.0	2.4	0.0	0.0	C	
1953	1	6	21	53	41.00	34° 0.00	119° 1.00'	0.0	3.4	0.0	0.0	B	
1955	12	13	21	13	6.00	34° 2.00	119° 3.00'	0.0	2.8	0.0	0.0	C	
1959	1	7	21	26	16.00	34° 1.00	119° 2.00'	0.0	3.0	0.0	0.0	C	
1960	8	1	2	55	15.00	34°18.00	119° 3.00'	0.0	3.4	0.0	0.0	C	
1961	12	28	4	38	5.80	34° 8.43	119° 4.24'	13.9	2.3	3.2	5.5	C	
1962	1	16	4	3	29.17	34°10.14	119° 5.06'	12.8	3.0	2.7	3.8	B	
1962	2	19	3	25	38.26	34°11.93	119° 8.27'	8.6	2.9	1.3	1.9	B	
1963	5	17	16	59	11.14	34°18.46	119° 8.63'	4.6	3.1	1.5	2.1	B	
1963	8	27	9	31	48.67	34° 8.34	119° 1.14'	-1.9	2.6	0.0	0.0	C	
1965	6	25	6	12	35.55	34° 4.83	119° 0.78'	1.3	2.6	0.0	0.0	C	
1965	7	30	3	1	38.82	34° 5.26	119° 9.37'	13.1	3.4	0.0	0.0	C	
1968	2	5	5	18	0.50	34°13.61	119° 7.92'	7.0	2.5	0.0	0.0	B	
1969	1	10	21	52	45.35	34° 3.03	119° 5.47'	-2.0	3.2	0.0	0.0	B	
1969	4	14	14	26	6.19	34° 7.59	119° 9.52'	8.6	3.3	0.0	0.0	B	
1935	7	2	23	48	0.00	34°12.00	119°10.00'	0.0	3.0	0.0	0.0	C	
1935	7	3	2	15	0.00	34°12.00	119°10.00'	0.0	2.0	0.0	0.0	C	
1947	3	22	22	38	40.00	34° 3.00	119°10.00'	0.0	2.5	0.0	0.0	D	
1948	2	13	21	27	12.00	34°16.00	119°11.00'	0.0	2.9	0.0	0.0	C	
1948	7	20	18	12	3.00	34° 2.00	119°10.00'	0.0	2.6	0.0	0.0	C	
1949	6	19	5	31	53.00	34° 9.00	119°15.00'	0.0	3.0	0.0	0.0	C	
1949	6	19	6	32	54.00	34° 9.00	119°15.00'	0.0	2.7	0.0	0.0	C	
1950	6	5	19	37	28.00	34°12.00	119°14.00'	0.0	3.4	0.0	0.0	C	
1950	6	8	5	9	10.00	34°16.00	119°17.00'	0.0	3.1	0.0	0.0	C	
1950	6	8	9	28	13.00	34°15.00	119°15.00'	0.0	3.9	0.0	0.0	C	
1950	6	10	7	5	0.00	34°15.00	119°15.00'	0.0	2.6	0.0	0.0	C	
1950	8	23	0	47	59.00	34° 9.00	119°19.00'	0.0	3.1	0.0	0.0	C	
1957	3	18	18	56	28.04	34° 7.09	119°13.20'	13.8	4.7	3.1	2.3	B	
1957	3	22	9	50	3.00	34°15.00	119°12.00'	0.0	2.9	0.0	0.0	C	
1962	4	15	7	8	24.51	34°16.09	119°17.58'	4.3	3.1	2.1	3.9	B	

1962	4	19	6	22	34.20	34°17,63	119°14,49'	14.9	3,8	2,1	2.0	B
1962	5	21	4	27	54.00	34° 6,00	119°12.00'	0,0	2,8	0,0	0.0	D
1963	3	17	10	10	53.05	34°19,57	119°11,51'	16,5	2,8	1,6	1.3	C
1965	4	6	0	23	55.28	34°15.58	119°11,34'	2,3	2,7	0,0	0,0	B
1966	10	23	9	24	40.07	34°12,18	119°13,63'	9,7	2.5	0.0	0.0	C
1969	3	11	21	53	6,95	34° 4.09	119°10.93'	10.0	2.5	0.0	0.0	B
1935	8	20	23	12	0.00	34°15.00	119°24.00'	0,0	2,5	0.0	0,0	C
1941	11	28	1	29	40,00	34°12,00	119°20,00'	0,0	3.5	0.0	0.0	C
1944	9	7	16	32	36.00	34° 6.00	119°29,00'	0.0	3.5	0,0	0.0	C
1946	10	11	20	23	44,00	34°14.00	119°29.00'	0,0	2,9	0,0	0.0	C
1950	4	17	15	32	19.00	34°17,00	119°20.00'	0.0	2.9	0.0	0.0	B
1950	8	17	14	37	10.00	34° 9,00	119°21.00'	0.0	2.8	0.0	0.0	B
1950	8	21	14	43	58.00	34° 9.00	119°21.00'	0,0	2,9	0.0	0.0	C
1950	8	22	22	47	58.00	34° 9.00	119°21.00'	0.0	4,2	0.0	0.0	B
1950	8	23	0	39	38.00	34° 9.00	119°21.00'	0.0	2,3	0.0	0.0	C
1950	8	23	0	40	59,00	34° 9.00	119°21.00'	0.0	2.5	0.0	0.0	C
1950	8	23	14	0	10.00	34° 9.00	119°21.00'	0.0	3.0	0.0	0.0	C
1950	8	23	17	50	16.00	34° 9.00	119°21.00'	0.0	2.4	0.0	0.0	C
1950	8	23	22	33	57,00	34° 9,00	119°21,00'	0.0	2.6	0.0	0.0	C
1950	8	23	23	54	16.00	34° 9.00	119°21.00'	0.0	2.5	0.0	0.0	C
1950	8	24	0	27	1.00	34° 9.00	119°21.00'	0.0	3.0	0.0	0.0	B
1950	8	24	1	48	21.00	34° 9.00	119°21.00'	0.0	2,7	0.0	0.0	C
1950	8	24	2	2	24.00	34° 9.00	119°21,00'	0,0	2.3	0.0	0.0	C
1950	8	24	4	15	28.00	34° 9.00	119°21.00'	0.0	3.2	0.0	0.0	C
1950	8	24	4	42	13.00	34°10.00	119°21.00'	0.0	3.4	0.0	0.0	B
1950	8	24	5	3	13.00	34° 9.00	119°21.00'	0.0	2,7	0.0	0.0	B
1950	8	24	7	52	19.00	34° 9.00	119°21.00'	0.0	2.5	0.0	0.0	C
1950	8	24	9	8	48.00	34° 9.00	119°21.00'	0.0	3.3	0.0	0.0	B
1950	8	24	9	31	29.00	34° 9.00	119°21.00'	0.0	2.5	0.0	0.0	C
1950	8	26	11	20	2,00	34° 9.00	119°21,00'	0.0	2.6	0.0	0.0	B
1950	9	7	10	42	53.00	34°10.00	119°21.00'	0.0	3.0	0.0	0.0	B
1952	4	11	19	54	35,00	34° 0.00	119°23.00'	0.0	3,1	0.0	0.0	C
1957	8	3	19	8	7.00	34° 5.00	119°22.00'	0,0	3.1	0.0	0.0	C
1962	8	6	2	17	56.96	34°17.43	119°28.21'	9.8	2.9	2.5	2.7	B
1963	5	6	10	6	52.08	34°13.56	119°28.43'	11.7	2.8	1.3	1.6	B
1966	6	5	0	36	41.93	34°14.72	119°26.07'	14.5	2.0	0.0	0.0	C
1968	1	23	21	22	32.23	34°17.40	119°20.65'	10.0	2.6	0.0	0.0	B
1934	12	19	20	39	0.00	34°17.00	119°30.00'	0.0	2.5	0.0	0.0	B
1940	2	27	11	40	25.00	34°15.00	119°30.00'	0.0	3.0	0.0	0.0	B
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	C

1944	4	12	15	33	10.00	34°16.00	119°31.00'	0.0		4.0					0.0	0.0	C	
1946	12	13	0	40	1.00	34°10.00	119°32.00'	0.0		3.5					0.0	0.0	C	
1947	6	25	18	39	53.00	34°15.00	119°30.00'	0.0		3.1					0.0	0.0	C	
1947	6	25	18	41	21.00	34°15.00	119°30.00'	0.0		3.6					0.0	0.0	C	
1947	6	25	18	48	26.00	34°15.00	119°30.00'	0.0		2.5					0.0	0.0	C	
1947	6	25	20	55	16.00	34°15.00	119°30.00'	0.0		3.2					0.0	0.0	C	
1947	6	25	20	55	54.00	34°15.00	119°30.00'	0.0		3.8					0.0	0.0	C	
1949	4	14	1	46	12.00	34°17.00	119°31.00'	0.0		2.6					0.0	0.0	C	
1952	1	31	20	9	2.00	34°11.00	119°32.00'	0.0		2.6					0.0	0.0	C	
1957	2	16	11	43	50.00	34°18.00	119°32.00'	0.0		3.5					0.0	0.0	C	
1959	10	1	5	52	55.00	34°12.00	119°30.00'	0.0		3.2	No	Gap	DMIN	RMS	0.0	0.0	C	
1970	03	23	13	16	9.17	34° 0.28	119° 6.41'	4.22		1.92	6	189	12.3	0.02	0.3	0.3	Cl	U.S.G.S.
1970	07	24	11	55	27.14	34° 1.09	119° 9.06'	3.61		2.49	9	163	12.9	0.05	0.3	0.5	Bl	
1970	11	22	12	0	31.96	34° 8.35	119° 2.25'	11.52		1.90	5	187	4.1	0.06	1.3	1.2	Cl	
1971	02	01	17	9	50.37	34°15.14	119° 8.71'	2.33		2.50	8	108	17.5	0.10	0.7	0.8	Bl	
1970	08	26	1	8	59.71	34°18.05	119°14.26'	7.90	*	3.61	18	69	16.8	0.40	1.5	1.8	Cl	
1971	01	01	20	36	20.41	34°18.96	119°20.92'	1.99	*	3.12	8	85	10.8	0.38	2.34	99.9	Cl	
1971	05	12	14	51	23.51	34°19.84	119°21.77'	0.21		2.47	6	82	9.1	0.47	4.07	80.7	Cl	
1971	09	27	20	59	3.26	34°17.59	119°21.52'	8.81	*	3.14	11	108	33.9	0.18	1.0	1.1	Cl	
1972	03	15	11	13	13,10	34° 1,00	119° 6,60'	5,40		2,1								
1972	03	18	06	52	43,10	34°15,80	119°11,40'	7,10		2,6								
1972	04	27	04	45	16.90	34° 2.30	119° 5,20'	6,70		3.2								
1972	08	04	09	25	14.60	34° 4.70	119° 3,80'	13,90		2,2								
1972	08	04	19	36	9.80	34° 2,80	119° 8,30'	15,90		2,4								
1972	08	07	10	17	50,30	34°15,60	119°26,60'	9.90		2,7								
1972	08	24	11	41	48,80	34° 4.70	119°14.00'	7,3		2,8								
1972	11	05	11	34	10.80	34°14.10	119°41,30'	15.6		2,8								
1973	02	14	19	08	33,20	34° 4.90	119° 2,30'	13.7		2,2								
1973	04	08	01	36	29,60	33°55,80	119°14,70'	2.8		1,5								
1973	04	17	10	15	14,20	33°55,80	119°13,30'	2.8		2,0								
1973	05	19	22	26	2,50	34°19 70	119°10,30'	2.4		1.9								
1973	05	19	22	35	38.60	34°19,70	119°10.90'	1,6		2.0								
1973	05	30	03	35	47.90	34°20.50	119°20,80'	1,6		1,9								
1973	06	06	03	14	10.90	34°19.00	119°12.50'	5.9		2.5								
1973	08	06	23	29	16.70	33°57.40	119°27.80'	11.0		4,8								
1973	08	06	23	47	35.40	33°58.50	119°27.20'	12.1		1.9								
1973	08	06	23	53	46.40	33°58.40	119°27.20'	12.5		1.9								
1973	08	07	00	16	59,10	33°56.70	119°26.90'	14.0		1.4								
1973	08	07	01	40	50.20	33°58.20	119°26.40'	14.6		1.9								
1973	08	15	02	16	21.70	34°18.70	119°20.00'	[illegible]		3.1								

1973	11	1	22	43	58.90	34°18.10	119°30.70'	13.6	2.0
1974	1	9	20	02	34.63	34°10.96	119° 0.20'	0.06	1.52
1974	1	10	18	41	59.67	34° 3.28	119° 3.60'	14.77	2.13
1974	1	10	22	26	17.52	34° 5.12	119° 1.47'	13.34	1.52
1974	1	12	02	24	10.42	34° 1.71	119° 2,75'	10.78	2.16
1974	1	17	08	00	16.21	34° 6.26	119° 0.66'	8.00	1.48
1974	1	24	03	36	4.32	34° 1.84	119° 0.88'	4.84	0.73
1974	1	27	02	08	22.51	34° 0.80	119° 0.10'	6.87	1.41
1974	2	14	17	44	28.49	34° 5.19	119° 1.23'	13.86	1,21
1974	2	20	05	18	15.14	33°58.83	119°26.61'	13.32	2.14
1974	2	22	12	49	48.46	34°17.32	119°30.84'	10.22	1.80
1974	2	27	12	25	36.49	34°17.07	119°30.90'	10,11	2,33
1974	3	3	16	32	34.95	34° 0.73	119° 0.24'	9.16	2.32
1974	3	3	16	59	22.61	33°59.59	119° 1.69'	9.26	2,34
1974	3	8	13	40	57.92	34°11.96	119°12.48'	5.00	1.42
1974	3	9	14	36	12,42	34° 2.48	119° 0.58'	11.74	0.48
1974	3	12	07	25	37.14	34° 0.01	119° 6.19'	10.77	0,31
1974	3	22	13	36	31.03	34° 3.72	119° 2.58'	9.07	0.48
1974	4	4	08	22	44.64	34°20.06	119°17.99'	5.00	1.57
1974	4	11	03	21	54.81	34° 1.43	119° 0.95'	8.00	0.78
1974	4	14	10	29	48.59	34° 4.64	119° 1.32'	16.86	0.56
1974	4	25	08	23	53.60	34° 1.52	119° 5.93'	9.52	2,79
1974	4	25	08	28	41.96	34° 0.71	119° 6.42'	11.08	1.88
1974	5	4	02	17	16.78	34°11.26	119°12.89'	8.00	0,86
1974	5	21	12	14	53.86	34°19.80	119°20.73'	0.57	1.47
1974	5	22	23	39	48.49	34° 1.10	119° 0.82'	7.52	1.38
1974	6	21	02	05	18.16	34° 5.55	119° 0.14'	16.12	2.27
1974	7	1	05	56	2.04	34° 2.79	119° 0.82'	12.97	0.55
1974	7	6	21	36	59.52	34° 2.43	119° 0.98'	14.05	1.83
1974	7	8	21	23	21.25	34°10.72	119° 0.07'	0.39	1,00
1974	7	9	00	36	3.87	34° 5.61	119° 1.47'	12.00	0.64
1974	7	10	08	44	38.04	34° 5.02	119° 1.19'	14.40	0.45
1974	7	18	22	30	33.37	34°10.76	119° 0.12'	0.25	0.95
1974	7	26	23	27	51.92	34°10.74	119° 0.20'	0.41	1,01
1974	10	8	01	02	13.02	34° 3.00	119° 0.00'	0.91	0.51
1974	10	8	01	08	53.62	34° 2.81	119° 0.08'	2.11	1.73
1974	10	8	01	10	25.93	34° 3.27	119° 0.19'	0.83	0.72
1974	10	8	01	11	10.28	34° 3.01	119° 0.26'	1.05	1.23
1974	10	8	01	13	2.01	34° 2.87	119° 0.11'	1.03	1.05
1974	10	8	01	25	7.34	34° 3.20	119° 0.08'	0.45	0.72
1974	10	8	01	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

1974	10	8	02	15	41.69	34° 1.17	119° 1.11'	3.27	0.52
1974	10	9	09	26	57.54	34° 2.84	119° 0.20'	1.33	1.08
1974	10	9	09	28	9.76	34° 2.96	119° 0.23'	2.78	1.15
1974	10	9	23	33	29.36	34° 0.63	119° 0.23'	4.82	0.66
1974	10	10	12	46	27.48	34° 3.03	119° 0.04'	3.39	0.67
1974	10	12	10	10	39.64	34° 3.24	119° 0.10'	0.77	1.56
1974	10	12	10	25	8.18	34° 2.39	119° 0.30'	0.23	1.47
1974	10	13	18	15	28.26	34° 2.78	119° 0.29'	1.30	0.60
1974	10	14	18	15	28.20	34° 2.44	119° 0.03'	1.23	0.60
1974	10	15	22	40	30.46	34°11.92	119° 1.77'	1.48	1.60
1974	10	16	22	40	30.54	34°10.19	119° 0.00'	0.76	1.59
1974	10	16	15	56	34.41	34° 2.63	119° 1.02'	4.24	0.66
1974	10	18	23	25	24.85	34° 2.67	119° 0.61'	1.41	1.17
1974	10	22	00	06	24.22	34° 3.13	119° 0.16'	0.83	1.11
1974	10	22	22	53	41.60	34° 3.48	119° 0.75'	1.49	0.69
1974	10	29	09	10	48.85	34° 3.75	119° 0.11'	1.14	0.43
1974	11	3	18	59	42.70	34° 5.59	119°14.35'	8.42	1.50
1974	11	12	10	37	54.35	34° 3.46	119° 0.32'	1.96	0.63
1974	11	12	10	11	18.70	34° 1.72	119° 1.02'	8.00	1.76
1974	11	14	11	04	48.52	34° 3.23	119° 0.01'	1.38	1.04
1974	11	19	15	21	37.61	34° 2.21	119° 0.00'	2.07	0.91
1974	12	7	07	12	8.81	34° 3.78	119° 0.25'	3.99	1.02
1974	12	9	22	29	25.64	34°10.62	119° 0.53'	0.23	1.15
1974	12	25	11	16	38.24	34° 1.60	119° 1.41'	7.82	1.89
1975	1	24	11	01	53.73	34° 2.30	119° 0.48'	11.32	2.04
1975	1	30	12	18	52.85	33°58.53	119° 9.04'	5.00	1.44
1975	2	5	15	50	6.92	33°56.81	119°10.97'	5.00	1.49
1975	2	24	13	11	56.77	34°14.79	119°32.07'	5.00	1.14
1975	4	3	16	28	41.00	34°15.62	119° 2.09'	4.00	1.82
1975	4	14	04	55	8.18	34° 2.32	119° 0.49'	18.45	1.66
1975	6	6	13	07	12.94	34°11.57	119°25.28'	5.00	1.54
1975	6	21	20	03	42.36	34° 2.30	119° 1.10'	5.00	1.85
1975	9	26	06	06	34.62	34° 3.31	119° 1.10'	9.44	1.33
1975	10	2	22	36	40.37	34°12.02	119° 5.84'	8.00	1.30
1975	10	3	08	59	17.08	34°11.16	119° 7.05'	7.47	2.18
1975	10	10	07	59	52.90	34°14.95	119°31.48'	14.93	1.75

Analysis of first motions suggests reverse faulting, north side thrust up along a fault plane that dips approximately 50° north and strikes N80°E. The earthquake probably occurred along the Malibu Coast fault that may surface on the ocean floor somewhere along the northern slope of the Santa Monica Basin (W.L. Ellsworth, oral commun., 1973).

GEOLOGIC HISTORY

Rand (1951, p. 52) suggests that the Santa Barbara Basin is the submerged seaward extension of the Ventura Basin. Emery (1960, p. 74-75) feels that both basins are controlled by regional tectonics and that the present Paleogene physiography probably existed prior to this time, as hypothesized by Clarke, Howell, and Nilsen (1975). The subsurface limits of the Miocene, Pliocene, and Pleistocene sediments of the offshore extension of Ventura Basin shown in Plate 3 roughly parallel the physiographic limits of eastern Santa Barbara Basin, which supports the view of Clarke, Howell, and Nilsen (1975). Well records and seismic exploration show that the volume of post-Miocene sediments in Ventura Basin is about 16,100 km^3 (4,025 mi^3).

The seismic reflection data show that the Santa Barbara and Ventura basins have been subjected to basin-forming tectonics - recurrent marginal uplift followed by periods of relative quiescence - throughout the past ten million years (Pl. 13). Beginning in early Miocene time, regional subsidence was accompanied by a marine transgression. This resulted in the deposition of argillaceous sediments of the Rincon Shale as well as sandstone and conglomerate of the undifferentiated Vaqueros and Topanga formations. Land areas were exposed only in the vicinity of the Santa Monica Mountains (Emery, 1960, p. 74-75). Normal sedimentation along the south, east, and northwest margins of the area was interrupted by explosive eruptions and sea floor intrusion of volcanic material. At this time the Conejo volcanics were deposited in rapidly subsiding basins (Gamble, 1957; Vedder and others, 1969, p. 11). Calcareous, phosphatic, and siliceous sediments of the Monterey Shale were deposited during middle and late Miocene time. Land areas were present around Santa Cruz and San Miguel islands and possibly for a short time around Anacapa Islands. Regional uplift in late Miocene time exposed these Miocene and older rocks along the Anacapa ridge. Erosion beveled the rocks and supplied some detritus to a shallow basin to the north (Emery, 1960; Vedder and others, 1969).

From early Pliocene to early Pleistocene time fault blocks restricted seas to narrow and elongate bays. Emergent land areas were present along the north margin of Santa Barbara Channel and to the south along a ridge connecting the northern Channel Islands with the Santa Monica Mountains. A narrow seaway was formed, and erosion of the bounding landmasses supplied sediments to the basins (Emery, 1960, p. 74-75; Vedder and others, 1969, p. 11).

The early and late Pliocene Pico Formation was deposited in a shallow basin north of Anacapa ridge. This ridge restricted the southward transport of debris through the basin. Also at this time small, prograding terraces were built across the insular shelves of Anacapa Islands. The Santa Barbara Formation was deposited during the latest Pliocene and earliest Pleistocene time. During the Pleistocene this debris reached sill level and may have overflowed into Santa Monica Basin. The early Pleistocene "San Pedro" formation was deposited in a nearly filled basin. The sources of sediments for these strata were the Santa Ynez Mountains and the interior areas to the north and east; debris was transported by the Santa Clara River and other smaller streams. A prograded shelf was developed at this time and was probably periodically emergent.

Major tectonism in middle Pleistocene time began to form most of the structural and geomorphic features evident in the region today. After deposition of early Pleistocene deposits, north-south compression folded and tilted beds over a large area and emergent areas were eroded. The

"San Pedro" formation was uplifted, folded, tilted, and faulted; extensive erosion of the formation as well as other Pliocene and early Pleistocene strata took place along high areas. At this time the Santa Clara River sought out its present line of drainage along downfaulted and downfolded strips of soft rock, the Montalvo anticline began to form, and many faults originated. Oxnard plain as it exists today was structurally blocked by the diastrophism, and the two uplifted "mounds" in Mound ground-water basin were probably formed at this time. This diastrophism, resulting in differential movement, faulting, and folding, probably continued into Holocene time (Mann, 1959, p. 11-24 to 11-26; State of Calif., 1965, p. 24; Vedder and others, 1969, p. 11). A hiatus occurred between early and late Pleistocene time, and erosion across most of the Ventura and Hueneme-Mugu shelf area removed some lower Pleistocene and older material. During the beginning of the late Pleistocene the sea probably transgressed to within 9.5 km (6 mi) of the present shoreline, as suggested by the acoustical feature mapped as a possible late Pleistocene strandline (Pl. 2); renewed deposition resulted in deposition of the upper Pleistocene (?) flood plain and alluvial deposits.

The Santa Clara River deposited sand, gravel, and silt on the Oxnard plain in late Pleistocene time. The entire Oxnard plain ground-water basin and the southern part of the Mound ground-water basin were covered by sediments deposited by the Santa Clara River and other streams that formed a broad flood plain over extensively eroded "San Pedro" strata. Moderate earth movement resulting from late Pleistocene diastrophism folded, tilted, and faulted the Santa Clara River deposits, and a period of erosion preceded the deposition of Holocene material (Mann, 1959, p. 11-26; State of Calif., 1965, p. 24).

At the end of the Pleistocene, a regressive sea and local diastrophism caused the shelf areas again to become emergent, and erosion attacked the upper Pleistocene surface. Then, probably at the start of Holocene time, the sea transgressed to approximately the present strandline and the modern marine sediments began to accumulate. The east end of the Santa Barbara Basin is presently filled, and some sediments appear to be transported southeast through an obscure erosional channel at the northeast end of the basin, where they are dumped over the sill into Santa Monica Basin (Pl. 13).

APPENDIX

Geophysical data collected during the survey consist of continuous high-resolution, intermediate, and deep-penetration seismic reflection profiles, and magnetic, bathymetric, wide angle seismic reflection (sonobuoy), and salinity-temperature-depth (STD) data. Details of the equipment, procedures, and methods used in collecting these data are given below.

High-Resolution Seismic System

The high-resolution seismic system utilized two, specially designed, sound sources developed by the U.S.G.S. (Greene, 1970). Between 400 and 800 joules of energy were discharged at a .5 sec fire rate from electrical storage capacitors into the water via two multi-point, sparker-type electrodes. This type of sound source generates a seismic signal with a fundamental frequency of about 500 hz. The sound sources were towed alongside the survey vessel, one about 1 m (3 ft) and the other about 3 m (10 ft) above section. A non-preamplified hydrophone streamer with 20 crystal elements spaced almost 0.15 m (0.5 ft) apart was used to recover the returning seismic energy. The hydrophone streamer was also towed alongside the survey vessel, between the sound sources, about 1.7 m (6 ft) outboard, at a depth of 1.5 m (5 ft) (Fig. 11).

Recovered signals were filtered and then amplified through a Teledyne high-resolution seismic filter-amplifier system. Frequencies recorded were generally between 100 and 590 hz. The seismic data were graphically recorded on a Gifft seismic recorder at a 0.25 second sweep rate.

Intermediate-Penetration Seismic System

The intermediate-penetration seismic system used a single-point sparker electrode called a "ladder", named because of the step-like

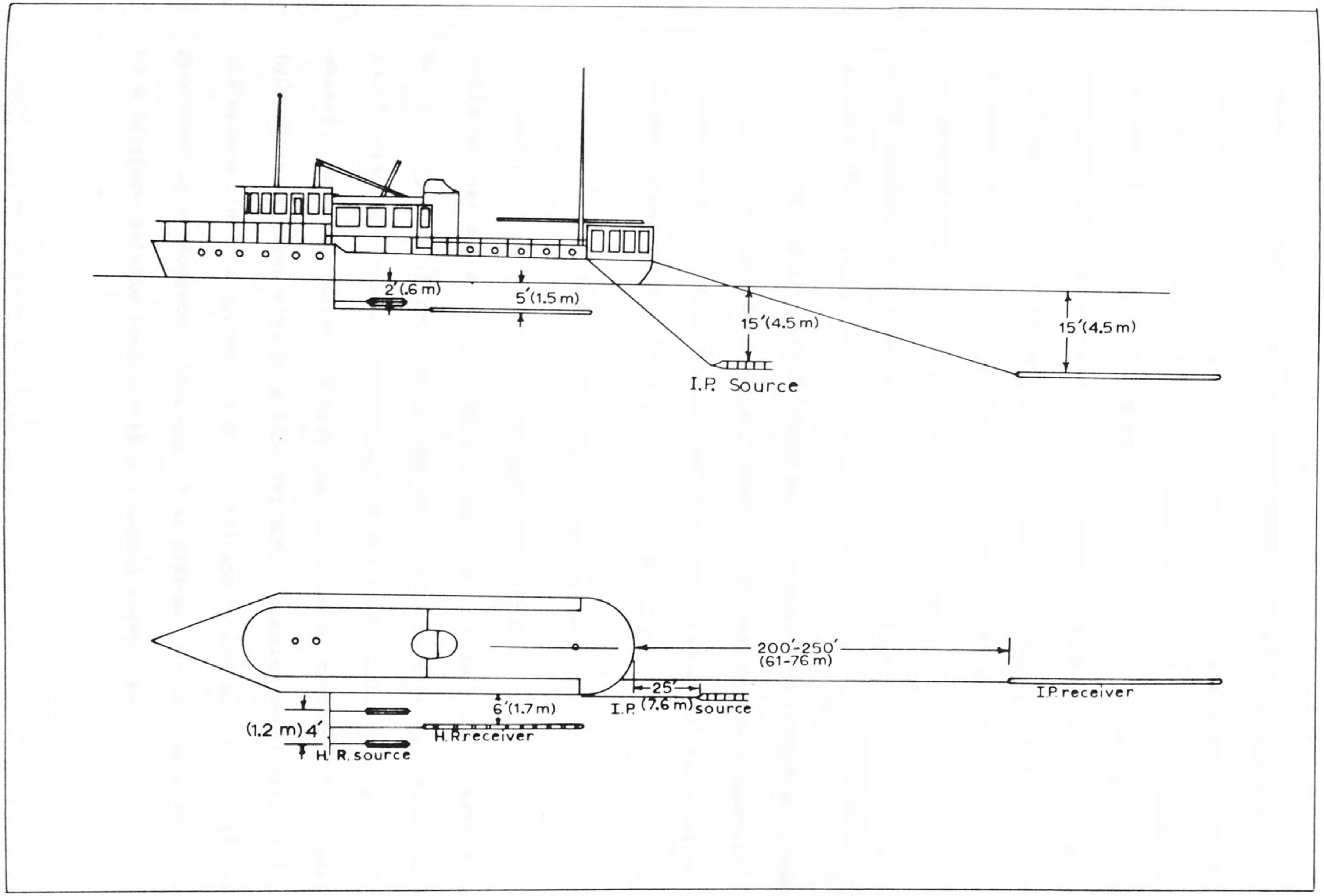

Figure 11. - Illustration of towing arrangement for high resolution (H.R.) and intermediate penetration (I.P.) seismic profiling systems.

braces that separate the positive electrode from the ground wire. A fundamental frequency of 60 to 80 hz is generated by the discharge of 33,000 joules of electrical energy from storage capacitors. This energy was discharged at a 3-second fire rate. A 23 m (75 ft) active section, pre-amplified hydrophone streamer with 50 crystal elements spaced 0.5 m (1.5 ft) apart recovered the returning seismic energy (Fig. 11). The hydrophone streamer was towed 61-76 m (200-250 ft) behind the survey vessel, and about the same distance from the seismic source. Both sound source and hydrophone streamer were towed approximately 4.5 m (15 ft) beneath the water surface (Fig. 11).

Incoming signals were filtered and then amplified through a Geospace seismic filter-amplifier system. Frequencies recorded were generally between 10 and 125 hz. The seismic data were graphically recorded on a Raytheon seismic recorder at a 1.5 second sweep rate.

Deep Penetration Seismic System

Deep penetration seismic profiles were obtained in 1969 by a 160,000 joule sparker system aboard the M/V OIL CITY. Seismic energy with a fundamental frequency of about 60 hz was released every 4 seconds from "ladder" electrodes, each towed approximately 76 m (250 ft) behind the survey vessel. Returning seismic energy was recovered by a preamplified Teledyne hydrophone streamer with 46 m (150 ft) active section consisting of 100 hydrophone elements spaced 0.5 m (1.5 ft) apart. Returning signals were processed by a Geospace filter-amplifier system. Seismic data were recorded on a Raytheon seismic recorder at a 4 second sweep rate.

Magnetometer System

A Varian marine proton precession magnetometer was used to collect the magnetic data. The total magnetic intensity field of the area was continuously measured at a 6 second sampling rate throughout the survey. Raw data from the shipboard magnetometer were processed by a computer and corrected for International Geophysical Reference Field (IGRF).

Fathometer System

Bathymetric data were continuously collected during the survey by a 12.5 hz hull-mounted transducer and graphically displayed on a Gifft facsimile recorder. No corrections were made for tidal changes in sea level.

Wide-Angle Reflection Data

Apparent interval velocities of subsurface sediments were determined for the nearshore part of the eastern Santa Barbara Channel by the sonobuoy variable-angle reflection technique. Both the high-resolution and intermediate-penetration sound sources were used to produce the acoustical energy. Military type AN/SSQ-38 and AN/SSQ-41 sonobuoys were used to recover the reflected and refracted seismic energy. A sonobuoy may contain one or several hydrophones suspended from the buoy by a cable 20 to 100 m (65.5 to 328 ft) long. Sea-water activated batteries supply power to the sonobuoy's radio and have a life expectancy of 6 hours. The sonobuoy is programmed to sink after either 3 or 6 hours. Variable angle reflection data are received and transmitted by radio from the passive expendable sonobuoy, launched while the survey vessel is underway. The data transmitted by the sonobuoy are received on a tunable FM transmitter-receiver system and recorded on a Gifft or Raytheon seismic recorder.

A time-distance graph is essentially produced on the recorder from the sonobuoy-transmitted data. Determination of interval velocities can be calculated by several methods, as described by Dix (1955), Katz and Ewing (1956), Houtz and Ewing (1963 and 1964), Knox (1965), and Clay and Rona (1965). Two methods of calculations for interval velocities were done for this study. One method utilizes a T-X to T^2-X^2 conversion chart where times picked along a travel time curve are plotted on the graph and interval velocities are read directly from the graph. The other method consists of calculation done with the formula:

$$\gamma = \frac{X^2}{2To\Delta t}$$

where:

γ = interval velocity

X = horizontal distance between start of run and an arbitrary later time

To = initial reflection time to reflector of interest

ΔT = difference in initial reflection time of reflector of interest and reflection time at X distance away.

For a more complete description of velocity measurements with a sonobuoy, the reader is referred to articles by LePichon and others (1968) and Houtz and others (1968).

Six sonobuoy runs were made in the survey area near the end of the investigation when all continuous seismic reflection data had been collected and could be used for determining the most desirable location for the runs. All sonobuoy runs were made in areas where the ocean bottom and underlying reflectors are flat-lying. Three runs were made with the high-resolution sound source to determine interval velocities of the shallow, unconsolidated, subsurface sediments and three runs were made with the intermediate-penetration sound source to determine interval velocities of the deeper strata.

Navigation

Precision navigation was done under contract by Offshore Navigation, Inc., using a Hirex marine navigation system. Hirex uses frequencies in the X-band radar range, specifically 9300-9500 mhz, and has a positioning accuracy of ± 7.5 to 15 m (25 to 50 ft). This system consists of two shore-based slave stations and one shipboard master station. Navigation fixes were taken every 305 m (1000 ft) along a traverse, and correlating location marks were printed on the geophysical records every 1,525 m (5,000 ft). Processed navigation data were plotted at a scale of 1:48,000 with positions and time plotted every 1,525 m (5,000 ft).

STD System

A CM^2 Inc. Model 516 STD (Salinity-temperature-depth) conductivity meter was used by L.E. Schemel of the U.S. Geological Survey to obtain instantaneous STD data within Hueneme Canyon along part of the northern Santa Barbara Basin slope. The continuous vertical STD stations were made from the R/V VANTUNA during April 7 and 8, 1971. Salinity measurements were made in the range of 0-20 0/00 of chloride ion concentration with an accuracy of ± 0.1 0/00. Temperature was measured in the range of -2^{o} to $32^{o}C$ at a ± $0.1^{o}C$ accuracy. Depth range was from 0-100 m (0-328 ft) with an accuracy of ± 1 m (3.3 ft).

This system exhibits slight thermal hysteresis when the probe penetrates steep thermoclines, which is probably caused by the large size and consequent large heat capacity of the conductivity probe. This hysteresis is eliminated by decreasing the rate of descent. Deviations of ± 0.2 0/00 were noted on the descent and ascent of the probe through the most intense layer of the thermocline during the March 8, 1971 cruise. Data were averaged to obtain the most probable salinity.

Three hydrocast stations were made in the deeper parts of Hueneme Canyon, over the axis, and *in situ* water samples were taken with 8-liter PVC Niskin bottles. Salinity was measured several days later in a shore-based laboratory with a Bisset-Berman induction salinometer that gave an accuracy of ± 0.05 0/00. Maximum depth ranged from 150 to 250 m (490 to 820 ft). Four Niskin bottles were used on every cast with distances between the bottles varying from 25 to 50 m (80 to 160 ft).

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