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Late Cenozoic History of the Santa Monica Bay Area: California

by Thomas Richard Nardin

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LATE CENOZOIC HISTORY OF THE SANTA MONICA BAY AREA: CALIFORNIA

by

Thomas Richard Nardin

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ABSTRACT

Geophysical and geological survey methods, including high resolution (3.5 kHz) and deeper penetrating air gun seismic-reflection records, magnetometer profiles, and jet core data have been used to study the Late Cenozoic history of Santa Monica Bay.

Late Cenozoic strata are divided into preorogenic and postorogenic units. In the southern one-half of the bay, preorogenic strata consisting chiefly of shale have been folded into three northwest-trending *en echelon* anticlinoria. Immediately north of Redondo Submarine Canyon, the central anticlinorium has been depressed in a graben and buried beneath a sequence of postorogenic sands and silts. The graben facilitated the initial development of the canyon during late Pleistocene time. West-southwest-trending faults bound the graben and have been active during the Late Quaternary. Dextral shear along the northwest-trending Palos Verdes fault during middle to early late Pliocene time is probably responsible for the formation of the anticlinoria and the faults. However, the absence of significant displacements in postorogenic strata beneath the inner shelf indicates that the Palos

Verdes fault has been relatively inactive in the area north of the canyon since latest Pliocene time. It seems likely, therefore, that the Late Quaternary uplift of the Palos Verdes Hills also occurred along the Redondo Canyon fault. Quaternary displacements along faults along the San Pedro Escarpment also are suggested.

Beneath the narrow shelf adjacent to the Santa Monica Mountains the preorogenic unit is lithologically variable and is similar to Miocene strata cropping out south of the Malibu Coast fault. These preorogenic strata form a southward dipping homocline transected by a west-southwest-trending normal fault which also shows Late Quaternary displacements.

Examination of high resolution profiles indicates that numerous hydrocarbon seeps are present in the bay and are directly related to geologic structure. Hydrocarbons have also been detected in Late Quaternary sediments.

INTRODUCTION

General Statement

The Santa Monica shelf forms an offshore extension of the western margin of the Los Angeles Basin (Fig. 1), and as such has been the site of significant tectonic activity since middle Miocene time. Until recently, the nature and timing of this activity could only be inferred from onshore geology. That is, hypotheses concerning the geologic evolution of the shelf were necessarily based on assumed offshore extrapolations of onshore structures. Offshore extrapolations, however, are subject to uncertainty because the shelf is situated at the intersection of two major structural provinces, the Peninsular and Transverse Ranges, and may contain transitional features. Moreover, inasmuch as the tectonic history of the Palos Verdes Hills has differed, at times, from the remainder of the basin's western margin, assumptions regarding the existence of the Palos Verdes fault and anticlinorium beneath the shelf become particularly critical to the accuracy of proposed shelf histories. The purpose of this investigation, therefore, is to delineate the salient structural and stratigraphic features beneath the shelf and

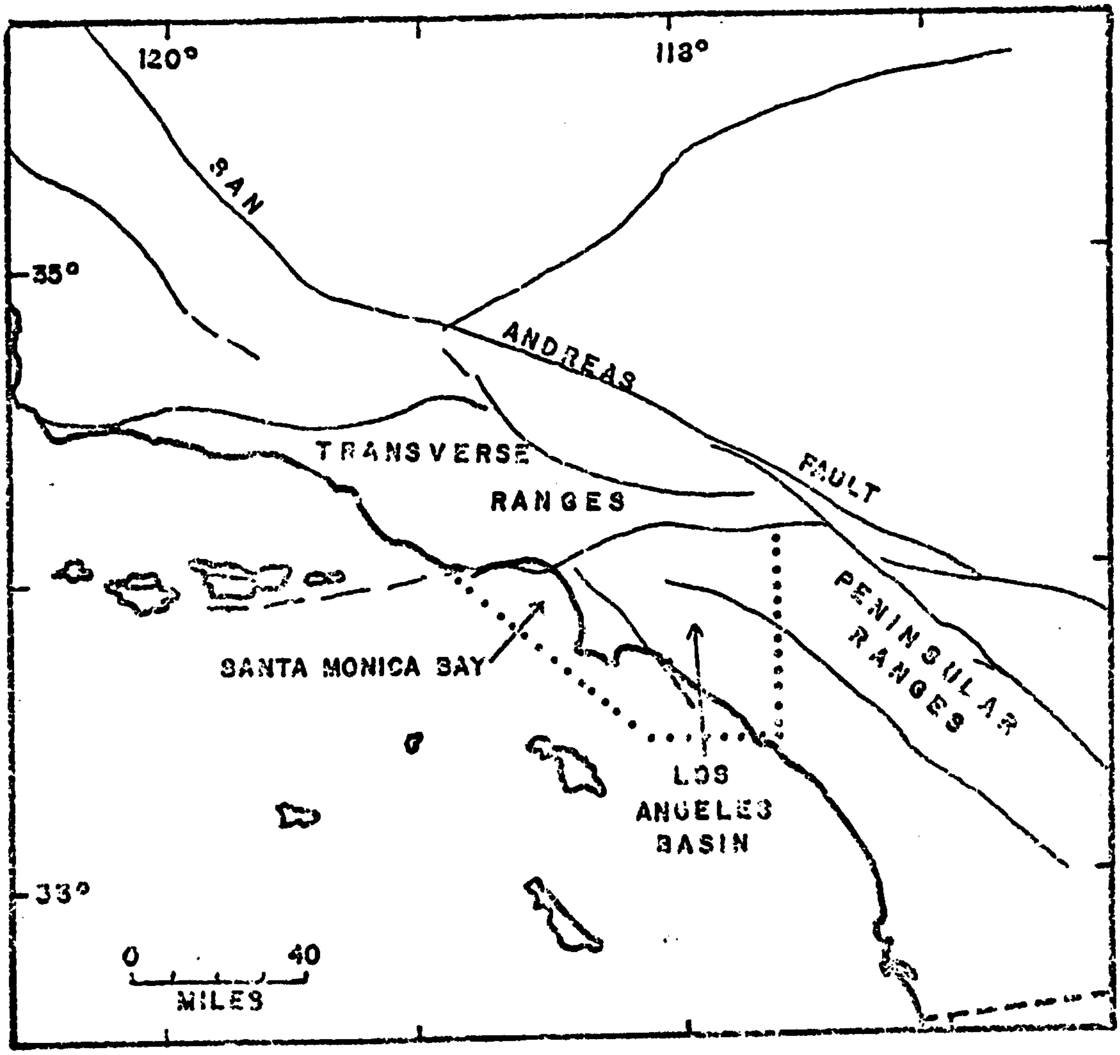

Figure 1. Location of Santa Monica Bay. The bay is part of the western margin of the Los Angeles Basin (area enclosed within the dotted line) (after Yerkes and others, 1965).

thus provide a clearer understanding of the timing and nature of the tectonic events responsible for their formation.

In order to achieve these goals, seismic-reflection records, including high resolution and deeper penetration profiles, magnetometer profiles, and jet core descriptions were studied. Because upper Pliocene strata are not preserved on the Palos Verdes Hills, which has been the primary source of detailed geologic information for the basin's western margin, these data constitute a potential source of new information concerning the late Pliocene history of the area. The seismic-reflection data also provide information concerning the recency of displacements along major faults and thus are applicable to seismicity studies now in progress in southern California. Further, the high resolution profiles permit the detection of hydrocarbons in both the water column and Quaternary sediments. Because these data can be studied in the context of the structural investigations, a secondary contribution is the evaluation of the significance of hydrocarbon seepage in the bay.

Acknowledgments

The author wishes to express his appreciation to the members of his thesis committee, Drs. Thomas L. Henyey, Donn S. Gorsline, and Robert H. Osborne for their continuous interest and encouragement during the course of this study. He is particularly indebted to Dr. Thomas L. Henyey who first proposed the problem and gave guidance through numerous stimulating discussions. Professor Richard O. Stone also read the manuscript and offered many useful suggestions for its improvement.

Additional thanks go to the crews of the R/V Velero IV and the fellow students who participated in the collection of the geophysical data. The assistance and cooperation given by Carol McClenning and Barbara Nardin during the preparation of the manuscript was invaluable.

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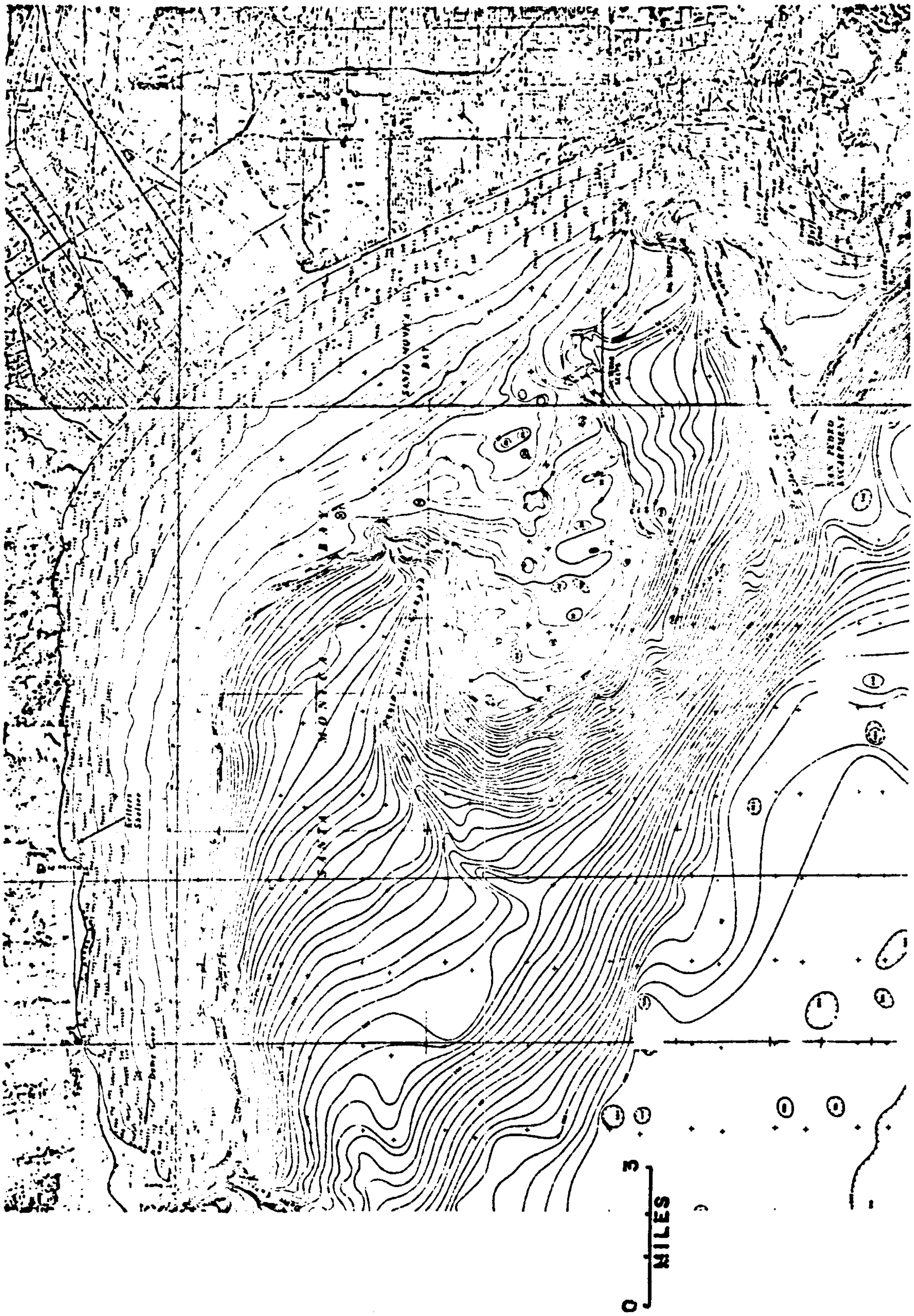
Finally, the author is especially grateful to Barbara Nardin for her love and patience.

Bathymetric Setting

The detailed bathymetry of Santa Monica Bay as well as its principal physiographic subdivisions, including a shelf, basin slopes, and two submarine canyons, are shown in Figure 2.

Figure 2. Detailed bathymetry of Santa Monica Bay (from Continental Shelf Data Systems, copyrighted 1967). Contour intervals are 1 fm to the 50 fm isobath, 5 fm from 50 to 100, and 10 fm from 100 to 500.


0
3
MILES

The shelf is defined as the shallow platform dipping less than 1.5^{o} between Point Dume and Palos Verdes Point. Throughout the bay, with the exception of those areas near the heads of the submarine canyons, the shelf break is at a depth of approximately 50 fm (fathoms). Shelf width ranges from less than 3 mi adjacent to the Santa Monica Mountains and Palos Verdes Peninsula to 12 mi west of El Segundo. The widest portion of the shelf, between Redondo and Santa Monica Submarine Canyons, has been termed the "shelf projection" by Terry and others (1956). Their designation is retained in other sections of this study. In contrast to the smooth slope of the inner shelf, the shelf projection is characterized by numerous irregularities. Terry and others (1956) studied these small scale bathymetric features. Their findings and conclusions are summarized in a later section of this report (p. 20).

Since two submarine canyons cut into the shelf, the basin slope in Santa Monica Bay is geographically restricted to the San Pedro Escarpment near Palos Verdes Point and a short slope segment west of the shelf projection. The San Pedro Escarpment is a steeply dipping (15^{o}) surface extending southeast to the San Pedro Sea Valley. West of the shelf projection the slope is less steep and characterized by small scale undulations trending normal to the slope's dip.

The axis of Redondo Submarine Canyon, a straight deep incision into the shelf, trends northeast and is steepest near its head which occurs within one-quarter of a mile of the coast near Redondo Beach. The canyon's gradient decreases in a series of steps toward the basin. While its south wall is extremely steep (25°), its north wall forms a relatively gently dipping platform, or terrace at depths less than 150 fm. For convenience, during discussion of the north wall in later sections of this report it is designated the Redondo platform or simply the platform. The north wall of the canyon is also characterized by two large re-entrants or tributaries.

Santa Monica Submarine Canyon is approximately 4 mi west of Ballona Creek. While it is a much broader feature than Redondo Submarine Canyon, it exhibits some common characteristics. The most striking similarity is its asymmetry. Like Redondo Canyon, its north wall dips very gently displacing the axis of the canyon southward. However, in contrast, the axis follows a more sinuous course.

Field Studies

General Statement

High resolution (3.5 kHz) seismic-reflection records, low energy air gun records, and magnetic profiles have been gathered in Santa Monica Bay. High resolution profiling with close transect spacing was used to investigate the Late Quaternary stratigraphy on the shelf as well as detailed structural patterns in older strata and recency of fault displacements. Air gun data were used to supplement the high resolution information in order to gain a better understanding of the deeper structure and the Late Cenozoic evolution of the shelf. Magnetic profiling was undertaken to provide information concerning the distribution and nature of basement rocks beneath the shelf as well as the locations of major faults. Representative seismic-reflection profiles chosen for inclusion as figures in this paper appear in the appendix. The location of these profiles are shown in Figures A1 and A2.

High Resolution Seismic-Reflection Profiling

High resolution seismic-reflection profiles were obtained using an Edo Western Model 248C transceiver, booster (3.5x), and 3.5 kHz piezoelectric transducer in combination with a series 4000 GIFFT wet-paper recorder.

Resolution is a function of sweep scale and pulse duration (percent of sweep duration) and is independent of depth. Virtually all the high resolution profiles were recorded using a 0.25 sec sweep duration and a 0.1 percent pulse duration. Assuming that the velocity of sound in sea water is 4800 ft/sec, a 0.25 sec sweep duration for GIFFT recording paper is equivalent to a 100 fm/20 division/18 in vertical scale. This system is capable of providing visual resolution of reflecting horizons approximately 3 ft apart. Penetration seemed to differ strongly as a function of substrate type. For example, near shore where the surface sediments consist chiefly of clean sand, the high acoustic impedance contrast between the sand and seawater resulted in only a few msec (milliseconds) of penetration. In other areas where the substrate consists of fine silts or even folded Miocene shale penetration sometimes exceeded 20 msec. Damuth (1975), also using a 3.5 kHz system, found similar relationships between echo type and the relative amounts of coarse sediment on the floor of the equatorial Atlantic.

The horizontal scale varied as a function of the ship's speed and the speed of the paper feed through the recorder. These were adjusted to minimize vertical exaggeration which characteristically was about 10 to 1.

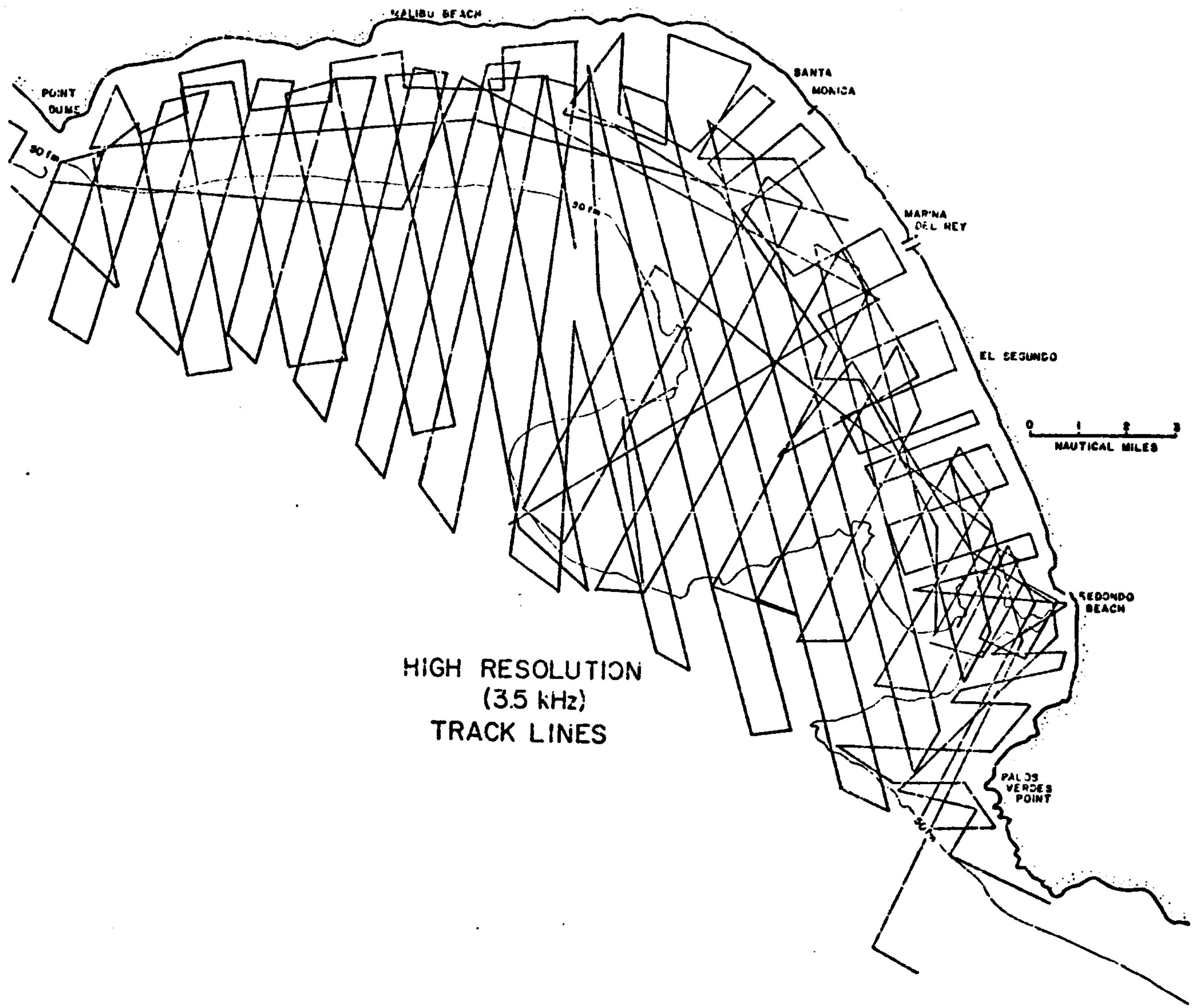
In addition to the usual bottom multiple reflections which accompany the records, a prominent multiple occurs on those records taken when the transducer was towed below the surface (depth approximately 30 ft), owing to the reflection from the sea-air interface. Although easily recognizable (Figs. A6 through A13), it often obscures or masks buried reflecting horizons within the Quaternary overburden. Elimination of the multiple was accomplished in later recordings by adjusting the "sled" (transducer housing) so that it towed at the surface (Figs. A3, A4, and A5). Interestingly, additional flow noise due to the apparent increase in turbulence was not manifested in these recordings.

Approximately 400 mi of trackline were covered in the survey area (Fig. 3). Tracklines were run both normal and obliquely to the regional structural grain in order to provide sufficient control.

Air Gun Profiling

Deeper penetration records were gathered using a Bolt model 600B air gun and model 1011 streamer (6 element/ 20 ft array) and a series 4000 GIFFT recorder. In order to limit vertical exaggeration to about 15 to 1, a 0.5 sec sweep duration (200 fm scale), fast paper feed, and slow ship speed (4 knots) were used. Since this system required rapid firing of the air gun and already had the disadvantage of limiting penetration, only a 10 in^3 chamber was employed on the gun in order to maintain air pressure. Penetration in undeformed post-Miocene sediments was as much as 250 msec (equivalent to full scale) but sometimes was not appreciably better than that of the high resolution system in folded Miocene strata. Low cut and high cut filters of 80 Hz and 640 Hz, respectively, were most often used. This pass band offered the best compromise among resolution, noise reduction, and penetration. Ap-

Figure 3. Tracklines covered in Santa Monica Bay with high resolution (3.5 kHz) profiling system.



HIGH RESOLUTION
(3.5 kHz)
TRACK LINES

proximately 210 mi of air gun trackline were covered (Fig. 4). Most of the profiles were collected from the southern one-half of the bay near Redondo Submarine Canyon and were oriented for optimum recording of structural elements observed on high resolution profiles gathered earlier.

Magnetometer Profiling

Magnetic profiling was accomplished with a Geometrics marine proton magnetometer (model G-801) and Moseley Model 680 strip chart recorder. Sensitivity of the system is 1 gamma. The rate at which the paper was fed through the recorder was kept low (8 in/hr) in order to enhance the high frequency component of the field. About 225 mi of proton magnetometer tracklines were covered (Fig. 5), and for the most part are approximately coincident with high resolution seismic-reflection tracklines.

Navigation

Positioning was accomplished using the ship's 16 in. radar system. Resolution of the system is within $\pm$ 5 percent of the distance to the target. Therefore, the tracklines crossing the outer shelf and slope could have location errors of as much as 1 mi. However, at each trackline intersection point the depths recorded on the seismic-reflection profiles were compared to each other as well as to a detailed bathymetric chart in an effort to

Figure 4. Air gun ($10\ in^3$) tracklines covered during survey of Santa Monica Bay.

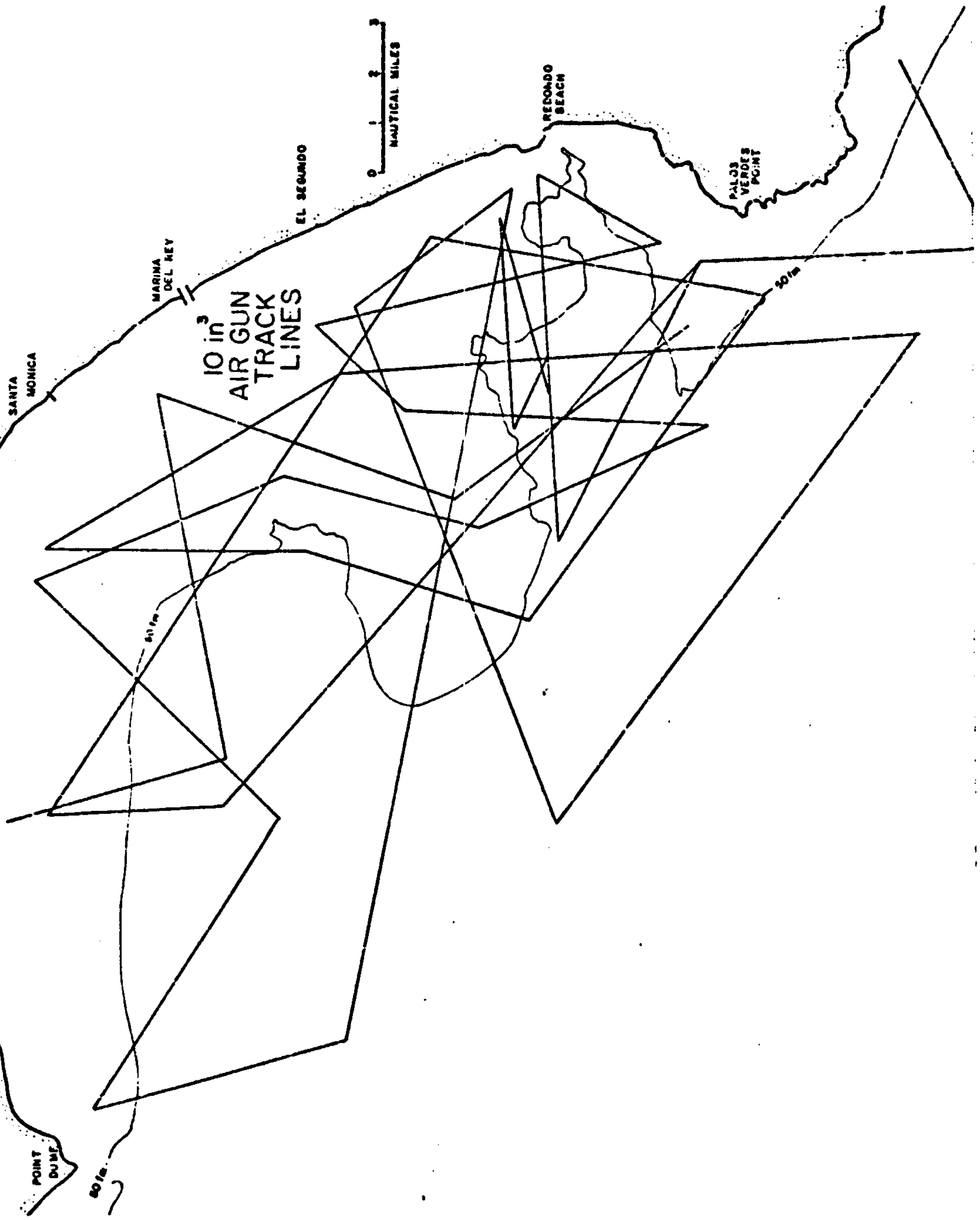
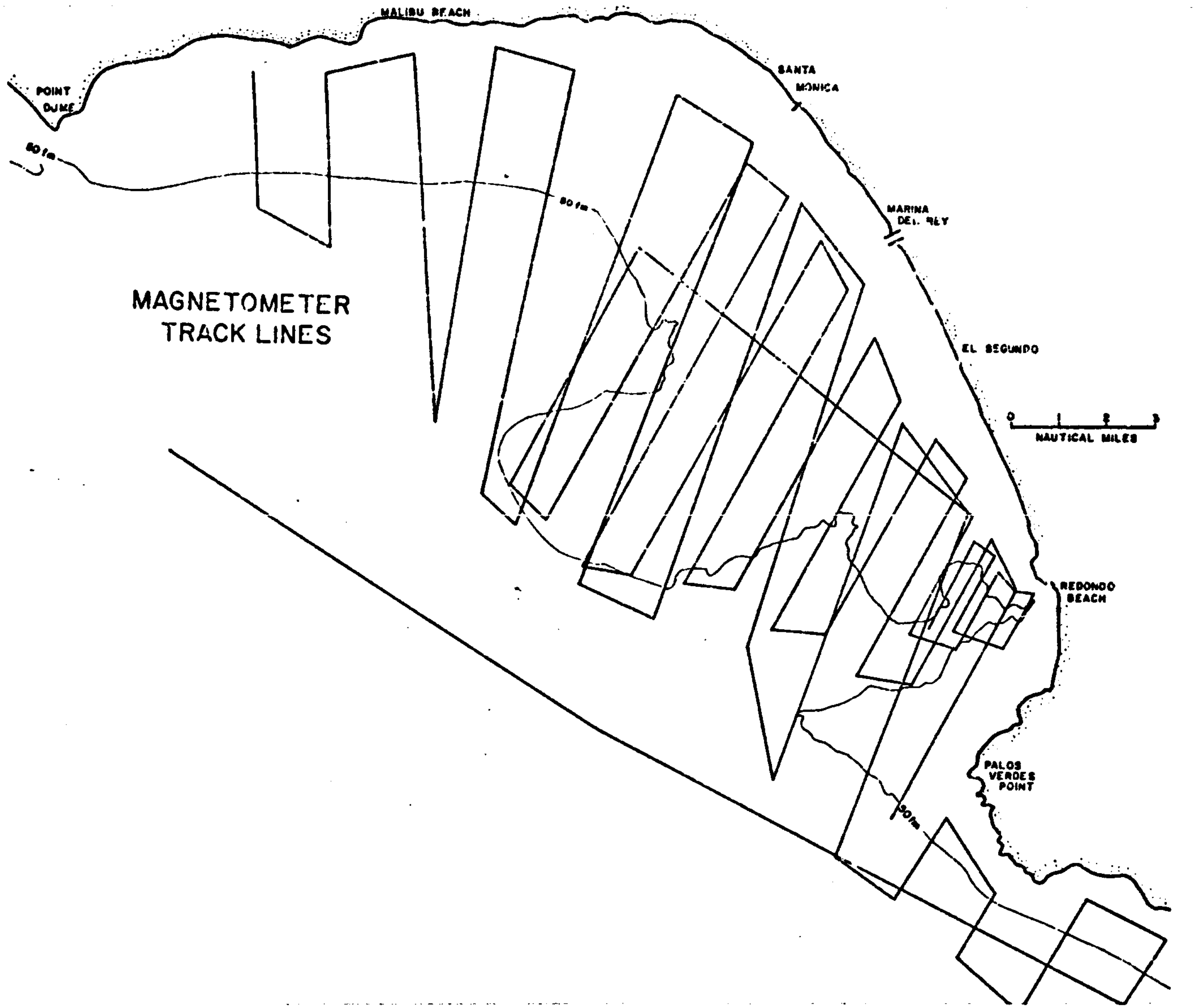

10 in³ AIR GUN TRACK LINES
NAUTICAL MILES
0
1
2
3
REDONDO BEACH
PALOS VERDES POINT
EL SEGUNDO
MARINA DEL REY
SANTA MONICA
MALIBU BEACH
POINT DUME
50 fm

Figure 5. Tracklines covered during magnetometer survey of Santa Monica Bay.



MAGNETOMETER TRACK LINES

correct positioning error. Depth can be read accurately from the profiles using the spacing between the seafloor trace and the first multiple. This method enabled location errors to be reduced to less than 0.5 mi.

Previous Work

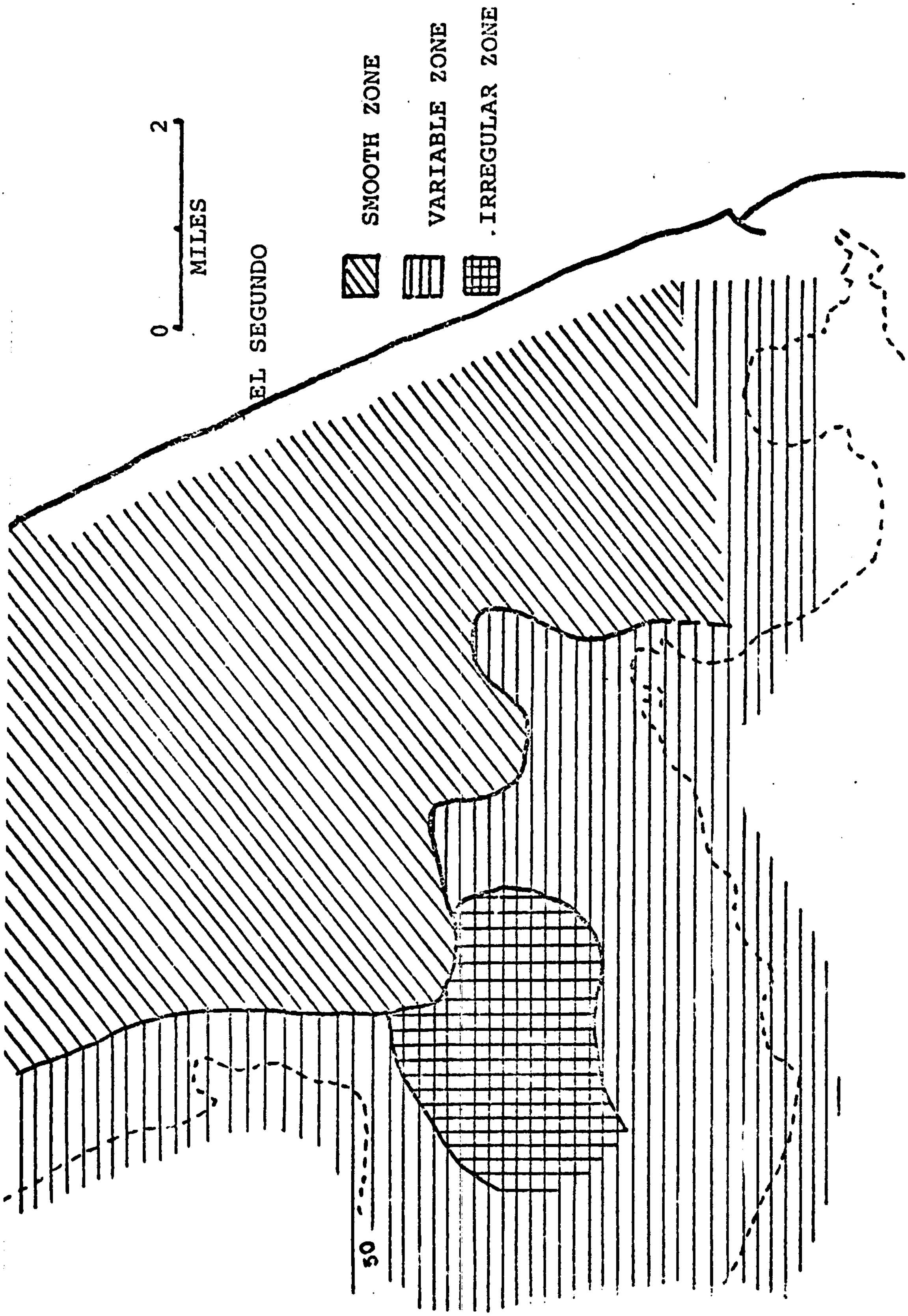
General Statement

Most geological research in Santa Monica Bay has dealt principally with the distribution and origin of bottom material (for example, see Emery, 1952). Terry and others (1956) were the first investigators to attempt a comprehensive study of the area. In addition to surface sediment studies, they investigated bathymetry, bedrock type and distribution, and geologic structure. Structural interpretations based on published seismic-reflection records did not appear until over a decade later (Yerkes and others, 1967). Subsequently, the only additional information concerning the structure of Santa Monica Bay has come from regional surveys of the entire Borderland (Moore, 1969; Ziony and others, 1974; Vedder and others, 1974). The following summary of these and other investigations, as they pertain to the present study, can be conveniently divided into four parts: bathymetry, bedrock lithology, structure, and gravity and seismicity.

Bathymetry

In the context of this study, the most relevant aspect of the bathymetry of Santa Monica Bay, and one that has received particular attention from early investigators, is the pattern of the shelf's small scale relief. Irregularities on the shelf having amplitudes generally less than 45 ft were termed microrelief by Terry and others (1956) and Terry and Stevenson (1957). They noted three areas of contrasting microrelief (Fig. 6). The most subdued area, the smooth zone, is generally contained between the shoreline and the 30 fm isobath. A study of the bottom materials and well data revealed that this zone is an area of active sedimentation and is underlain by thick sequences of unconsolidated sediments. The central portion of the shelf projection is a zone of irregular microrelief characterized by steeply flanked mounds. Dredging indicated that the irregular zone is composed largely of rock and residual deposits composed of well-rounded gravel, and is essentially an area of nondeposition. Bedrock samples of shale, mudstone, and schist have been recovered from this area. The third area which appears to be a transition between the smooth and irregular zones almost completely surrounds the irregular zone and extends beyond the shelf break. Within this variable zone are sections with no microrelief and others containing small mounds and undula-

Figure 6. Areas of contrasting microrelief in the southern half of Santa Monica Bay as defined and mapped by Terry and others (1956).


0
MILES
2
EL SEGUNDO
SMOOTH ZONE
VARIABLE ZONE
IRREGULAR ZONE
50

tions. A number of notches and small terraces noted near the shelf break and upper slope were thought to be remnants of lower stands of sea level. Fathograms collected by Terry and others (1956) showed small gullies similar to those described by Emery and Terry (1956) along the San Pedro Escarpment and were believed to be scars formed by submarine slumping. Terry and others (1956) suggested that the patchy nature of this zone was because of partial burial of the bedrock surface by discontinuously distributed sediments. Terry and Stevenson (1957) also proposed that the bedrock within this zone may be more easily eroded than in the irregular zone.

The narrow shelf between Point Dume and Santa Monica was omitted in the study of Terry and others (1956) but, according to their criteria, would be mapped as part of the smooth zone. This area was included as part of a Borderland acoustic sounding survey conducted by Emery (1958) who discovered 5 platforms superimposed on shelves and banks. Emery, recognizing 4 of the platforms in Santa Monica Bay, hypothesized that they were erosional terraces cut during the Wisconsin glaciation. Terraces 2, 4, and 5 (shelf break), possessing outer or deeper edges at depths of 80, 255, and 290 ft, respectively, are easily seen on Figure 2.

Bedrock Lithology

Before the acquisition of seismic-reflection data, attempts to extrapolate onshore geology into the offshore area were based largely on sediment or bedrock samples recovered from the seafloor. Shepard and MacDonald (1938) recognized that the outer Santa Monica Shelf between Redondo and Santa Monica Submarine Canyons had a rocky bottom and that shales dredged from this region were similar to those of the Monterey Shale. A regional dredging survey conducted by Emery and Shepard (1945) obtained samples thought to be representative of the local bedrock lithology, which were examined for fossils diagnostic of age. Miocene mudstone was present in dredges along the walls of the western end of Redondo Submarine Canyon. Miocene shale as well as Pliocene and Pleistocene conglomerate were recovered along the south wall of Santa Monica Submarine Canyon. Again, the similarity of these rocks to strata cropping out in the Palos Verdes Hills and the Santa Monica Mountains suggested that the seaward continuation of these strata into Santa Monica Bay was likely. Terry and others (1956) carried out a more extensive survey in Santa Monica Bay, particularly in the zone of irregular microrelief and found shales, including siliceous shales of Monterey type, the most abundant rocks on the outer shelf. Mudstone, siltstone, and sandstone followed in importance. Though few samples contained diagnostic foraminifera, several were identified as probable Miocene and one positively as lower Mohnian (middle to upper Miocene). Schist fragments recovered near a prominent ridge that bisects the zone of irregular microrelief were thought to have been derived from a basement outcrop or possibly from middle Miocene strata containing schist detritus.

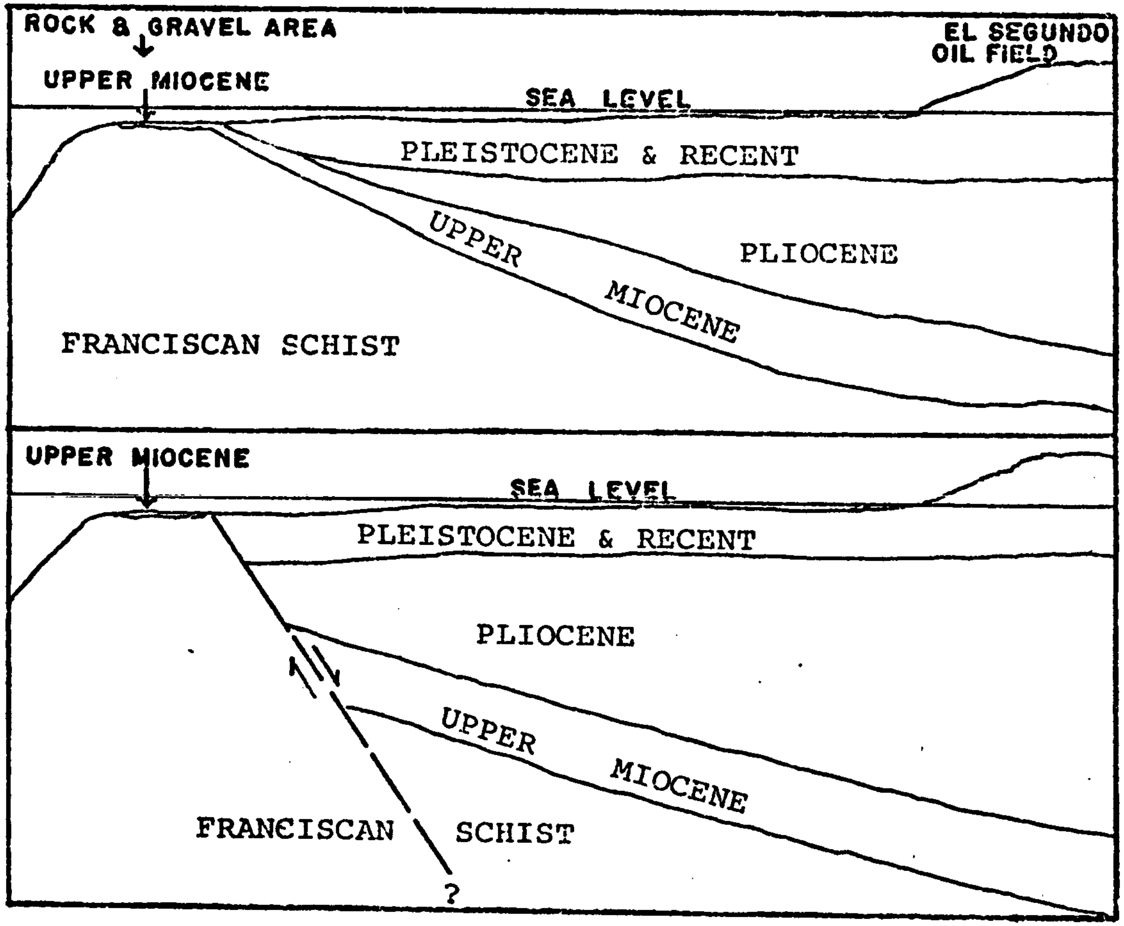
Structure

Offshore structural interpretations by early investigators were often based solely on bathymetric characteristics suggestive of faulting or folding. For example, steep basin slopes were commonly interpreted as fault scarps formed during Miocene block faulting of the Borderland. Shepard and MacDonald (1938) noted that the topographic outline of the Palos Verdes Peninsula was not reflected along the straight basin slope between Santa Monica Submarine Canyon and the San Pedro Sea Valley and suggested the presence of a fault along the base of slope (the San Pedro Escarpment fault of Shepard and Emery, 1941). Yerkes and others (1967) and Moore (1969) indicated that seismic-reflection records reveal a normal fault dipping southwest at the base of the slope (Fig. 9). Hackett (1970), studying the morphology of the Redondo submarine fan, reported that the San Pedro fault consists of several recently active faults which continue northwestward across Redondo Submarine Canyon and are, in part, responsible for much of the slumping along the escarpment. Hackett discovered another fault, also expressed as an escarpment, trending northwest across the fan. Similarly, a northwest-trending fault, apparently displacing pre-Pliocene to early Pleistocene strata, was mapped a few miles west of the slope (Ziony and others, 1974; and Vedder and others, 1974) and may be related to it (Fig. 10).

Terry and others (1956) provided most of the early structural interpretation in Santa Monica Bay; they were interested principally with the origin of the bedrock area (zone of irregular microrelief) of the shelf projection and the possibility of a seaward continuation of the Palos Verdes fault. They reasoned that if schist is indeed outcropping on the outer shelf, then only schist or basement rock should be found along the walls of the flanking submarine canyon. However, since the bulk of rocks recovered from Santa Monica Submarine Canyon had been dated as Miocene, they necessarily assumed that either the shelf projection had been uplifted along a west-trending fault near the canyon's axis or that the shelf projection represents an eroded dome-like structure. As support of their first hypothesis they cited Poland and others (1948) who proposed faulting and southward tilting along

Ballona Creek. Though the sense of displacement along the Ballona Creek fault was opposite that needed, Terry and others suggested that it was possible that the fault continued westward along the axis of the submarine canyon and that the outer shelf had been uplifted along it. They also proposed that after leaving the coast in the vicinity of Redondo Beach, the Palos Verdes fault might turn south along the axis of Redondo Submarine Canyon. However, they could find no seismological evidence suggesting faulting along the canyon, and instead concluded that the fault continues in a northwestward direction. They cited the following reasons for their hypothesis: (1) hydrocarbon seeps occur near the head of Redondo Submarine Canyon and to the northwest, (2) earthquakes tend to group along the seaward projection of the fault in Santa Monica Submarine Canyon, (3) the general bathymetric pattern suggests faulting, and (4) schist recovered from the shelf projection appears correlative with the Catalina Schist exposed on the Palos Verdes Hills. Two possible interpretations of the structure along a line from the shelf break to coast were made based on a knowledge of the lithology and age of the bedrock on the shelf projection and the stratigraphy of the nearby El Segundo oil field (Fig. 7). The Palos Verdes fault was excluded from the first interpretation. Instead a gently dipping syncline or trough formed landward of the shelf projection which they hypothesized stood as an island

Figure 7. Stratigraphy beneath the El Segundo oil field and alternative interpretations of the structure beneath the shelf made by Terry and others (1956).



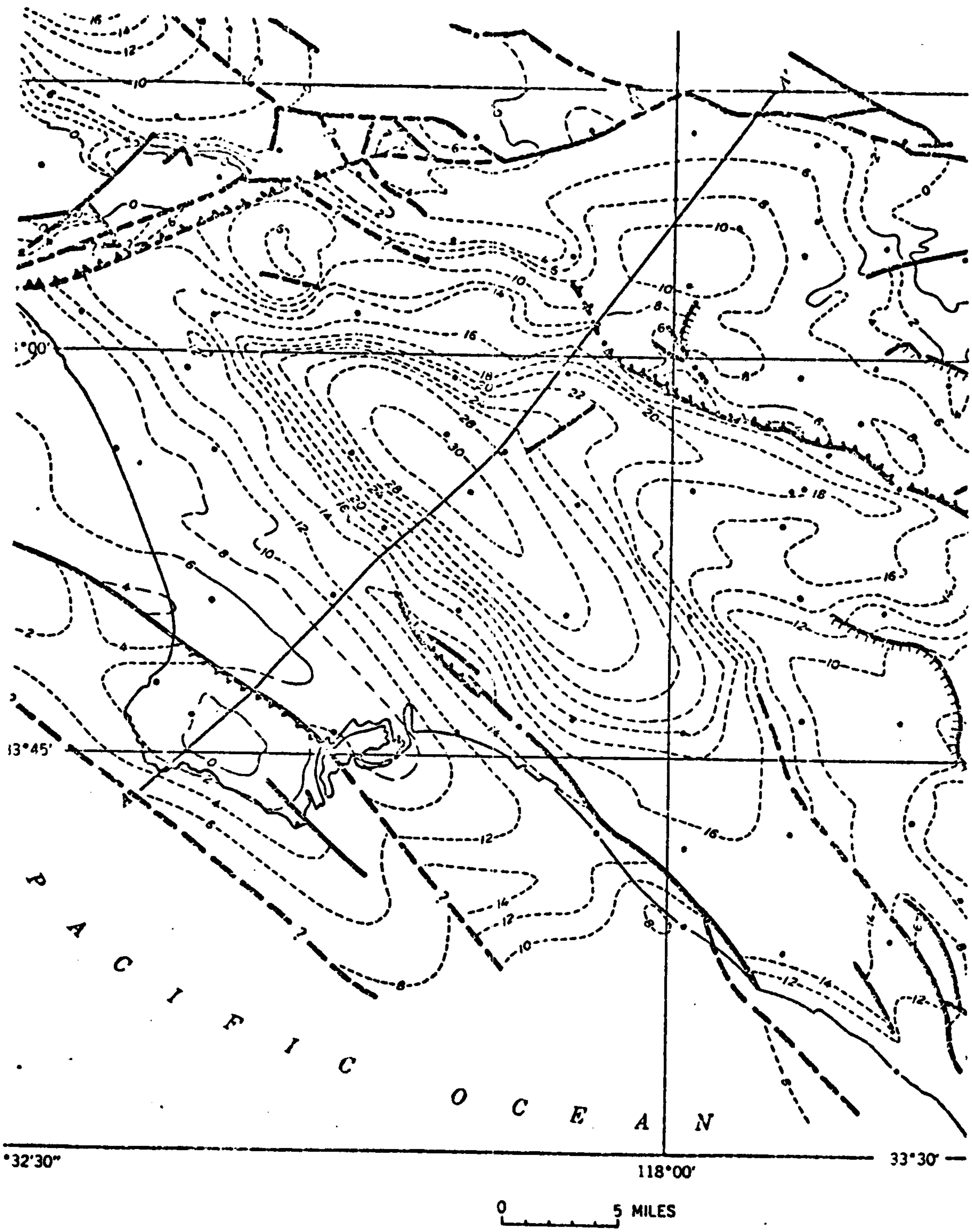
EL SEGUNDO OIL FIELD

FORMATION	THICKNESS (feet)	EPOCH	
alluvium	100	RECENT	
	200	PLEISTOCENE	
Pico	5400	PLIOCENE	Upper
Repetto		PLIOCENE	Lower
Puente	1500	MIOCENE	Upper
Franciscan schist	400+	JURASSIC ?	

at the end of Miocene time. The trough was subsequently filled with Pliocene and Pleistocene sediments derived from the island and sources to the east. According to the second interpretation, the shelf projection had been uplisted along the Palos Verdes fault at the end of Miocene time. Though on land the Palos Verdes fault dips steeply to the southwest, Terry and others suggested that offshore the fault dips gently to the northeast. They based this interpretation on overburden data which indicated that the thickness of the sediment increased eastward from the shelf projection reaching only 500 ft 1 mi from the outcrop area.

Interestingly, a summary of the geology of Los Angeles Basin by Woodford and others (1954) included a block diagram of the basement surface showing the continuation of the Palos Verdes anticlinorium and the Palos Verdes fault across the Santa Monica Shelf. Similarly, McCulloh (1960) showed a definite northwestward continuation of the Palos Verdes fault in a structure-contour map of the basement which was constructed using seismic-reflection data (Fig. 8). Wilkinson (1972) plotted 6 separate oil and gas seeps along the submarine trace of the fault which he indicated extended about 12 mi into the bay. Conversely, Yerkes and others (1967), employing seismic-reflection data, could not positively identify the Palos Verdes reverse fault immediately north of Redondo Submarine Canyon.

Figure 8. Structure-contour map of the basement surface of the Los Angeles Basin (from McCulloh, 1960).

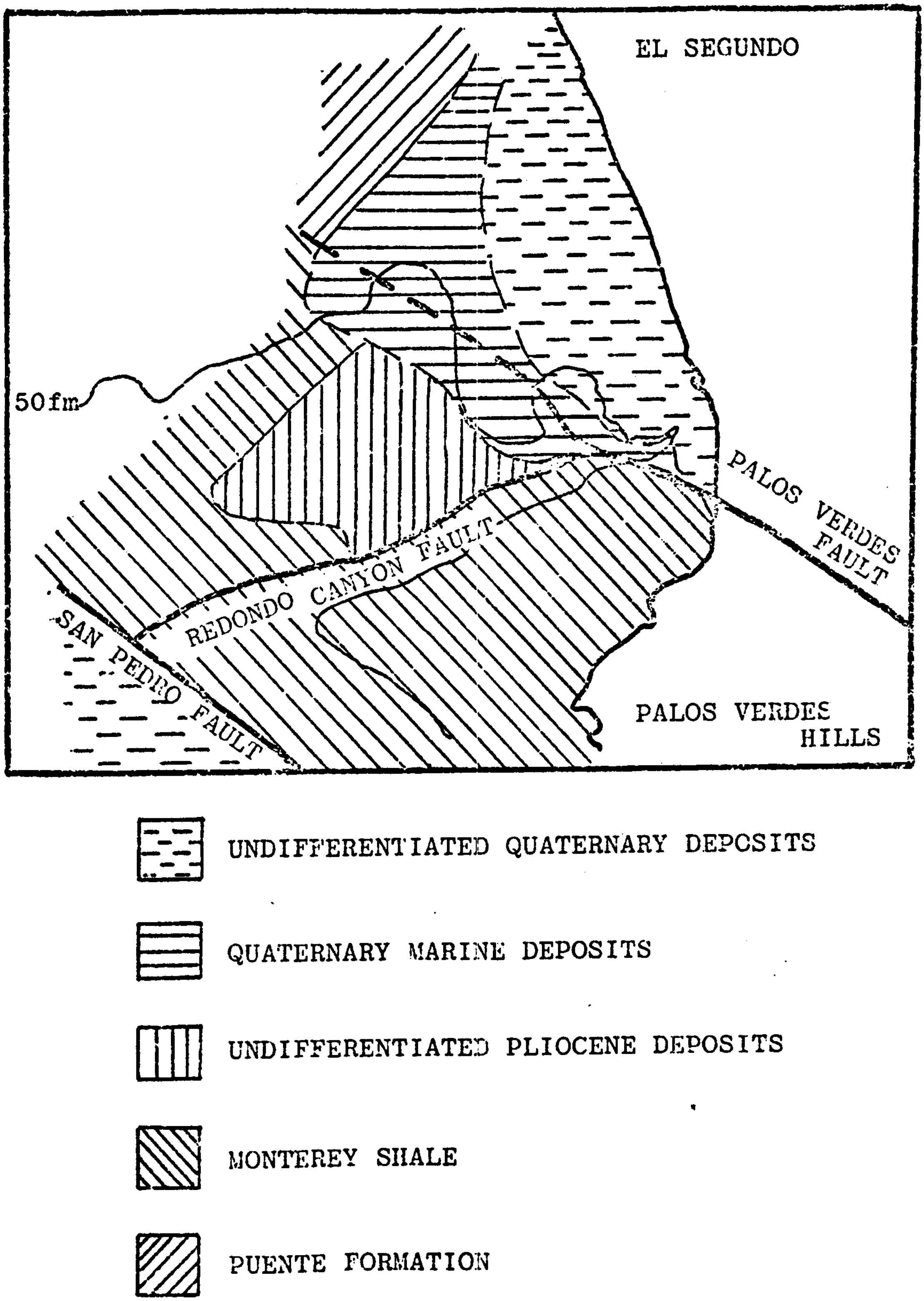


Contour Interval = 2000 ft

The presence of a fault in the area was suggested by their records but it apparently dipped southward with normal displacement. In addition, they mapped a normal fault trending S.70° W. along the axis of Redondo Submarine Canyon bounded by the Palos Verdes fault on the northeast of the and the San Pedro fault on the southwest (Fig. 9). The proposed Redondo Canyon fault forms the northwest boundary of the Palos Verdes Hills anticlinal structure and is thought to exhibit at least 1200 ft of vertical displacement attendant with the amount of uplift of the hills since middle Pleistocene time. However, the fault is not observed to displace strata younger than Pliocene. They hypothesized that during a low sea stand 120,000 years ago (Fairbridge, 1961) the canyon was eroded subaerially by the "Gardena River" which flowed along a structural trough created by middle Pleistocene faulting. In a study of Holocene and upper Pleistocene sediments, Riccio (1965) also linked the formation of the canyon to the river. Subsequent late Pleistocene subaerial and submarine erosional processes deepened the canyon. Yerkes and others also noted a thick wedge of relatively undeformed sediment along the north wall of Redondo Submarine Canyon which they suggest is probably Pliocene strata. These deposits unconformably overlie strata identified as the Monterey Shale which forms an eastward plunging structural depression.

In contrast to the late Pliocene (Pasadenan) folding of the

Figure 9. Geologic interpretation made by Yerkes and others (1967) in the region of Redondo Submarine Canyon. Unconsolidated surficial deposits are omitted. Faults and formation contacts dashed where inferred.


EL SEGUNDO
50 fm
PALOS VERDES FAULT
REDONDO CANYON FAULT
SAN PEDRO FAULT
PALOS VERDES HILLS
UNDIFFERENTIATED QUATERNARY DEPOSITS
QUATERNARY MARINE DEPOSITS
UNDIFFERENTIATED PLIOCENE DEPOSITS
MONTEREY SHALE
PUENTE FORMATION

Palos Verdes Hills postulated by Woodring and others (1946), Yerkes and others (1967) suggest a period of early Pliocene deformation with little later folding.

Two excellent maps, both recently published by the United States Geological Survey (Ziony and others, 1974; Vedder and others, 1974) and based on seismic reflection and other geophysical data, summarize the current structural information for the California Continental Borderland. They also serve to illustrate that the geologic framework of Santa Monica Bay has yet to be firmly established (Figs. 10 and 11). A fault map published by the State of California (Jennings, 1973) is similar to the map of Ziony and others (1974). However, the 1973 map was apparently prepared from unpublished Survey results used in the 1974 map and is, therefore, omitted from the following discussions. Both Survey maps show the Palos Verdes fault extending across the shelf but trending decidedly north of all earlier interpretations. Displacement of lower Pleistocene strata (estimated to be older than 500,000 yrs by Ziony and others) was observed along the fault. Although positioned differently on the maps, several short discontinuous faults are mapped adjacent to the principal Palos Verdes fault trend and range in maximum age from Miocene to late Pleistocene. Three faults shown on the map of Ziony and others are absent from the map of Vedder and others: (1) a fault of unknown age

Figure 10. Preliminary fault map of Santa Monica Bay prepared by Ziony and others (1974). Numbers refer to the most recent movements observed along the faults as determined from criteria outlined by Ziony and others. Except for pre-Pliocene faulting minimum ages are not indicated.

1.	Late Quaternary	$< 500{,}000$ y.b.p.
2.	Early Quaternary	$< 3 \times 10^6$ y.b.p.
3.	Pre-Pliocene	$> 5 \times 10^6$ y.b.p.
4.	Miocene	$< 12 \times 10^6$ y.b.p.
?	Unknown	

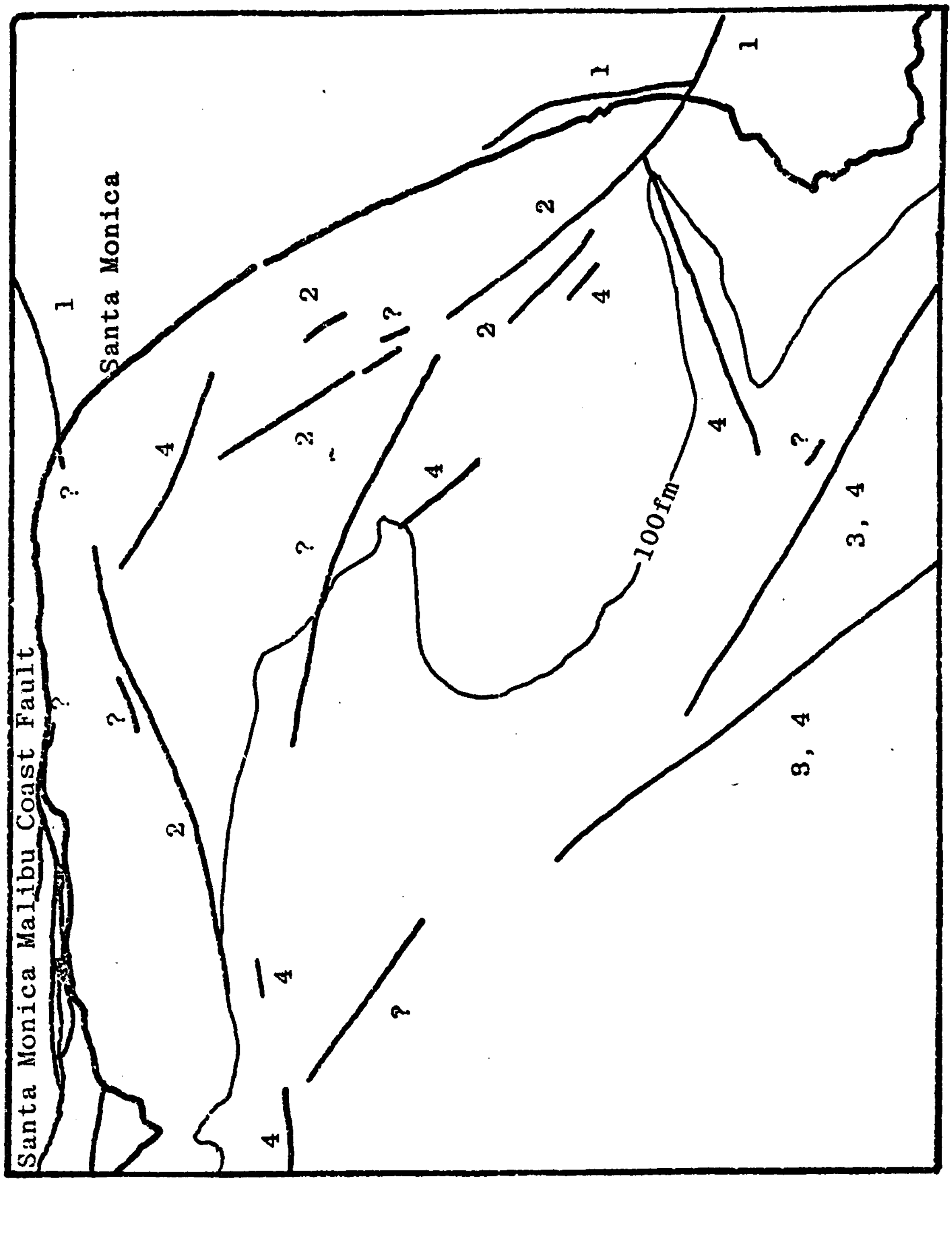
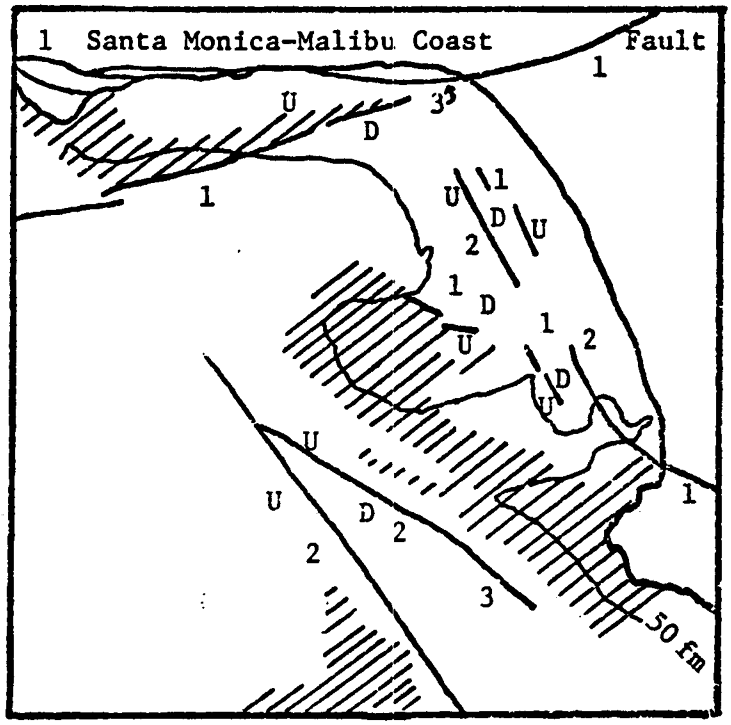

Santa Monica Malibu Coast Fault
Santa Monica
100fm
1
2
3, 4
4
?

Figure 11. Preliminary geologic map of Santa Monica Bay (after Vedder and others, 1974). Numbers adjacent to faults indicate recency of faulting.



MIOCENE

POST-MIOCENE

1 Displaces Quaternary and/or Pliocene strata within 150 feet of the seafloor or cuts the seafloor in older units

2 Pre-late Pleistocene

3 Pre-Pliocene

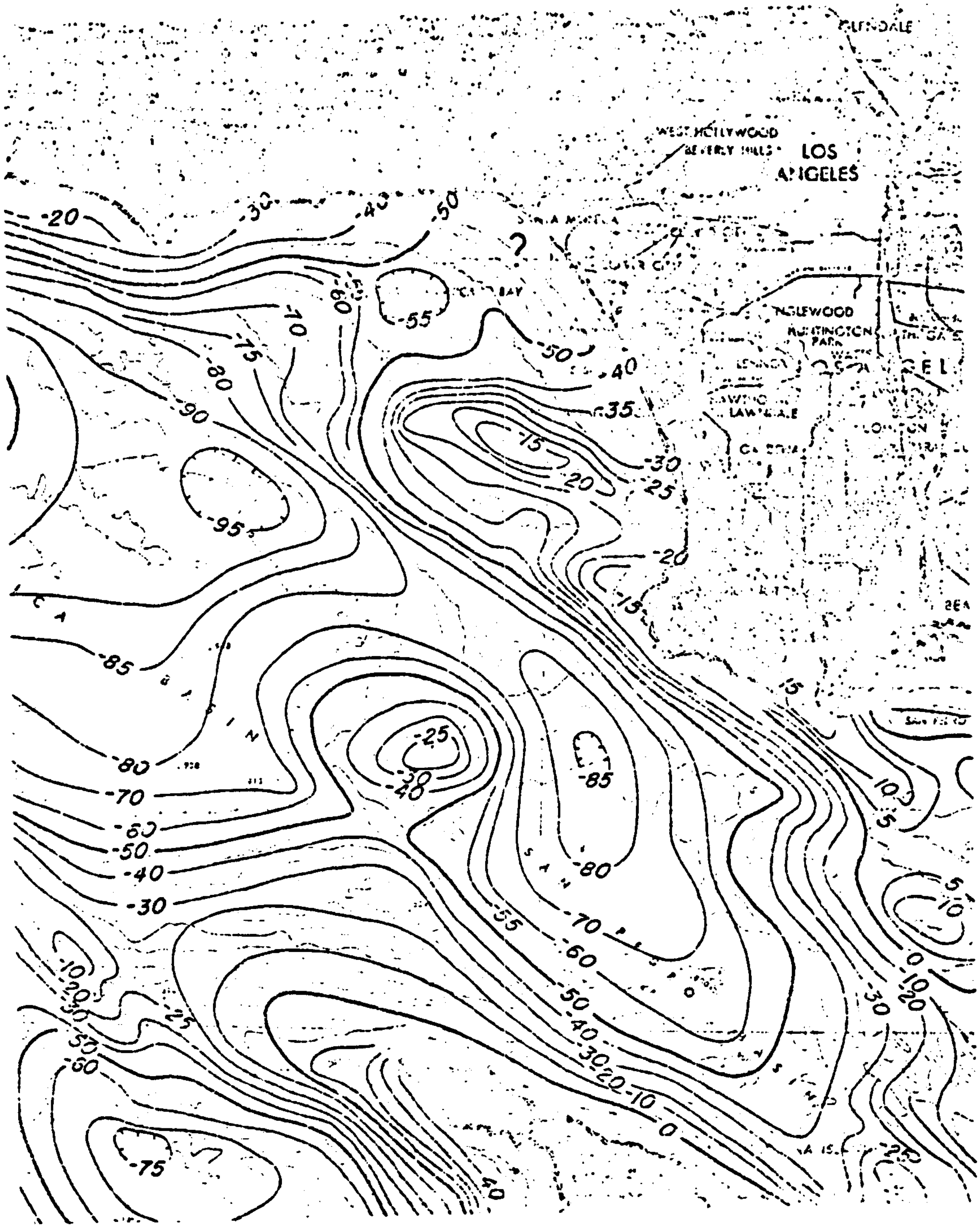
branching from the Palos Verdes fault west along the Santa Monica Submarine Canyon, (2) a northwest-trending fault southwest of the city of Santa Monica, and (3) the Redondo Canyon fault as mapped by Yerkes and others (1967). Both maps also show a west-southwest-trending fault on the shelf and slope south of the Santa Monica Mountains. Minimum age control is lacking but deposits as young as early Pleistocene are thought to be displaced along the fault. On the geologic map prepared by Vedder and others this fault separates Miocene strata near the coast from younger strata to the south. Ziony and others (1974) and Vedder and others (1974) noted that many future modifications of their preliminary offshore structural interpretations should be expected. In particular, additions of newly discovered structural elements as well as revised estimates of latest fault movements are likely.

Gravity and Seismicity

In addition to the seismic-reflection data gathered in Santa Monica Bay, information concerning the gravity and seismicity of the area also was obtained. Harrison and others (1966) constructed Bouguer gravity maps for the California Continental Borderland. Through spatial filtering techniques they were able to separate anomalies into short and long wavelength components. They observed that the short wavelength component exhibited a northwest trend and that gravity highs were associated with basement highs. It should be noted that Harrison and others defined the basement as metamorphic and igneous rocks older than Late Cretaceous. They concluded that, in the Borderland, small scale gravity variations are strongly influenced by depth to basement and sediment thickness. They suggested that if this is the case, then the Palos Verdes anticlinal structure probably extends across the outer shelf in Santa Monica Bay. The free-air gravity map of Santa Monica Bay constructed by Beyer and others (1974) also suggests that the Palos Verdes Hills anticlinorium extends across Santa Monica Bay (Fig. 12). In contrast, Harrison and others discovered that the long wavelength component exhibited a pronounced east-west trend. Surprisingly, this trend was not restricted to the Transverse Range province but extended at least as far south as latitude 33°N. Harrison and others hypothesized that the broad east-west variations may reflect large scale changes in basement thickness or an older topography dissected by post-Miocene Borderland tectonics.

A compilation of earthquakes for the years 1934 to 1946 in the offshore region of southern California revealed that Santa Monica Bay is seismically active (Clements and Emery, 1947). More recently, seismic monitoring with improved station control since 1968 (University of Southern California Geophysical Laboratory, Teng and Henyey, 1975)

Figure 12. Free-air gravity map of Santa Monica Bay prepared by Beyer and others (1974). Contour interval is 10 mgal with selected intermediate 5 mgal contours.


WEST HOLLYWOOD
LOS ANGELES
INGLEWOOD

provides better epicentral control and demonstrates continuing activity (Fig. 13). The pattern of seismicity near the head of Redondo Submarine Canyon appears to be correlative with the offshore extension of the Palos Verdes fault. A composite fault plane solution for these seismic events, however, gives two possible fault planes: (1) strike N.68°W., dip 66°NE, and (2) strike N.40°W., dip 27°SW. The second fault plane was discarded by Teng and Henyey because its low dip and the depth of the events (greater than 10 mi) mean that the surface projection of the plane would have to be much farther east than the trace of the Palos Verdes fault. Instead, they chose the northeast-dipping fault plane since the San Pedro Escarpment is near the surface projection of the plane. Moreover, a series of earthquakes approximately 5 mi south of the Malibu Coast fault may be associated with the proposed west-southwest-trending fault along the shelf and northern wall of Santa Monica Submarine Canyon.

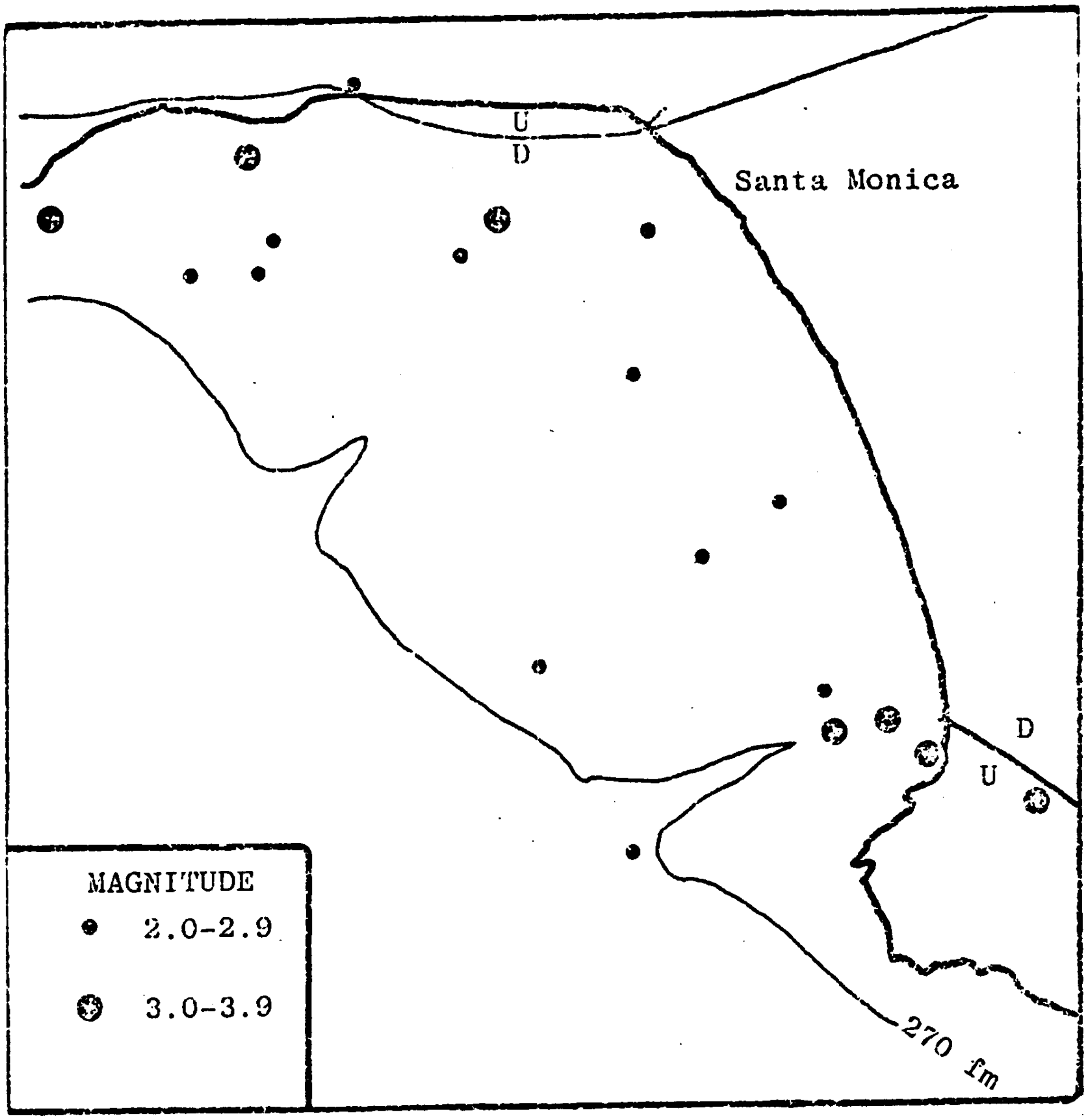


Figure 13. May 1971 to December 1974 seismicity of Santa Monica Bay (after Teng and Henyey, 1975). Most earthquakes occurred 10 to 15 mi below the surface.

GEOLOGIC SETTING

General Statement

For the most part, the Santa Monica Shelf is a seaward extension of that portion of the Los Angeles Basin west of the Newport-Inglewood fault zone. Yerkes and others (1965) recognized as did earlier investigators (for example, Reed and Hollister, 1936) that striking contrasts in basement rocks, structural style, and Cenozoic stratigraphy exist across the Newport-Inglewood zone. They termed the area west of the fault zone the southwestern block and their designation has been retained in this report. However, the shelf's history is not totally allied with the history of the southwestern block. The shelf also is bordered by the Santa Monica Mountains which have influenced both its sedimentological as well as structural evolution. Therefore, assumptions and inferences concerning the shelf's history must consider the history of the southwestern block including the Newport-Inglewood zone, as well as the Santa Monica Mountains.

Much information relevant to this investigation is in the excellent summary of the geology of the Los Angeles

Basin by Yerkes and others (1965) and the detailed study of the geology of the Palos Verdes Hills by Woodring and others (1946). Appreciable use has been made of their work in the following discussions. Where applicable, interpretations of the Cenozoic history of the area in the context of plate tectonics as given chiefly by Atwater (1970), Hill (1971), and Yeats (1973) is also included.

Newport-Inglewood Fault Zone

The Newport-Inglewood fault zone, a belt of northwest-trending *en echelon* faults and subparallel west-northwest-trending folds extends from Newport Beach to Beverly Hills, and is apparent topographically as a series of gentle hills (Fig. 14). Early investigations summarized by Reed and Hollister (1936), suggested that the *en echelon* structural character indicated that a basement or master fault exists along which dextral shearing stresses have been operative. Basement terrain contrasts on either side of the fault tend to support the master fault hypotheses. As a result, the Newport-Inglewood zone generally is considered to be a major tectonic boundary separating Catalina Schist basement on the west from predominantly granitic basement on the east. At its northwestern end the Newport-Inglewood zone is terminated by the Santa Monica fault zone south of the Santa Monica Mountains. However, the intersection between the Newport-Inglewood

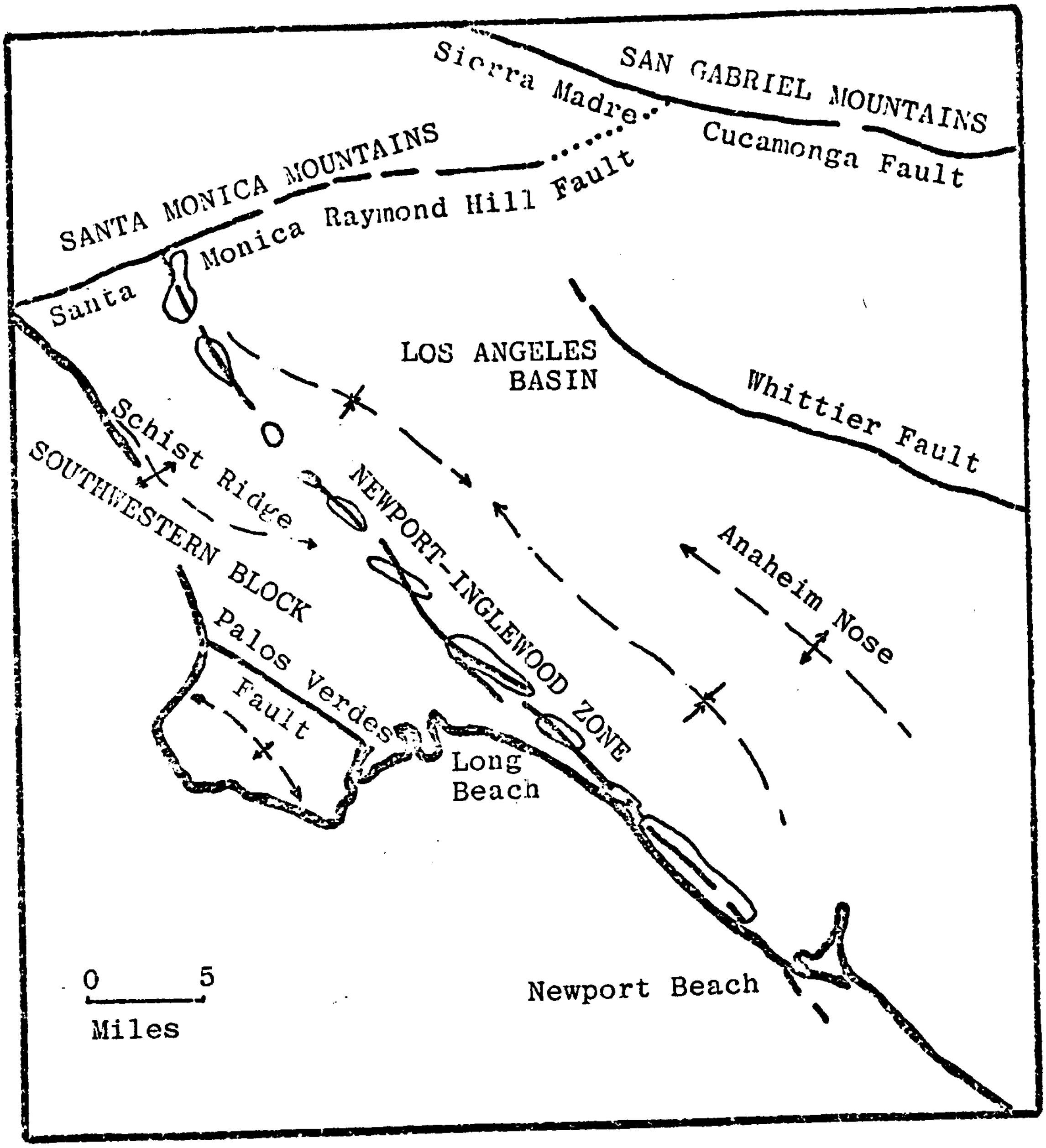


Figure 14. The Newport-Inglewood zone of <u>en echelon</u> folds and faults forms the eastern boundary of the southwestern block (after Hill, 1971, and Yerkes and others, 1965).

zone and the mountains marks the boundary between the granitic basement beneath the eastern mountains and Jurassic phyllites and schists that comprise the top of the basement in the western mountains.

Juxtaposition of contrasting basement complexes along the fault zone is thought to have occurred sometime between Late Cretaceous and middle Miocene time (Yerkes and others, 1965). According to Hill (1971) the basement contact marks the location of the Southern California subduction zone which separates oceanic (western basement complex) and continental facies (eastern basement complex). Active during Cretaceous time, the subduction zone extended both southeast along Baja California and northwest, across the Transverse Ranges, where it is delineated by the Sur-Nacimiento zone in the southern California Coast Ranges. Yeats (1973) generally agreed with Hill's subduction zone hypothesis but, because greenschist facies are found both east and west of the Newport-Inglewood zone, suggested that the basement contact does not follow the fault zone in the Los Angeles Basin. Yeats proposed instead that it diverges from the fault zone north of the Sunset Beach oil field and continues north around the Anaheim nose. Similarly, chiefly because the Catalina Schist is not observed in wells north of the Schist Ridge, Barrows (1974) hypothesized that the basement contact coincides with the Schist Ridge north of the Dominguez Hills oil field. At Playa del Rey the contact continues northwest and merges with the Malibu Coast fault.

Northwest-southeast compression and propagation of basement anistropies into superjacent strata began in the southern California region at the end of Miocene time. However, localization of shear strain and deformation along the Newport-Inglewood zone began chiefly during the initiation of the Pasadenan orogeny in late Pliocene time (Yeats, 1973). Locally along the fault zone 4000 ft of dextral offset has been suggested (Wright and others, 1973). Vertical displacement of the basement surface is as much as 4000 ft in some places, but decreases progressively in younger strata (Yerkes and others, 1965).

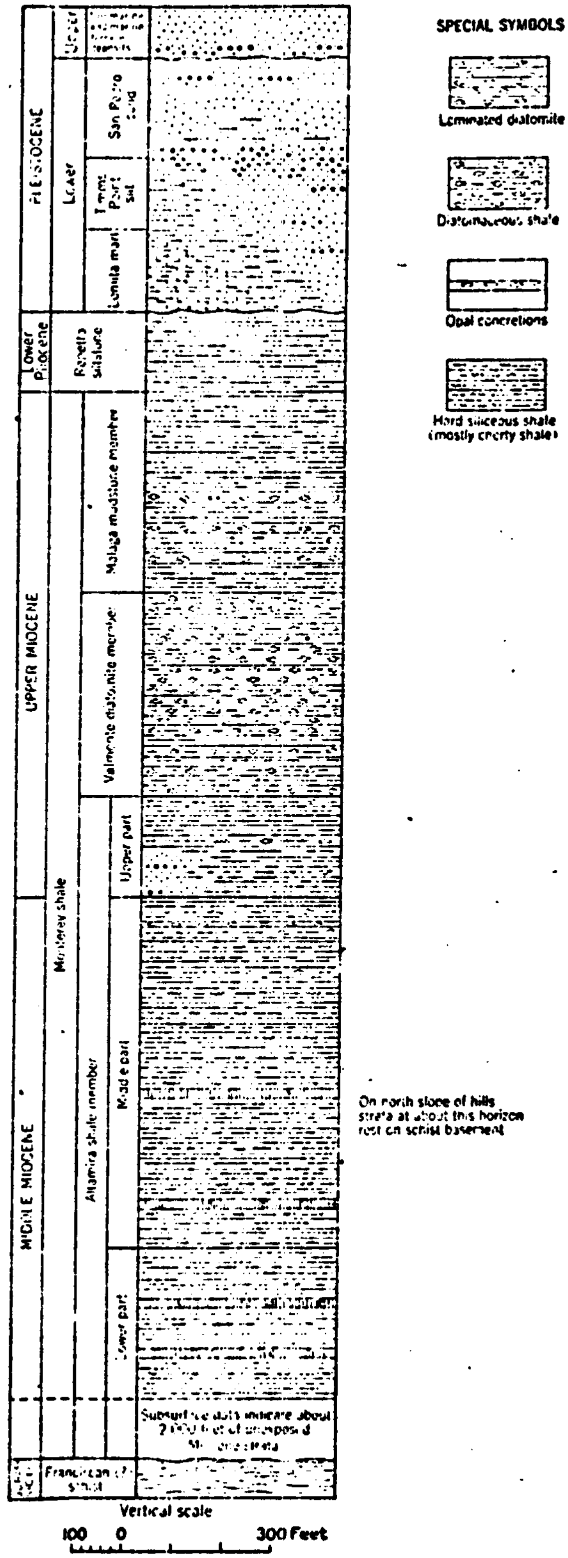
Southwestern Block

Topographically the southwestern block is a low plain extending from Santa Monica to Long Beach (Fig. 14). Rising more than 1300 ft above the plain, the Palos Verdes Hills represent the only significant relief. The Palos Verdes Hills is essentially a broad, doubly plunging anticline that has been uplifted along a steep southwest-dipping reverse fault termed the Palos Verdes fault (Woodring and others, 1946).

Basement rocks are exposed only on the Palos Verdes Hills but samples of basement have been recovered from wells drilled through superjacent Cenozoic strata beneath the block's many oil fields. Basement rocks consist chiefly of a fine-grained, intensely foliated, chlorite schist which contains secondary amounts of the blueschist-facies minerals, glaucophane and lawsonite (Woodford and others, 1954), although actinolite bearing greenschists characterize the basement near the Newport-Inglewood zone (Yeats, 1973). These rocks, referred to as the Catalina Schist, also are exposed 20 mi offshore on Catalina Island, and during part of Miocene time formed an extensive highland termed Catalinia by Woodford and others (1954). Prior to metamorphism the schist on Catalina Island consisted of shale, graywacke, conglomerate, mafic volcanic rocks, and chert. These are similar in proportion to the unmetamorphosed part of the Coast Ranges' Upper Jurassic to Upper Cretaceous Franciscan Formation and is considered equivalent to that formation (Bailey and others, 1964). The basement reaches a maximum elevation of 1000 ft above sea level on Palos Verdes Hills and dips to 2000 ft below sea level near the southwest side of the Palos Verdes fault (Fig. 8). On the northeast side of the fault the basement abruptly drops to 5000 to 8000 ft below sea level. A steep Bouguer gravity gradient present on the northeast side of the hills appears to be associated with this difference in basement elevation (McCulloh, 1957). Beneath the coastal plain to the north its surface generally slopes northeastward from 5000 ft below sea level near the coast to 14,000 ft below sea level along the Newport-Inglewood zone (McCulloh, 1960). The Torrance-Wilmington basement high and a northwest-trending series of basement arches known as the Schist Ridge interrupt the basement gradient. The Alondra, Lawndale, El Segundo, Hyperion, Playa del Rey, and Torrance-Wilmington oil fields occur over anticlines which may in part represent incidental folds draped over basement structures formed prior to middle Miocene time (Woodford and others, 1954; Yerkes and others, 1965). Pliocene deformation is probably responsible for most of the folding, however (Conrey, 1967).

Tertiary strata older than middle Miocene are not known to occur in the southwestern block (Figs. 7 and 15). Whether their absence is because of erosion or nondeposition is unknown. Yerkes and others (1965) prefer erosion as 14,000 ft of Upper Cretaceous to Oligocene rocks occurring to the east in the San Joaquin Hills probably extended across the present site of the Newport-Inglewood zone to the southwestern block. Reed and Hollister (1936) and Woodring and others (1946) suggested that the Catalina uplift may have occupied the western Los Angeles Basin and the shelf area as early as Paleocene time. The uplift could have been covered with Cretaceous sediments which were not stripped away until the end of Miocene time, thus delaying exposure of the Catalina Schist, the source for the middle Miocene San Onofre Breccia. Contrastingly,

Figure 15. Generalized stratigraphic section in the Palos Verdes Hills (from Woodring and others, 1946).



PLEISTOCENE
Lower
San Pedro sand
Lomita marl
Lower Pliocene
Repetto siltstone
UPPER MIOCENE
Malaga mudstone member
Valmonte diatomite member
Monterey shale
Upper part
MIDDLE MIOCENE
Altamira shale member
Middle part
Lower part
SPECIAL SYMBOLS
Laminated diatomite
Diatomaceous shale
Opal concretions
Hard siliceous shale (mostly cherty shale)
On north slope of hills strata at about this horizon rest on schist basement
Vertical scale
100
0
300 Feet

Yeats (1973) reported that it is unlikely that pre-middle Miocene strata would be entirely removed by erosion while none of the Catalina Schist would have been eroded and subsequently deposited as sedimentary rocks. Though the evidence is indirect it does indicate that prior to Miocene time the Catalina basement did not receive sediments and was not subject to erosion. Instead, the Catalina Schist was tectonically exposed to sedimentation and erosion as a ridge in early middle Miocene time.

Approximately 2000 ft of middle and upper Miocene strata of the Monterey Shale are exposed on the Palos Verdes Hills (Fig. 15). Outcrop and subsurface data indicate that the strata thicken southward and reach a minimum thickness of 4000 ft near Point Fermin (Woodring and others, 1946). Thickening is accomplished through addition of older strata at the section's base. Middle Miocene rocks belong to the lower and middle parts of the Altamira Shale Member. The lower sequence is at least 275 ft thick and consists principally of silty and sandy shale with minor amounts of siliceous shale, tuff, and schist breccia. The lower sequence is not observed to lie directly on basement indicating possibly that the schist breccia at this horizon is derived from a source further west and is temporally equivalent to the San Onofre Breccia. The middle part of the Altamira Shale is about 700 ft thick, consists chiefly of cherty shale, and is the most widely distributed division of the Monterey Shale. On the north slope of the hills, the middle sequence rests directly on Catalina Schist.

Oil field data sheets (California Division of Oil and Gas Fields, Part 2, 1961) reveal a conspicuous absence of middle Miocene rocks from areas of the coastal plain to the north of Palos Verdes Hills (Fig. 7) denoting exposure of the area at the end of middle Miocene time. An extensive area of the southwestern block was uplifted along the Newport-Inglewood zone during late middle Miocene time such that the southwest shore of the middle Miocene Los Angeles Basin was probably only a few miles west of the present coastline (Yerkes and others, 1965). According to Yeats (1973) early middle Miocene east-west extension occurred in southern California as a result of the intersection of the East Pacific Rise and the North American plate. Displacements along north to northwest-trending fractures initiated the formation of the Los Angeles Basin and, more generally, the fault block topography of the Borderland. In contrast, subsidence and continuous deposition occurred in the Palos Verdes Hills area until early Pliocene time (Woodring and others, 1946), perhaps recording for the first time movement along the Palos Verdes fault.

In the Los Angeles Basin upper Miocene strata can be divided into two contemporaneous facies (Yerkes and others, 1965). The thicker eastern facies consists of a series of micaceous shale and siltstone, sandstone, and conglomerate derived from the north or northeast and occur throughout the basin. The western facies, exposed only in the southwestern block and in the San Joaquin Hills, is characterized by organic sediments, differing amounts of Catalina Schist detritus, a scarcity of coarse-grained rocks, and northward or eastward onlap of strata. In the Palos Verdes Hills the western facies is represented by the upper part of the Altamira Shale, Valmonte Diatomite, and Malaga Mudstone Members. The upper part of the Altamira Shale is characterized by phosphatic and bituminous shale which grade into the relatively pure diatomaceous strata of the Valmonte which in turn grade into the radiolarian mudstone of the Malaga Member (Fig. 15). Increasing amounts of eastern basement sediment contributions may be contained in the upper parts of the western facies. Fauna in middle to mid-upper Miocene sediments indicate accumulation in water depth ranging from less than 600 ft to more than 1800 ft (Woodring and others, 1946). Ingle (1967) suggested that the laminated diatomite of the Valmonte cropping out in Malaga Cove was deposited adjacent to a sill as deep as 3000 ft. Further, Malaga Mudstone fauna indicate destruction of the effective sill by progressive deepening of the Palos Verdes Hills area to over 9000 ft during late Miocene time. The maximum thickness of upper Miocene strata is approximately 1400 ft along the hills' southern slope but thin northward as basal strata decrease progressively in age. Beneath the coastal plane, however, the upper Miocene Puente Formation thickens eastward from 800 ft at the Playa del Rey oil field to 3200 ft at the Alondra field. Immediately east of the Palos Verdes Hills beneath the Torrance field the Puente is 2230 ft thick. After the middle Miocene emergence of the western basement north of the Palos Verdes fault upper Miocene deposits derived from eastern basement sources onlapped western basement from northeast to southwest. Yerkes and others (1965) suggest this pattern of sedimentation indicates that the subsidence of the upper Miocene Los Angeles Basin began southeast of the southwestern block and spread north and west. According to Atwater (1970) the subsidence was due to crustal stretching resulting from the nonalignment of the coast and San Andreas trend after the attachment of the Pacific and North American plates.

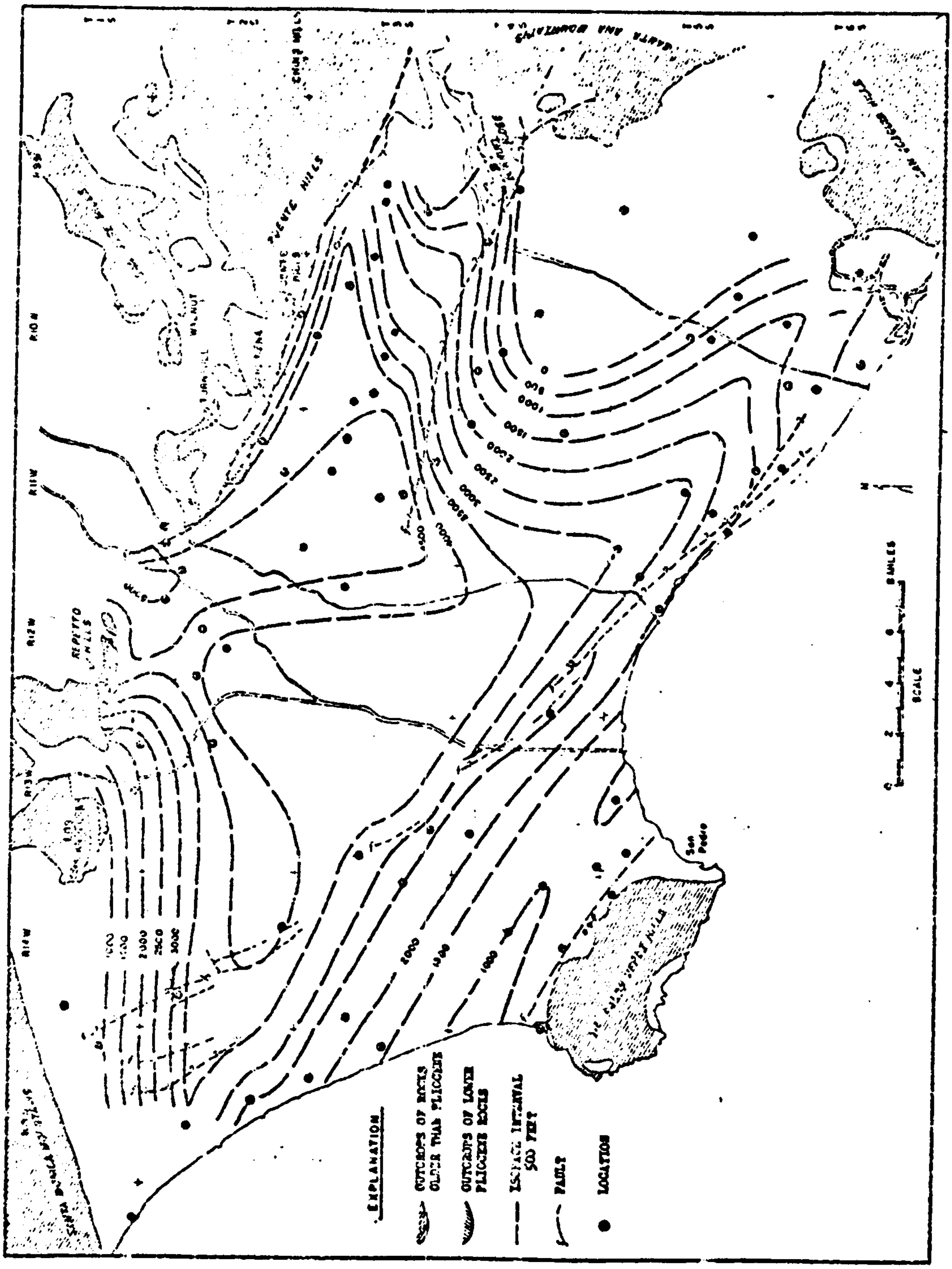
Lower Pliocene strata, the Repetto Formation, are as thick as 5000 ft in the Los Angeles Basin but thin progressively westward to 1000 ft beneath the Wilmington oil field and 400 ft beneath the Torrance field (California Oil and Gas Fields, Part 2, 1961). In the Palos Verdes Hills the Repetto is represented by 150 ft of soft, massive, glauconitic siltstone containing some Catalina

Schist detritus apparently derived from the south or west (Woodring and others, 1946); however, most sediment was derived from sources north of the hills. Foraminifera similar to forms presently living in Borderland basins indicate that the Repetto accumulated in seas as deep as 6000 ft (Woodring and others, 1946; Ingle, 1967). Ingle (1967) suggested that the Repetto exposed in Malaga Cove was deposited on the flanks of a bottom prominence initially produced at the end of Miocene time. The top of the unit has been eroded and fauna indicate that the entire lower Repetto and part of the middle Repetto, represented by 150 ft of strata beneath the Torrance field, are missing. Stratigraphic equivalents of a significant part of the basin section, however, are present. Together with the westward thinning of lower Pliocene strata these data suggest that the original thickness was never significantly greater than that presently exposed. The hiatus at the base of the section indicates renewed movement of the Palos Verdes Hills relative to the remainder of the southwestern block at the end of Miocene or beginning of Pliocene time. Woodford and others (1954) believed that during early Pliocene time the southwestern block stood several thousand feet higher than the central part of the basin. Conrey (1967) performed a detailed study of lower Pliocene faunal and sedimentary patterns and concluded that a submarine sill 6000 ft deep in the vicinity of the Palos

Verdes Hills and Santa Monica Bay again separated the Los Angeles and Santa Monica Basins. At the end of early Pliocene time the sill rose to a minimum depth of 4000 ft. Ingle (1967), also using faunal data, proposed that by middle Pliocene time the sill had been uplifted almost to sea level along the trend which today forms the Palos Verdes Hills, the San Pedro Shelf, and the Lasuen Knoll. Conrey (1967) attributed the shoaling of the sill to dip-slip movement along the Palos Verdes fault forming a submarine scarp that extended northwest and southeast of the present fault trend on land. Additional evidence for tectonic unrest is seen from isopach maps which reveal that the Torrance-Wilmington and Playa del Rey structures initiated development chiefly during early Pliocene time (Fig. 16). According to [illegible] (1973) this deformational episode is due to the attachment of the Peninsular Ranges and Los Angeles Basin to the Pacific plate which was moving northwest relative to the North American plate. This resulted in propagation of basement anisotropies into superjacent strata as dextral shear along northwest-trending faults, normal movement along north-trending faults, and reverse movement along west-trending faults. As Ingle (1967) stressed, uplift of the Palos Verdes Hills area occurred during the period of maximum subsidence in the Los Angeles Basin.

According to Woodring and others (1946), the strong-

Figure 16. Isopach map of lower Pliocene strata showing incipient formation of the Torrance-Wilmington and Playa del Rey structures (from Conrey, 1967).



EXPLANATION
OUTCROPS OF ROCKS OLDER THAN PLIOCENE
OUTCROPS OF LOWER PLIOCENE ROCKS
ISOPACH INTERVAL 500 FEET
FAULT
LOCATION
SCALE
MILES
SANTA ANA MOUNTAINS
PUENTE HILLS
REPETTO HILLS
San Pedro

est interval of deformation in the Palos Verdes Hills area occurred during the Pasadenan orogeny beginning in late Pliocene time. Miocene and lower Pliocene strata were folded into the Palos Verdes Hills anticlinorium which subsequently stood as an island. As a result, although 3000 ft of upper Pliocene Pico Formation occur along the Schist Ridge and 1800 ft beneath the Torrance field (California Oil and Gas Fields, Part 2, 1961), upper Pliocene deposits are absent from the hills. Large areas along the Newport-Inglewood zone and parts of the southwestern block also were exposed to erosion. In addition, important dextral offset along pre-existing northwest-trending faults began during latest Pliocene time and is still continuing (Wright and others, 1973). Abrupt contrasts in basement surface configuration as well as lithology and thickness of Miocene through Pliocene strata may be because of lateral movement across the Palos Verdes fault, especially in Quaternary time (Yerkes and others, 1965). This hypothesis is consistent with frequent observations that abrupt changes in thickness on opposite sides of faults in the Los Angeles Basin are due to horizontal movement rather than progressive vertical displacement contemporaneous with deposition (Wissler, 1941). Dextral shear along northwest-trending faults initiated in southern California at the end of Miocene time. Localization of strain along the Newport-Inglewood zone, however, did not begin until the late Pliocene (Yeats, 1973). For the first time, the southwestern block began to move as a rigid plate with respect to the remainder of the Los Angeles Basin. As a result, dip-slip movement along the Santa Monica fault ceased east of the Newport-Inglewood zone.

Subsidence occurred again in the southwestern block during early Pleistocene time and as much as 1000 ft of coarse marine sediments were deposited (Yerkes and others, 1965). In the Palos Verdes Hills area these deposits are subdivided into three units, the San Pedro Sand, the Timms Point Silt, and Lomita Marl. Woodring and others (1946) assigned formation rank to each even though they appear to be facies of a single major stratigraphic unit. However, the granitic sand facies is encountered most frequently and for this reason the name San Pedro Sand is commonly used to designate the entire lower Pleistocene sequence. This latter terminology has been adopted in this paper. The Lomita Marl and Timms Point Silt occupy the base of the section wherever they occur and on the basis of faunal and stratigraphic evidence are considered to be essentially synchronous deposits (Woodring and others, 1946). Though parts of the San Pedro Sand are the same age as the Lomita Marl and Timms Point Silt, most of the unit is younger. Correlation with fossiliferous coarse deposits near Long Beach and Santa Monica (Woodring and others, 1946; Poland and others, 1956; Poland and others, 1959) and along the coast immediately north of Palos Verdes Hills (Zielbauer and Burnham, 1959; Poland and others, 1959) have been made. Between Santa Monica and Palos Verdes Hills, the top of the San Pedro Sand is generally less than 150 ft below sea level. Faunal associations within all three units indicated deposition in waters ranging in depth from less than 60 ft to about 500 ft suggesting the Palos Verdes Hills formed a shallow bank during early Pleistocene time (Woodring and others, 1946). At the end of early Pleistocene time most of southwestern block was only slightly submerged and a series of shoals may have existed along the Newport-Inglewood zone (Yerkes and others, 1965).

Deformation of the Palos Verdes Hills area was renewed during middle to late Pleistocene time and the hills were uplifted as a block along the Palos Verdes fault. Areas immediately adjacent to the hills may have been depressed 500 to 1000 ft allowing the hills to form an island (Yerkes and others, 1965). Thirteen well-defined terraces, evidence of this uplift, ring the hills. The oldest terrace is at an elevation of approximately 1300 ft, the youngest or first terrace at 100 ft. The time interval between the deposition of the San Pedro Sand and the cutting of the oldest terrace is unknown but may represent more than one-third of Pleistocene time (Woodring and others, 1946). Marine deposits on the oldest terrace have been dated from 330,000 ± 50,000 to 420,000 ±

60,000 years by Fanale and Schaeffer (1965 helium-uranium ratios). Marine sand and gravels on the youngest platform are the only terrace deposits to receive formal stratigraphic designation. These deposits, the Palos Verdes Sand, have been dated at 70,000 ± 10,000 to 110,000 ± 15,000 years by Szabo and Rosholt (1969, open system U-series method), and 95,000 ± 15,000 to 130,000 ± 20,000 years by Fanale and Schaeffer (1965, helium-uranium ratios). These dates are in general agreement with those measured for emergent terrace deposits near Santa Cruz, on San Nicholas Island, and in the Santa Monica Mountains (Birkeland, 1972). Irrespective of whether a long or short chronology for the glacial Pleistocene is adopted, paleotemperature and eustatic sea level curves, summarized by Cooke (1973), indicate that the Palos Verdes Sand was deposited during an interglacial period, 80,000 to 150,000 y.b.p. Seawater temperatures indicated by Palos Verdes fauna are also suggestive of deposition during an interglacial period (Woodring and others, 1946). Inasmuch as the first terrace as well as the Palos Verdes Sand occurs on all sides of the hills, Woodring and others (1946) concluded that the hills continued to stand as an island during Palos Verdes time. Similarly, Valentine (1961) reconstructed the Palos Verdes shoreline on the basis of molluscan assemblages. He extended it as far as 15 mi inland from the present shoreline so that a shallow protected sea existed on the lee side of Palos Verdes Hills. According to the sea level curve of Fairbridge (1961) and the paleotemperature curve and summary of high sea level ages presented by Emiliani and Rona (1969), however, the Palos Verdes Sand also could have been deposited during a lowstand (Illinoian ?) approximately 110,000 y.b.p. The near surface coastal stratigraphy tends to support this view. Within the southwestern block faunal correlations have been made with deposits along the coast from Long Beach to Santa Monica (Woodring and others, 1946; Poland and others, 1956; Poland and others, 1959; Zielbauer and Burnham, 1959). Although generally less than 10 ft thick on the first terrace, the Palos Verdes Sand is as much as 60 ft thick along the coast between the hills and Manhattan Beach. The deposits are characterized by large lateral as well as vertical lithologic variations and are thought to represent shallow lagoonal, tidal, and beach sediments accumulated under rapidly changing conditions (Zielbauer and Burnham, 1959). The position of these deposits along the present coastline indicate the shoreline during Palos Verdes time was west of the position suggested by Valentine (1961). This interpretation is reinforced by the presence of a buried stream channel near Redondo Beach. This channel, the "Gardena River" (Zielbauer and Burnham, 1959), is believed to be important in the erosional history of Redondo Submarine Canyon (Riccio, 1965; Yerkes and others, 1967). The Gardena River is an ancestral principal distributary of the Los Angeles River drainage system and is filled with mixed estuarine and fluvial deposits termed the Gardena Sand. The Gardena Sand is temporarily equivalent to and slightly older than the Palos Verdes Sand. It seems possible, if a short glacial chronology assumed, that the "Gardena River" was cut as early as the Illinoian Glaciation and backfilled during the Sangamonian transgression. If interpreted in the context of a long chronology, the Palos Verdes Sand would have been deposited entirely during the Wisconsin glaciation. In either case, it can be reasonably inferred that the Palos Verdes Sand accumulated during a period of significant fluctuations in sea level.

Similarly, unnamed upper Pleistocene deposits, in part equivalent to marine deposits on the upper 12 terraces on Palos Verdes Hills, are inferred to have both marine and continental origins (Poland and others, 1959; Riccio, 1965). The lower half of the deposits ("200-foot sand"), may be locally conformable above the San Pedro Sand and consists of sand and gravel probably deposited in littoral and deltaic environments. During their accumulation the shoreline was along the Newport-Inglewood zone. The upper half, mostly silt, clay, and sand, is inferred to represent flood plain deposits formed after the Los Angeles Basin had completely filled with sediment (Poland

and others, 1959). The unnamed upper Pleistocene deposits are thickest (400 (?) feet) along the axis of a near-surface synclinal trough that underlies much of the coastal plain south of Ballona Creek. Although these deposits thin toward the west, they are in hydraulic contact with salt water (Poland and others, 1959) and, consequently, may exist offshore beyond the syncline's western limb (Riccio, 1965).

Where the Palos Verdes fault intersects the present shoreline it appears as a "broad crush zone" within Quaternary strata (Zielbauer and Burnham, 1959). Curiously, cumulative displacement of the San Pedro Sand and the lower part of the Palos Verdes Sand along the many subparallel fault planes is only 250 ft. Younger strata are only slightly displaced or deformed. The crush zone is believed to be the result of the intersection of the Palos Verdes fault and an inferred fault which trends northward, the Coastal fault. The Coastal fault depressed strata on the east and [illegible]ght to have been active principally during the latter hal[illegible] Pedro time. Total displacement probably does not exceed 180 ft and Palos Verdes deposits remain unaffected.

From the preceding discussion it is apparent that the Palos Verdes Hills and the remainder of the southwestern block have not always acted as a single tectonic unit with respect to the central part of the Los Angeles

Basin. Although uplift of the hills along the Palos Verdes fault can be conclusively demonstrated only for late Pleistocene time, it is probable that Miocene, Pliocene, and early Pleistocene movement also occurred. Both vertical and horizontal displacements are indicated. As a result, the area now occupied by the Palos Verdes Hills was a submerged portion of Catalinia during middle Miocene time. During the late Miocene and again in early Pliocene time it formed part of an extensive sill that separated the Los Angeles Basin from the Santa Monica and San Pedro Basins. By middle Pliocene time the sill had risen to within a few feet of sea level. Owing to folding at the initiation of the late Pliocene Pasadenan orogeny the hills emerged as an island. Erosion and subsidence followed allowing the formation of another shallow bank at the beginning of the Pleistocene Epoch. During late Pleistocene time at least 1300 ft of uplift occurred and again the hills stood as an island. By latest Pleistocene time the hills had merged with the mainland to form a peninsula.

Santa Monica Mountains

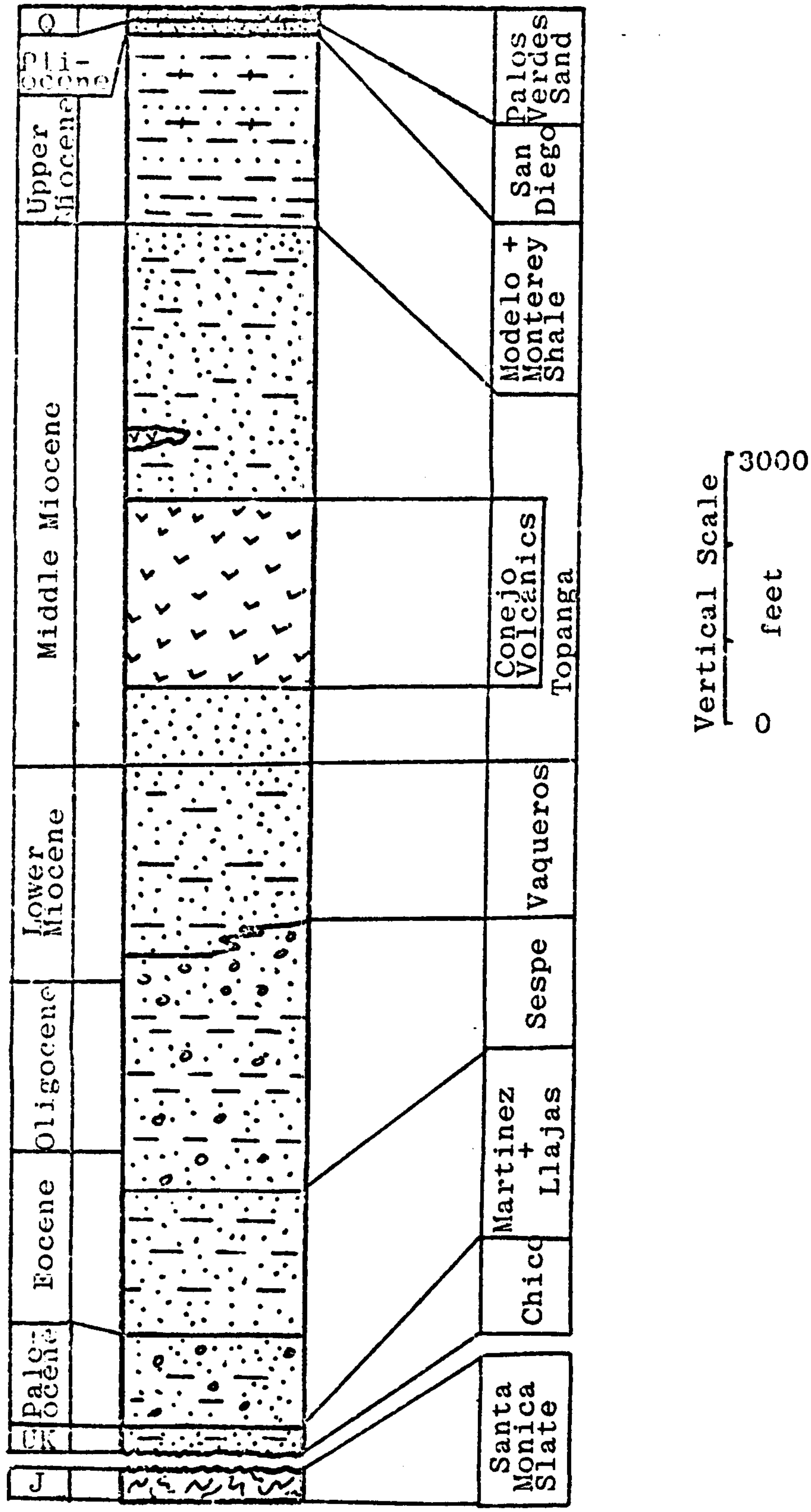
The Santa Monica Mountains, part of the Transverse Ranges, rise as much as 3000 ft above the northern part of the Los Angeles Basin (Fig. 1). The Channel Islands, San Miguel, Santa Rosa, Santa Cruz, and Anacapa represent the westward continuation of the mountains. The following discussion is concentrated on that portion of the range west of its intersection with the Newport-Inglewood zone. This includes the western Santa Monica Mountains and the Northern Channel Islands, that is, Anacapia (Reed and Hollister, 1936).

The Santa Monica Mountains are essentially a broad westward plunging fold with a steep south flank. Similarly, Santa Cruz and Santa Rosa Islands are anticlines truncated by large west-trending faults near their axes (Bailey and Jahns, 1954). The Santa Monica-Malibu Coast fault (Figs. 8 and 11) is a north-dipping reverse fault separating the western Santa Monica Mountains from the southwestern block and the Los Angeles Basin. The basement surface is upthrown more than 7500 ft along the fault zone but displacements progressively diminish in younger strata. Though upper Pliocene beds transgress the fault east of the Newport-Inglewood zone, Pliocene and Pleistocene strata west of Beverly Hills are cut by the fault.

The western Santa Monica Mountains basement rocks include slates, phyllites, and schist collectively termed the Santa Monica Slate. In the eastern mountains these rocks have been intruded by plutonic rocks of granodioritic composition. The Santa Monica Slate shows no compositional or textural features in common with the Franciscan Formation. However, at least part of the Santa Monica Slate is of Late Jurassic age (Imlay, 1963) indicating that both assemblages were deposited contemporaneously, as suggested by Reed and Hollister (1936). In contrast to the southwestern block, Upper Cretaceous through lower Miocene marine and nonmarine strata occur in Anacapia (Fig. 17).

According to Yeats (1973), early middle Miocene tectonic activity was the result of east-west extension associated with the intersection of the East Pacific Rise and the continent. Westward rafting of the area now occupied by the Santa Monica Mountains with respect to the incipient Los Angeles Basin allowed Franciscan basement to rise up in the rift bounded presumably on its north side by the Santa Monica-Malibu Coast fault though the actual location of the fault may be further south. The area north of the basement ridge remained submerged and received detritus shed from it. Middle Miocene strata (Topanga Formation) are widespread and consist of 3000 to 15,000 ft of coarse-grained marine sediments with lesser amounts of siliceous shale. Lenses of San Onofre Breccia are present on Santa Cruz Island in the lower part of the section and thick sequences of plutonic and volcanic rocks, ranging in composition from basalt to andesite, occur in the upper part (Bailey and Jahn, 1954). South of the Malibu Coast fault unnamed middle Miocene rocks include shale, sandstone, dolomite, chert, breccia, and volcanic rocks (Jennings and Strand, 1969). Following the deposition of the

Figure 17. Generalized stratigraphic section in the Santa Monica Mountains (after Vedder and others, 1974).


Q
Pli-ocene
Upper Miocene
Middle Miocene
Lower Miocene
Oligocene
Eocene
Paleocene
UK
J
Palos Verdes Sand
San Diego
Modelo + Monterey Shale
Conejo Volcanics
Topanga
Vaqueros
Sespe
Martinez + Llajas
Chico
Santa Monica Slate
Vertical Scale
3000
feet
0

shallow water Topanga deposits the Santa Monica Mountains were uplifted. An angular discordance of as much as 90° is observed in some localities in the eastern half of the mountains (Woodford and others, 1954). This unconformity, however, is not apparent farther west (Reed and Hollister, 1936) suggesting that at least parts of Anacapia remained submerged at the end of middle Miocene time. As in the southwestern block, subsidence renewed deposition over the entire area of the Santa Monica Mountains in late Miocene time.

The upper Miocene Modelo Formation belongs to the eastern facies described by Yerkes and others (1965). The eastern facies is characterized by its lithologic variability and contains strata ranging from shale to pebble conglomerate. Siliceous and diatomaceous shale of the Monterey type are common in some localities (Reed and Hollister, 1936) particularly south of the Malibu Coast fault near Point Dume (Jennings and Strand, 1969). The source for the coarse-grained sediments in the Santa Monica Mountains is believed to be in an area now occupied by the San Gabriel Mountains less than 50 mi to the northeast.

According to Vedder and others (1974), only very thin sections of Pliocene clastic sediment are exposed in the western Santa Monica Mountains (approximately 50 ft) and on Santa Cruz Island (less than 85 ft). Near the beginning of Pliocene time Anacapia was uplifted and has remained emergent ever since. The mountains acted as a source for lower Pliocene sediments deposited in the basin and southwestern block (Conrey, 1971), but evidently by late Pliocene time their contribution had been significantly reduced (Yerkes and others, 1965).

Late Miocene and early Pliocene tectonism was dominated by north-south compression in addition to sinistral movement (6 to 8 mi) along the Santa Monica-Malibu Coast fault system (Wright and others, 1973). Yeats (1973) suggested that the north-south compressional episode began at the end of Miocene time when the Pacific plate moved northwestward with respect to the North American plate. The basin and the southwestern block began moving beneath the rising Santa Monica Mountains. It should be emphasized that major deformation involving dextral offset on northwest-trending faults and reverse faulting in the Transverse Ranges did not begin until the Pasadenan orogony in late Pliocene time (Wright and others, 1973). After deposition of lower Pleistocene strata deformation was accelerated by dip-slip movement along the Santa Monica-Malibu Coast fault zone west of the Newport-Inglewood zone. The rate of uplift since the cutting of the 100,000 to 130,000 year old Dume and Corral terraces along the Malibu coast is estimated to be within the range of 1.0 to 1.5 ft per 1000 years (Birkeland, 1972).

Although the magnitude of displacements differ, the

Late Cenozoic histories of vertical tectonic movement of the Santa Monica Mountains and the Palos Verdes Hills are similar. Both areas were submerged portions of extensive highlands at the end of middle Miocene time. Subsidence during late Miocene time was followed by early Pliocene uplift and strong late Pliocene deformation. Uplift continued through Late Quaternary time.

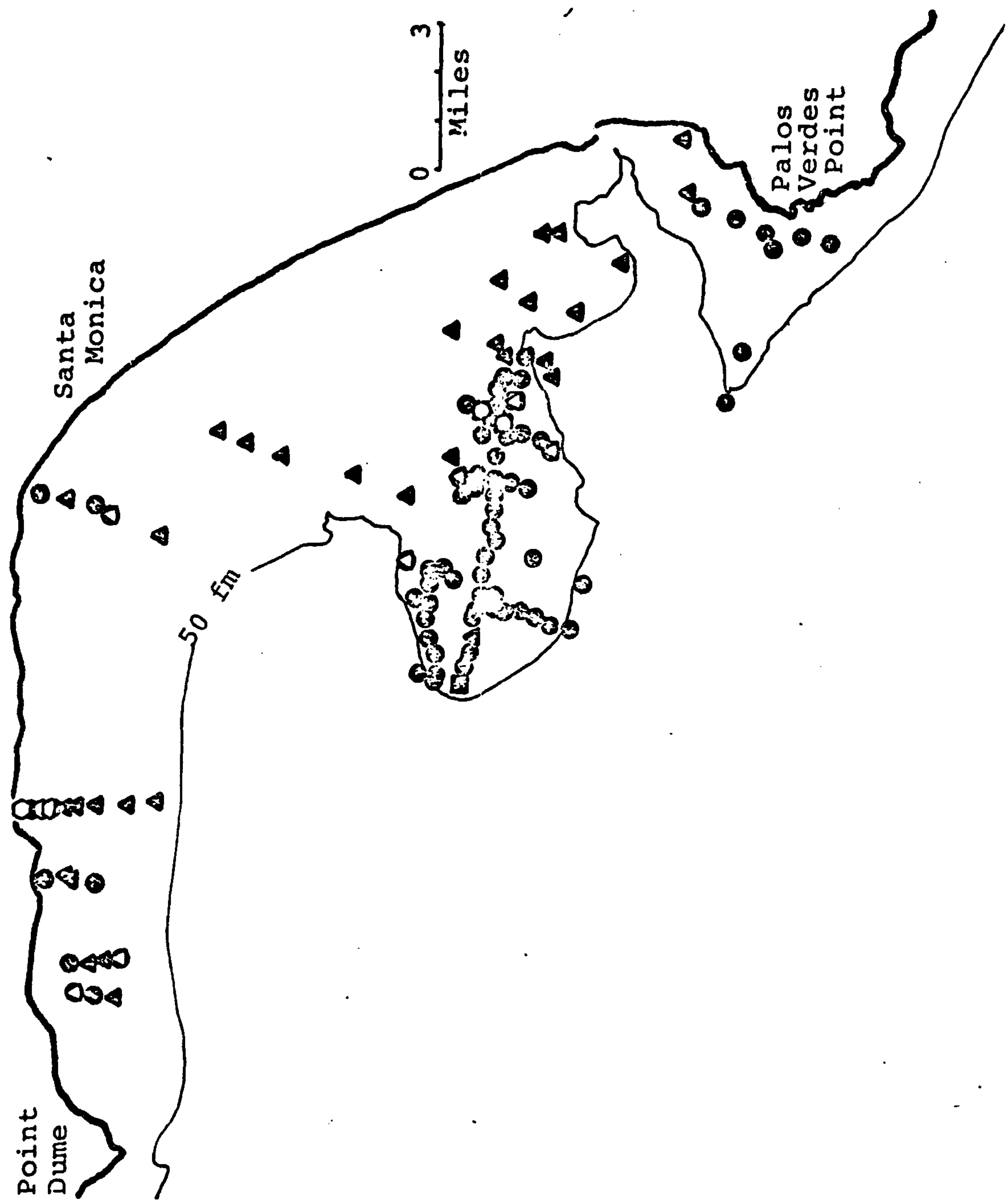
RESULTS

Bedrock Lithology

In order to more thoroughly determine the distribution of bedrock types in Santa Monica Bay, 107 jet core and dart core descriptions were obtained from unpublished sources. Micropaleontological results were not included in the descriptions. Location and basic lithology of the core samples are shown in Figure 18. Dart cores sample only the top foot of material and are useful primarily in the area of the shelf projection. Jet cores are obtained by jetting away the overburden as it is being penetrated. When resistence to coring is encountered, it is assumed that the bedrock surface has been reached and a discrete sample, generally less than 1 ft in length, is taken. In addition to detailed lithologic descriptions, information regarding the thickness and type of overburden usually is obtained. A comparison between the depth to the bedrock surface for each core and the minimum depth recorded on the seismic-reflection profiles, however, revealed that in many instances samples were recovered well below the bedrock surface. For example, penetration in the shelf projection where the overburden is less than 3 ft thick (Figs. A6 and

Figure 18. Location of jet and dart cores. The basic lithology of each sample is also shown.

- ● Shale
- ▲ Siltstone or sandstone
- ■ Limestone
- ⬢ Volcanic (Ash)



Santa Monica
Point Dume
Palos Verdes Point
50 fm
0
3
Miles

A7) was at times as much as 150 ft. Conversely, some samples were recovered within the Quaternary overburden when either a resistant conglomeratic layer was encountered or the maximum depth for the coring system was reached. Penetration exceeding 300 ft commonly was achieved in cores from along the inner shelf.

Core-profile comparisons were also done in order to determine whether lithologies could be matched with distinctive acoustic signatures. Seismic-reflection profiles show that the shelf projection and the narrow shelf adjacent to Palos Verdes Hills are characterized by folded reflecting surfaces (Figs. A6, A7, A8, A15, A18, A21, and A22). In these areas, 3 cores were discovered to contain bedrock samples of both sandstone and shale, 2 others sandstone alone, 1 limestone, 1 limestone and sandstone, and 2 limestone and shale. The remaining 63 cores contained only shale. Beneath the inner shelf south of Santa Monica, the profiles are characterized by relatively undeformed reflecting surfaces. Core samples (16) from these strata invariably consist of sand or silt. Thus, it appears that over a large portion of the shelf the lithology can be reasonably inferred from a profile's acoustic signature expressed as deformed or undeformed. The bedrock beneath the shelf adjacent to the Santa Monica Mountains cannot be characterized in this manner. Although the reflecting surfaces are folded and tilted, sandstone, siltstone, and volcanic ash in addition to shale have been recovered in cores.

Folded strata beneath the shelf projection is assigned to the Monterey Shale. Thirty-one of the cores contained samples of phosphatic shale similar to those in the upper part of the Altamira Member in the Palos Verdes Hills. Phosphatic shale was often associated with silty shale, which was either a primary or secondary constituent in 50 of the samples. Although silty shale occurs in all three parts of the Altamira, it is most abundant in the lower part. Eleven cores contained cherty shale, the principal constituent of the middle part of the Altamira Member. Only 5 cores contained samples of diatomaceous shale similar to the Valmonte Diatomite Member. Although Terry and others (1956) dredged mudstone from the area, samples characteristic of the Malaga Mudstone Member were absent from all cores. Schist pebbles were recovered, however, near the area where Terry and others also dredged schist fragments. It seems likely that the pebbles were recovered from a Miocene outcrop and not from the basement. These data suggest that the shelf projection is floored chiefly by middle and lower upper Miocene strata. Approximately 800 ft of upper Miocene, 150 ft of lower Pliocene, and 500 ft of lower Pleistocene strata present in the Palos Verdes Hills are apparently absent. A correlation between shale type and high resolution acoustic signature could not be found. Also, there is no obvious systematic distribution of shale types over the shelf projection.

Seismic-reflection records show that strata beneath the shelf adjacent to the Santa Monica Mountains are generally tilted toward the south (Figs. A10, A11, and A24). These strata are characterized by their lithologic variability and probably belong to middle and upper Miocene formations exposed in the mountains south of the Malibu Coast fault. Siltstone and silty shale are the most common rock types and are followed in abundance by sandstone, siliceous shale, and volcanic ash. Siltstone, sandstone, and shale sometimes occur at different depths within the same core hole. Record interpretations in this region have been unusually difficult because these strata apparently do not act as good reflectors. Penetration is limited and reflectors sometimes appear as indistinct discontinuous record surfaces.

Data from the Hyperion, El Segundo, and Playa del Rey oil fields along the coast (California Division of Oil and Gas Fields, Part 2, 1961) indicate that Pleistocene clastic sediments generally are less than 400 ft thick and that the top of the Pliocene section is little more than 500 ft below sea level. If these strata continue westward, then samples positioned along the inner shelf were probably recovered near the Pliocene-Pleistocene boundary. These samples consist chiefly of gray micaceous sandy silt and silty sand.

Interpretations of Seismic-Reflection Records

General Statement

Recognition and identification of geologic surfaces as represented on a graphic recording forms the basis for interpretation of seismic-reflection profiles. The first step in interpretative procedure is to differentiate traces of real reflecting surfaces from multiples and side echoes. Because all the profiles used in this study were direct products of an analog recorder, additional signal processing and record enhancement beyond initial amplification and filtering was not possible. For example, migration techniques which enable recorded surfaces to be relocated to their correct positions could not be used in this investigation. Differentiation between real and spurious reflectors had to be accomplished visually. Once a recorded surface has been established as real, then the reflecting surface it represents must be identified. A reflection is produced by an acoustic impedance contrast which is a function primarily of a density difference across a geologic discontinuity. The geologic discontinuity can be a sedimentary layer (or series of layers), an unconformity, or a fault plane. Records selected as an illustration in the text appears twice in each figure (for example, Figs. A3 and A14). Record surfaces believed to represent real features have been enhanced on only one duplicate so that each interpretation can be readily evaluated.

Overburden Thickness

Overburden thickness cannot be measured directly from the records because the velocity of sound in sediment or bedrock is greater than it is in water. The velocity of sound increases with increasing depth and in bedrock can be higher by a factor of 2 or more. Vedder and others (1974) used a constant velocity equal to 6400 ft/sec to calculate thicknesses of postorogenic strata. They recognized, however, that this value is undoubtedly too high for upper horizons. For example, typical Los Angeles Basin Pliocene sediments probably have velocities at shallow depths (less than 20 msec) not more than 25 percent greater than for seawater. In the Santa Monica and San Pedro Basins they used what they considered to be a more accurate velocity function: 4800 ft/sec = 0.5Z (Z = depth to the reflecting surface). However, they were reluctant to use this function elsewhere since variations in velocity from basin to basin can be large.

Generally, less error is associated with thickness estimates of Late Quaternary sediments. Using a submersible, Hamilton and others (1969) measured the <u>in situ</u> velocity of sound through different sediment types near La Jolla. They found that the velocity through clayey silts differed by less than 2.5 percent from the velocity through water at the same depths. Therefore, barring significant compaction, it is possible to read the thickness of Holocene sediment on the shelf directly from the records. However, velocities in pure sand sometimes differed by as much as 20 percent so that buried Pleistocene sand deposits could be 20 percent thicker than they appear on the records (Figs. A3, A4, A5, A10, A11, and A15).

As a result, maps depicting elevation, structure, and sediment thickness have been done in milliseconds rather than in feet (Figs. 25, 28, 29, and 33). Each map contains a conversion table which was constructed using the velocity of sound in seawater (4800 ft/sec) as the conversion factor. Therefore, only the minimum thickness of overburden or depth to a horizon can be determined from these tables.

Identification of Record Surfaces

Multiples can usually be identified and separated from real horizons since the first multiple appears at twice the water depth and has twice the slope of the seafloor trace. Each multiple occurs below the preceding one at a distance equal to the depth. Therefore, records gathered over shallow water can be expected to exhibit a number of multiples closely spaced near the top of the profile. The number and strength of the multiples increases in areas of high acoustic impedance contrasts. In these areas, the high resolution profiles contained more real reflectors and hence potentially more information than the air gun profiles.

A record surface generated by primary reflections from a real geologic interface (reflecting surface) will accurately represent the configuration of that interface only if its curvature is less than that of the wavefront. If the reflecting surface is sloping or uneven, then recorded reflections may return from it at different locations simultaneously or from a single location not directly beneath the shot point (Fig. 19). The result is that the recorded surface and the true reflecting surface are not coincident. Krause (1962) discussed several of the record traces to be expected from real reflecting surfaces. Figures 20, 21, 22, and 23 illustrate examples of record traces that represent geologic situations commonly encountered in seismic-reflection profiles. It is assumed that in the following examples the traverse was made parallel to the dip of the feature. Oblique and normal crossings produce somewhat different traces but the general principles and conclusions remain the same.

A situation often encountered is illustrated in Figure 20a. It shows a planar reflecting surface that

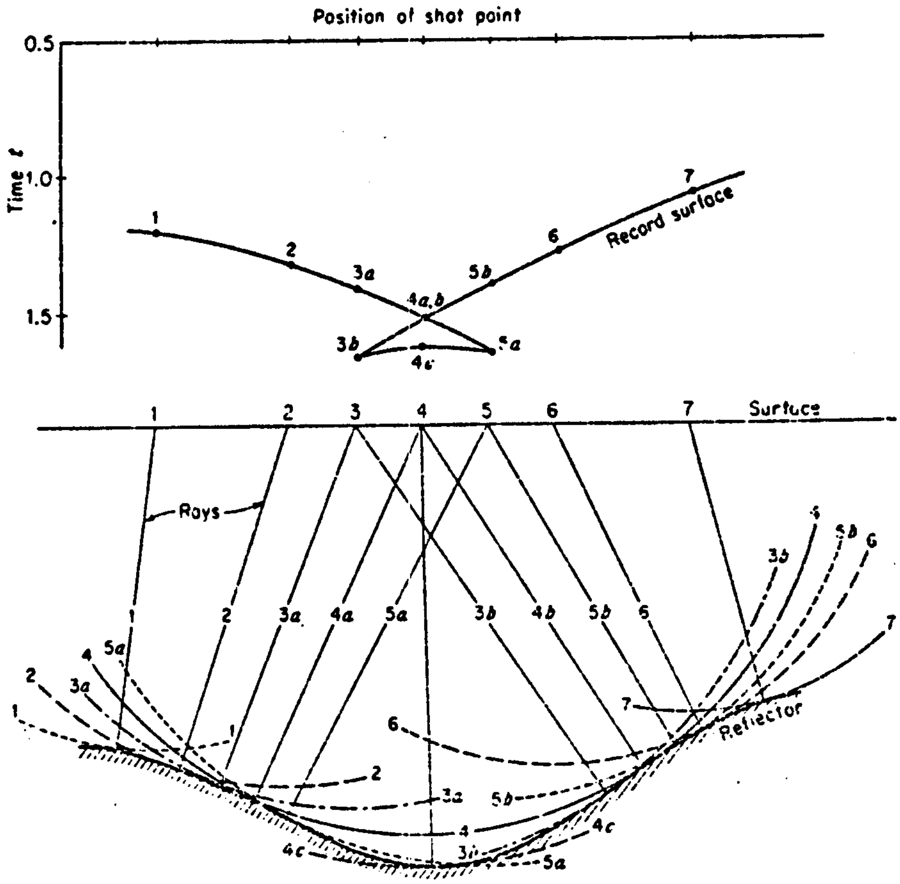
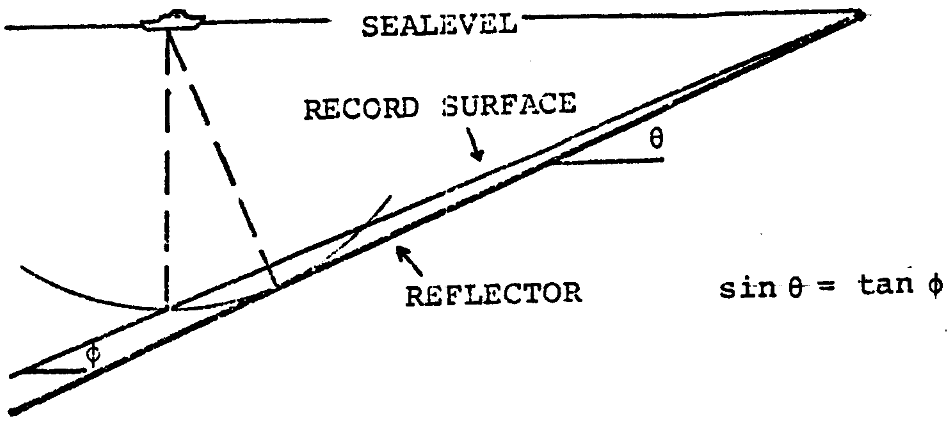


Figure 19. Double reflections from a surface more concave than the incident wavefront and the resulting record surface (from Grant and West, 1965).

Figure 20a. A reflecting surface with a constant slope is represented by a record surface with a smaller slope related by the function sin O = tan o (after Krause, 1962).

Figure 20b. Plot of O versus o shows that for slopes less than 30° slope corrections are negligible (from Krause, 1962).

A


SEALEVEL
RECORD SURFACE
θ
REFLECTOR
φ
sin θ = tan φ

B

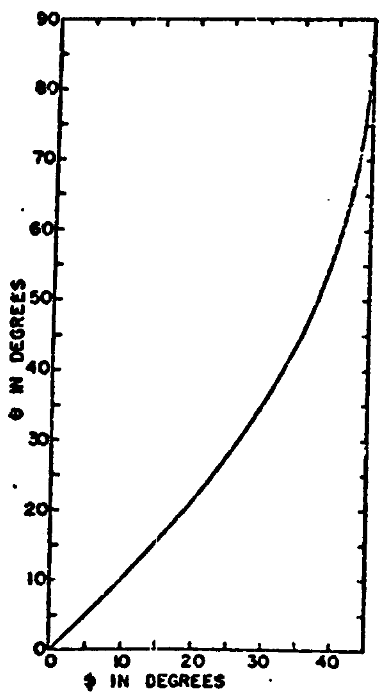
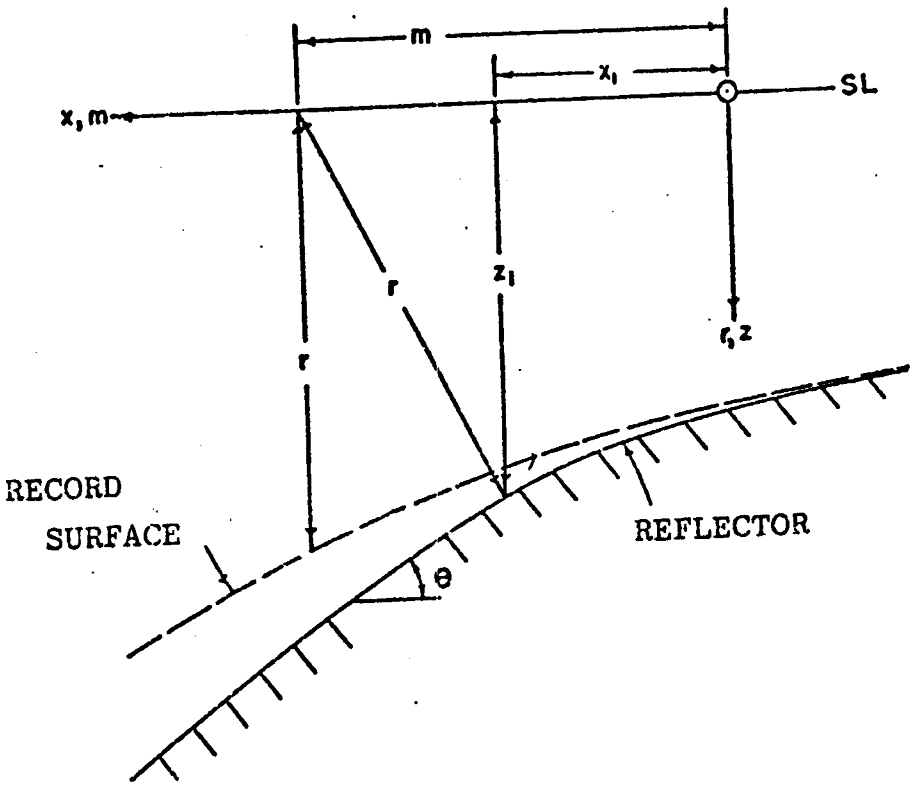

θ IN DEGREES
φ IN DEGREES
0
10
20
30
40
50
60
70
80
90

Figure 21. Record surface obtained from a reflecting surface with varying slope is expressed by the equation of a hyperbola (after Krause, 1962).



$$r^2 = (m-x_1)^2+z_1^2$$

where:

r = depth to record surface

x1 = horizontal coordinate of point of reflection

m = horizontal coordinate of sound source.

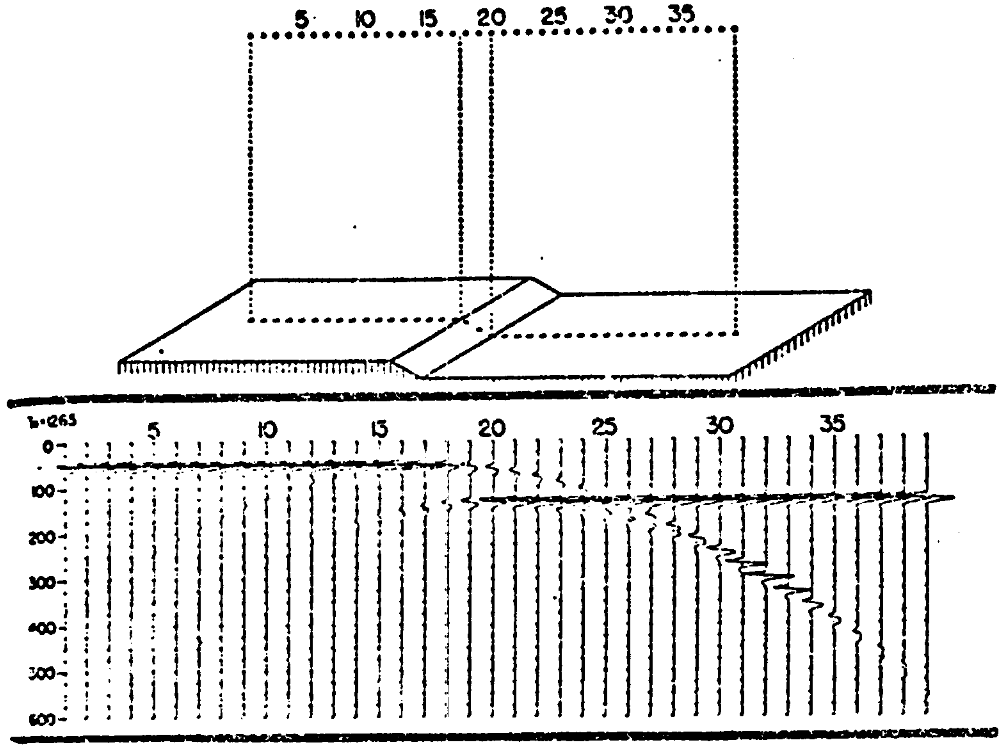


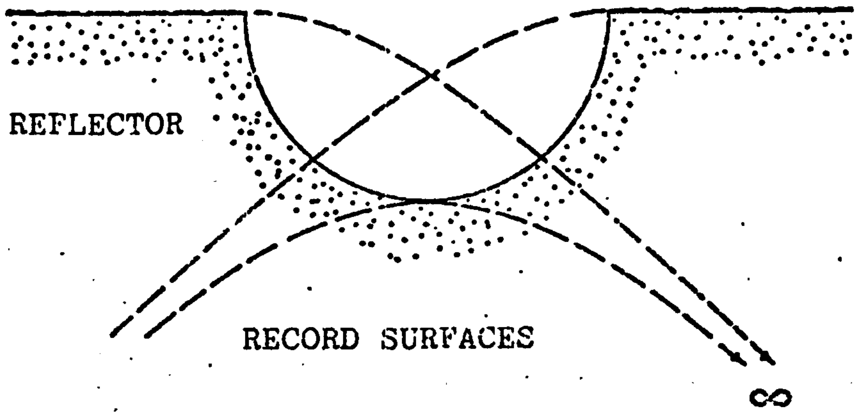
Figure 22. False record continuation past the reflecting surface termination is also hyperbolic (from Peterson and Walter, 1974).

Figure 23a. Record trace of a semicircular reflecting surface (after Krause, 1962).

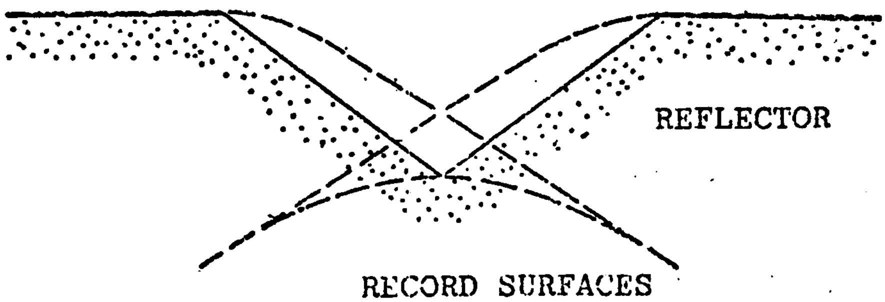
Figure 23b. Record trace of a "V"-shaped reflecting surface (after Krause, 1962).

Both features produce "crossovers" or side echoes.

A



B



could represent a basin slope, a submarine canyon wall, dipping Miocene strata, or a fault plane. Figure 20b shows that up to 30° the departure in these situations is small. Owing to the vertical exaggeration of the profiles, however, surfaces dipping more than 30° generally are not recorded. Submarine slopes rarely dip to that extent but tilted strata and particularly fault planes often do. As a result, fault planes are seldom represented as recorded surfaces and must be detected using different criteria. These criteria include discontinuities in acoustic signature possibly because of sudden lithologic changes (Fig. A8), displacement of strata (Figs. A8, A10, A16, A19, A20, A22, and A23), zones of chaotic bedding (Figs. A16 and A17), scarps (Figs. A8, A9, A10, A16, A19, A20, and A23), reverse drag along basin slopes (Figs. A21 and A24), and hyperbolic traces (Fig. A21). Unless the dips on fault planes can be determined (Fig. A23), the fault locations are shown as vertical lines on the profiles.

Hyperbolic record surfaces result if the reflecting surface is not planar but is instead characterized by a differing slope (Fig. 21). In general, hyperbolae are common features on seismic-reflection records and the following examples serve to illustrate why. On Figure 22 a reflecting surface analogous to a shelf break or terrace, or possibly displaced strata on either side of a fault, is depicted. The upper reflecting surface apparently continues far beyond its real termination. Figures 19 and 23 could represent submarine canyons, channels, or synclines. Note that in addition to the hyperbolae whose vertices are at the axes of the depressions, two other traces "cross over" the axis. In general at shelf and slope depths the horizontal and vertical errors introduced by hyperbolic traces are within the accuracy of trackline positioning and the resolution of the records. Therefore, they are not considered to seriously affect the accuracy of the structure-contour, isopach, or elevation maps. However, crossovers or apparent continuations of reflecting horizons may be mistaken for fault surfaces and thus complicate interpretations by obscuring real features within folded or faulted strata. Seismic-reflection profiles in Figures A16, A20, A21, A22, and A24 contain examples of hyperbolic traces and crossovers.

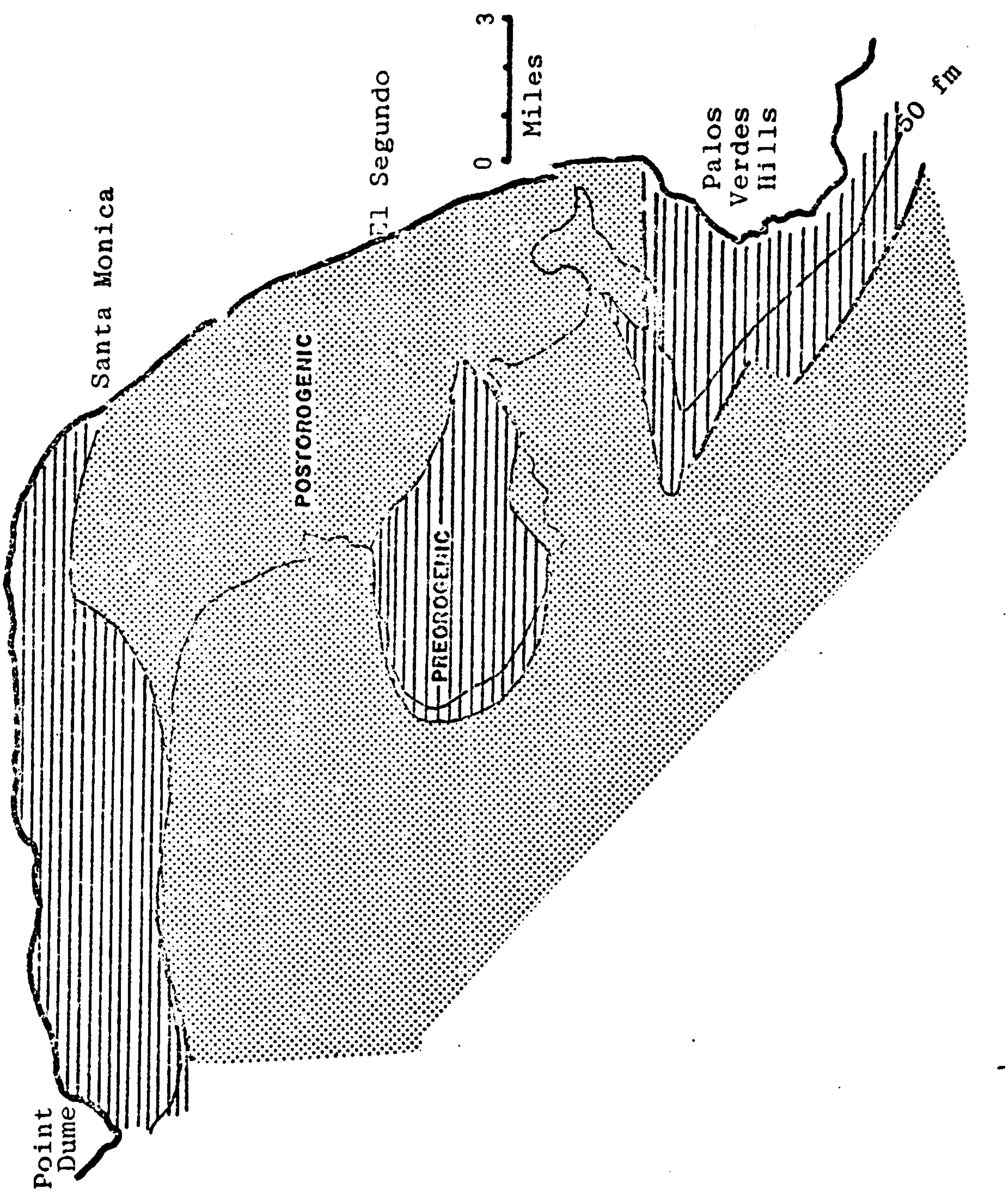
Nature and Significance of Reflecting Surfaces

The best means of determining the nature of a reflecting surface is to trace the surface to an area where it crops out and can be sampled. Of course, this is not always possible. Usually, subbottom control is provided by cores in which unconformities and bedding generally are apparent. Discontinuities visible in cores, however, are not always recorded on seismic-reflection profiles and *vice versa*. This is because most core discontinuities are lithologic, and lithologic changes do not consistently produce reflections. As stated earlier, reflections are produced by acoustic impedance contrasts which are largely functions of density. Since density is not solely dependent on lithology, a reflecting surface may have no relationship at all with lithology. Porosity, which is dependent on compaction, grain size (primary lithologic characteristic), and lithification, appears to be the important variable. For example, reflections can be easily produced between units of loose, water-laden sands and compact, relatively dry sands. Unless a reflecting surface can be coupled to a lithologic discontinuity, lithologic data does not represent a very useful aid to seismic-reflection profile interpretation. Instead, interpretations are based largely on the geometric configuration of record surfaces suggestive of common morphologic, sedimentologic, and structural features. For example, in this study, folds, faults, depositional structures such as cross stratification, and angular unconformities are generally recognized in this way (Figs. A3, A6, A10, A13, A14, and A20).

Vedder and others (1974) noted that for the California Continental Borderland both Miocene and post-Miocene sedimentary sequences appear as closely spaced reflectors, and that Miocene units show small-scale internal deformation to a greater extent than do younger units. Miocene and post-Miocene reflecting surfaces were easily differentiated when they occurred on the same profile since they were commonly separated by an angular unconformity. However, Moore (1967) (also Vedder and others, 1974) recognized that not all folded reflecting surfaces were necessarily pre-Pliocene strata because in some localities diastrophic activity continued into Pleistocene time. Therefore, locally where the precise age of an angular unconformity is unknown, deformed and undeformed strata can only be referred to as preorogenic and postorogenic, respectively. Similarly, Pinet (1975) found the preorogenic-postorogenic division necessary in interpreting seismic-reflection records from the Gulf of Honduras where fault block topography also is prevalent. It should be stressed that strata designated as postorogenic may exhibit folding and faulting, and that rock sequences are categorized on the basis of the last recognizable period of major deformation. Distribution of preorogenic and postorogenic strata in Santa Monica Bay is depicted on Figure 24.

Although lithologic changes need not produce reflecting surfaces, major geologic boundaries in the California Continental Borderland do often represent distinct lithologic contrasts that are recognizable on seismic-reflection records. Moore (1969) proposed that lithology can be inferred from seismic-reflection records because the

Figure 24. Distribution of preorogenic and postorogenic strata in Santa Monica Bay. Deposits believed to be younger than 100,000 years are omitted (see Figs. 28 and 29). Contacts dashed where inferred. In the southern one-half of the bay the figure represents a litho-orogenic map.


Point Dume
Santa Monica
El Segundo
0
3
Miles
Palos Verdes Hills
50 fm
POSTOROGENIC
PREOROGENIC

middle to late Miocene formation of fault block topography greatly altered the processes and patterns of sedimentation. Fine-grained preorogenic sediments, probably deposited across a broad continental shelf, contrast with postorogenic sediments which seem to be dominated by turbidite deposition in isolated basins. Inasmuch as lithology appeared to be associated with orogenic features and the precise age of the strata were unknown, Moore found it more convenient and useful to construct litho-orogenic maps rather than geologic maps. This convention can be effectively employed in Santa Monica Bay as well as it has already been demonstrated that south of Santa Monica lithology is coupled to acoustic signature which is expressed as deformed or undeformed. That is, preorogenic strata consist almost entirely of shale and postorogenic strata consist of siltstone and sandstone (Figs. 18 and A20). Therefore, Figure 24 can be viewed as a litho-orogenic map in the southern one-half of the bay. Pre-orogenic strata beneath the shelf between Point Dume and Santa Monica consist of shale, siltstone, and sandstone similar to middle and upper Miocene sediments south of the Malibu Coast fault in the Santa Monica Mountains.

Time of Major Deformation

In addition to providing the information concerning the distribution of preorogenic and postorogenic strata in

Santa Monica Bay, the seismic-reflection data permitted a refinement of the timing of tectonic events beyond that which can be inferred from the geology of the Palos Verdes Hills alone.

Yerkes and others (1967) suggested that the period of major deformation in Santa Monica Bay occurred during early Pliocene time. They recognized that folded strata belonging to the Monterey Shale which crops out on the shelf projection appear as closely spaced, well-defined record surfaces. The Monterey Shale is also characterized this way in both the high resolution and air gun records used in this study (Figs. A6 and A15). The records of Yerkes and others showed undeformed units as continuous, more widely spaced surfaces. These were considered to represent upper Pliocene and Pleistocene siltstones and sandstones similar to those beneath the Torrance oil field. Undeformed strata do not always appear as widely spaced reflectors in the records used in this study, however. Except for folding they often appear much like Miocene strata (Figs. A14, A17, A18, and A20). In contrast to the timing proposed by Yerkes and others, the history of the southwestern block and of the Palos Verdes Hills in particular indicates that the period of major deformation in Santa Monica Bay was after the deposition of the lower Pliocene Repetto Siltstone. High resolution records from nearby San Pedro Bay also suggest this is the case (Fig.

A13). Examination of rocks recovered from the shelf, basin slope, and San Pedro Sea Valley (Moore, 1954) indicates that the sharply defined record surfaces represent the Monterey Shale and that the thinly layered, faint reflecting surfaces are probably part of the Repetto Siltstone. This profile indicates that folding occurred after the formation of the Miocene-Pliocene disconformity and the deposition of the Repetto. Therefore, the age of the strong angular discordance apparent on most air gun profiles (Figs. A14, A16, and A20) is younger than early Pliocene.

The minimum age of the unconformity can be inferred if the ages of the postorogenic strata beneath the inner shelf can be estimated. Evaluation of coastal geology and the seismic-reflection data for the inner shelf suggest that these regions are sedimentologically and structurally contiguous. Consequently, the known coastal stratigraphy can be applied to the section beneath the inner shelf. The minimum thickness of inner shelf postorogenic strata visible on 250 msec seismic-reflection records is 1200 ft. Since data from nearby oil fields indicate that the base of the Pleistocene section is generally 300 to 600 ft below sea level, the entire Pleistocene section and a large part of the upper Pliocene Pico are represented on inner shelf profiles. Therefore, the major period of deformation ended before latest Pliocene time.

Structure

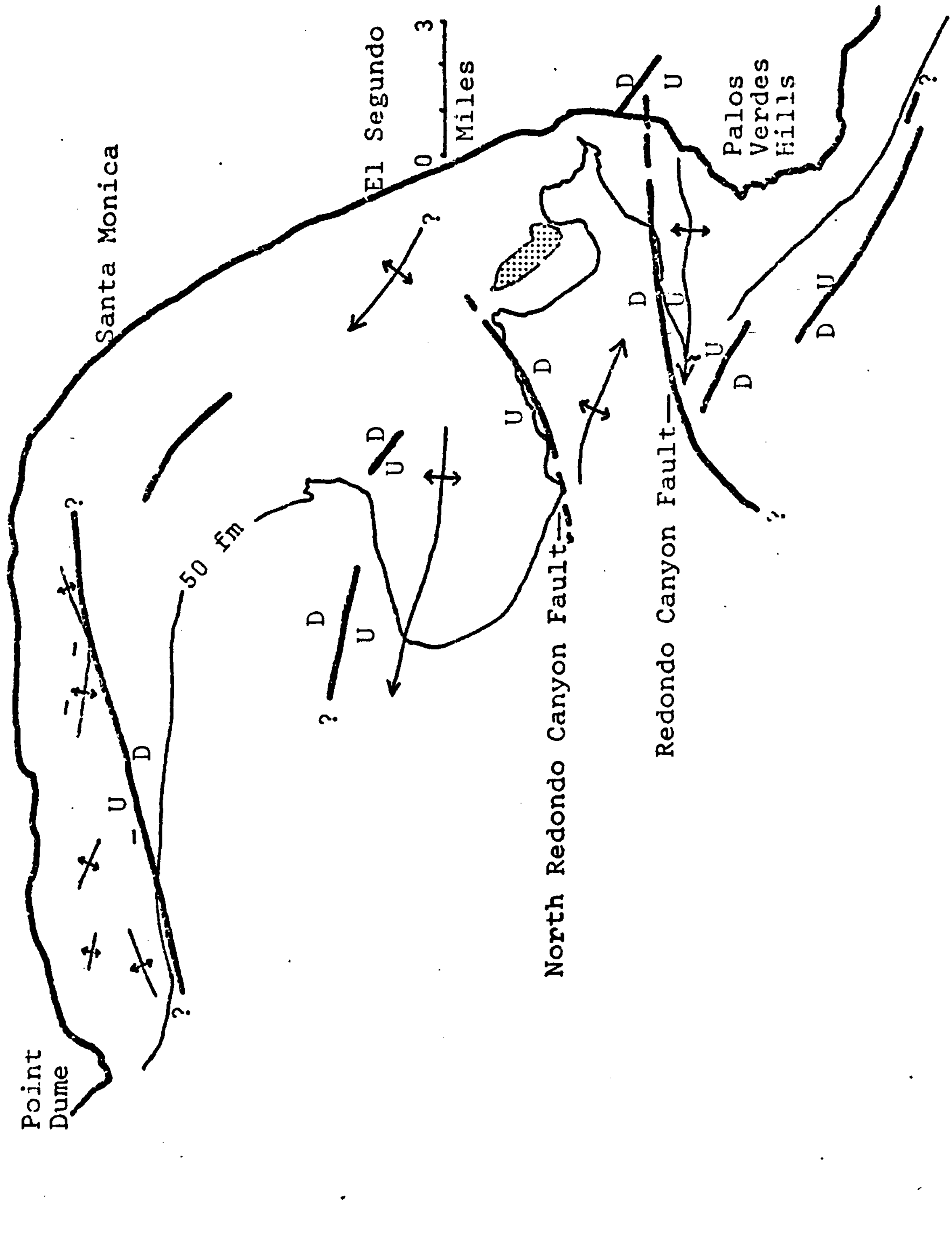
General Statement

The principal result of this investigation is the delineation of the salient structural elements in Santa Monica Bay (Fig. 25). In addition to outlining structures not previously reported, faults mapped in other studies are included if their presence is confirmed by the seismic-reflection records. Omission of previously mapped structures indicates only that they were not observed on the profiles. They may, however, exist either at depths not observable on 250 msec records or between tracklines in areas of sparse coverage.

Folds

The most prominent structural feature is the anticlinorium which forms the shelf projection. Broad and slightly asymmetrical, it is similar to the Palos Verdes Hills anticlinorium which continues beneath the shelf south of Redondo Submarine Canyon. The shelf projection anticlinorium is not a continuation of the Palos Verdes Hills structure but is rather *en echelon* to it, striking more westerly than the primary structural grain. In these respects it is similar to the structural style characteristic of the Newport-Inglewood zone as well as the Santa Rosa-Cortes Ridge where bathymetric highs also reflect underly-

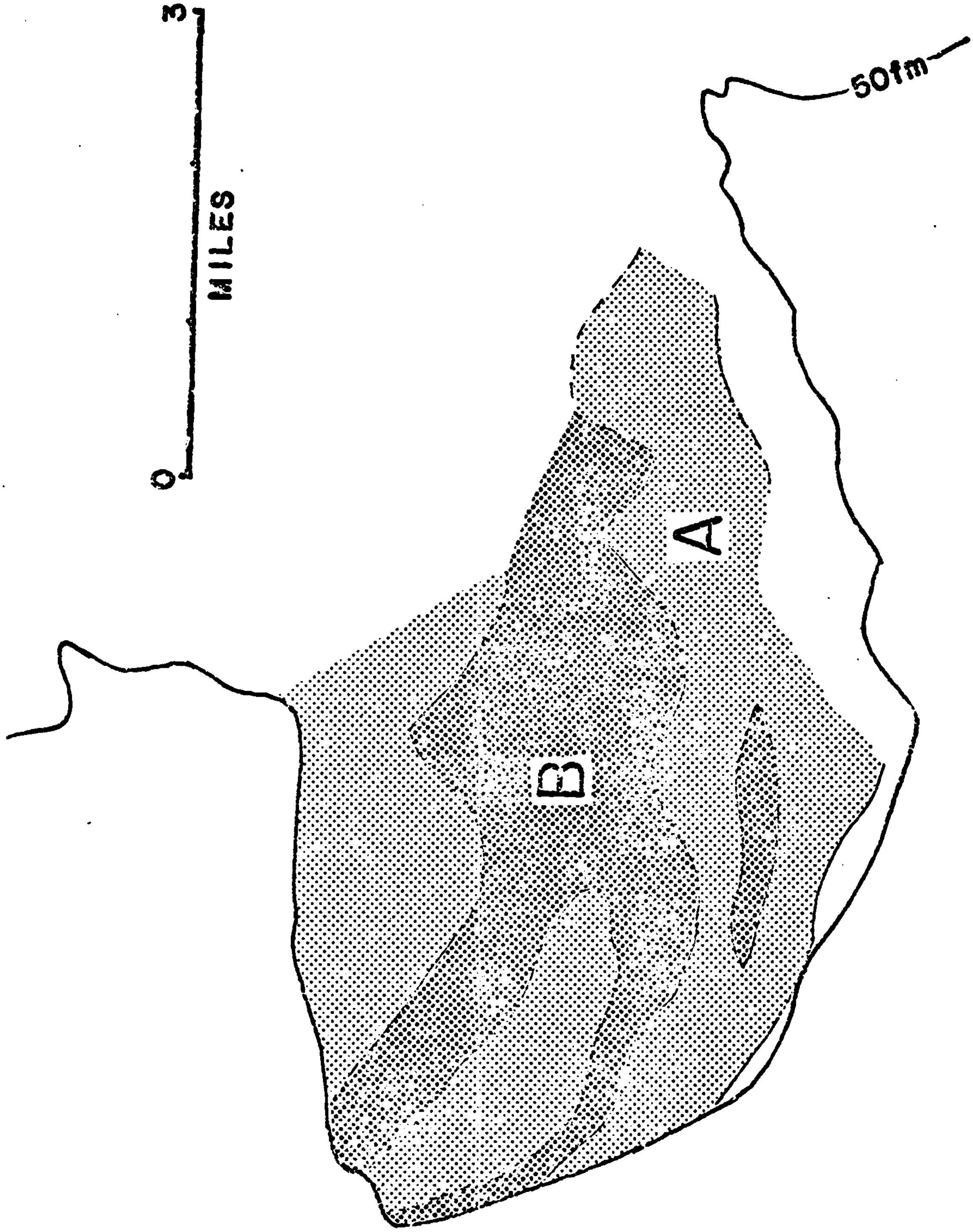
Figure 25. Distribution of major structural elements observed on 125 and 250 msec seismic-reflection records. Faults are dashed where inferred and queried at uncertain terminations. The stippled area near the head of Redondo Submarine Canyon represents an acoustically chaotic zone observed on air gun records as well as the probable trend of the Palos Verdes fault at depth.



Point Dume
Santa Monica
El Segundo
0
3
Miles
Palos Verdes Hills
50 fm
North Redondo Canyon Fault
Redondo Canyon Fault

ing anticlinal structures (Moore, 1969; Vedder and others, 1974). The main anticlinal axis follows the prominent bathymetric ridge which bisects the zone of irregular microrelief (Fig. 25). Minor folds and faults along the anticlinorium's flanks are subparallel to this axis. High resolution profiles reveal that the shelf projection is virtually devoid of sediment. Therefore, the contrast in microrelief between the irregular and variable zones is principally due to differential erosion between the strata beneath the crest of the anticlinorium and more easily erodable strata beneath the flanks. Closer examination of the profiles reveals that two distinct units can be recognized acoustically and m[illegible] 26). The younger unit, unit A, along the flanks of the antic[illegible]orium is characterized by numerous sharp reflectors. Unit B forms the resistant core of the anticlinorium and, in contrast, can be recognized as a dark, less detailed unit (Figs. A6 and A7). Several distinctive reflecting surfaces are traceable from fold to fold and aid in the differentiation of the units. Although these associations suggest that the acoustic signatures of units A and B are lithologically controlled, no correlation has been established between these units and the bedrock lithology as determined from jet core samples. Therefore, units A and B do not correspond to any formally designated part of the Altamira Member of the Monterey Shale. Moreover, air gun records indicate

Figure 26. Distribution of units A and B beneath the shelf projection. Contacts dashed where inferred.


0
3
MILES
50fm
A
B

that basement rocks are not exposed on the shelf projection although they may be near the surface. Schist samples recovered from the irregular zone probably represent Catalina Schist detritus incorporated into Miocene sediments.

Profile S-S' (Fig. A21), similar to the profile published by Yerkes and others (1967), and profile R-R' (Fig. A20) reveal that preorogenic strata are buried beneath the thick section of postorogenic strata that form the Redondo platform. A structure-contour map (Fig. 27) of the top of the preorogenic unit shows that it forms a smaller southeastward plunging anticlinorium which is consistent with the <u>en echelon</u> pattern of fold axes. Locally, deformation of Pliocene, upper Pleistocene, and possibly Holocene material over the crests of the small folds attests to its continuing growth (Figs. A9, A16, and A18). With the exception of slump features along the south side of Redondo and Santa Monica Submarine Canyons the small terraces along the upper slope noted by Terry and others (1956) are a result of either Late Quaternary growth along the anticlines or their incomplete burial by sediment.

Although the postorogenic strata beneath the inner shelf are relatively undeformed, minor folding and faulting is evident along a trend striking southeastward toward the coast in the vicinity of Manhattan Beach, and may be continuous with the Torrance oil field anticlinal struc-

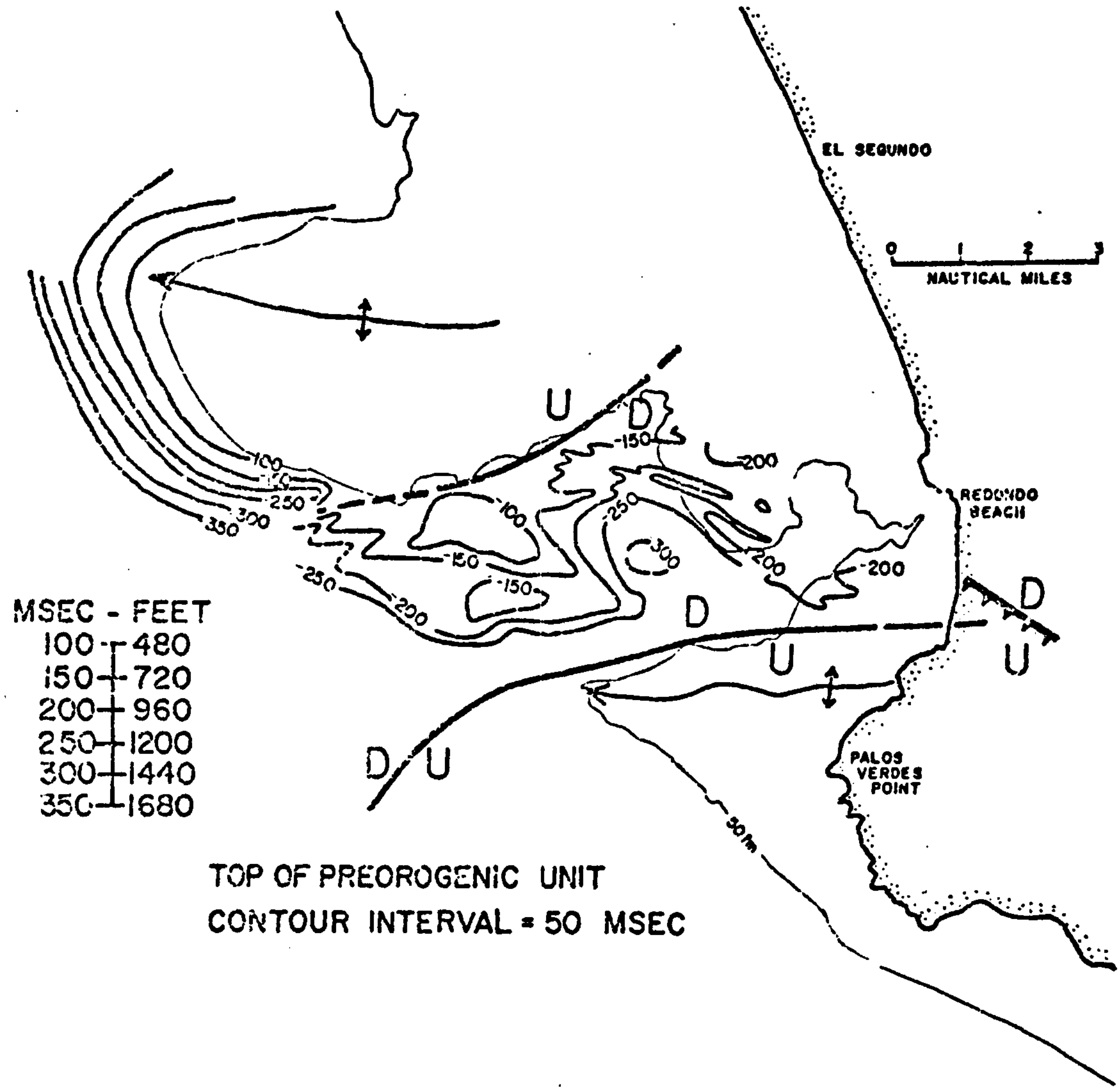


Figure 27. Elevation of the top of the pre-orogenic unit beneath the Redondo platform. Datum is sea level at mean lower low water. Conversion table gives minimum elevation below datum.

ture. On profile B-B' (Fig. A4) it is evident that a structural high, possibly associated with this trend, has formed near the surface and strata probably equivalent to the San Pedro Sand and unnamed upper Pleistocene deposits thicken away from it. Perhaps because of this high the upper half of air gun records from the inner shelf show reflecting surfaces dipping gently toward the west (Fig. A15). Because reflectors in the lower half are horizontal, the dip of these strata is believed to represent original depositional dip.

The preorogenic strata beneath the shelf adjacent to the Santa Monica Mountains form a southward dipping homocline occasionally interrupted by small scale folds which trend west-southwest or west-northwest. As Moore (1960) observed for many Borderland slopes, the steep upper slope of the north wall of the Santa Monica Submarine Canyon near Point Dume is parallel to the dip of the strata beneath the shelf and thus forms a dip-slope. Farther east deposition of postorogenic sediments and slumping have, however, lessened the slope considerably (Fig. 2).

Faults

Although it is beyond the scope of this investigation to detail the Late Quaternary history of the shelf, the upper 100 ft of postorogenic strata have been differentiated in order to more accurately determine the time of the latest observable movement along major faults. Additional application of Late Quaternary stratigraphy can be made in future studies aimed at deciphering late Pleistocene eustatic sea level fluctuations and their influence on shelf and basin sedimentation. For example, in this context high resolution profiles from San Pedro and Santa Monica Bays reveal that, in some localities, Emery's (1958) second (80 ft) terrace does represent a true erosional (Wisconsin ?) platform. The third (160 ft) and fourth (255 ft) terraces, however, appear to be controlled by structure and the shapes of Late Quaternary sedimentary deposits. Moore (1960) discovered similar features for other Borderland shelves.

Examination of the high resolution profiles together with the near surface coastal stratigraphy suggests that the San Pedro Sand and possibly unnamed upper Pleistocene deposits extend seaward beneath the shelf (Nardin, 1975). These strata have been truncated by an unconformity, horizon II (Fig. 28), which can be traced over the entire bay (Figs. A3, A4, A5, and A12). Horizon II also truncates preorogenic strata (Miocene) adjacent to the Palos Verdes Hills (Fig. A8) and the Santa Monica Mountains (Figs. A10 and A11). Thickness of the Quaternary sediment overlying horizon II is shown on Figure 29. These sediments are differentiated into two units separated by another uncon-

Figure 28. Elevation of horizon II, an unconformity truncating both preorogenic and post-orogenic strata beneath much of the shelf. Datum is sea level at mean lower low water. Conversion table gives minimum elevation below datum.

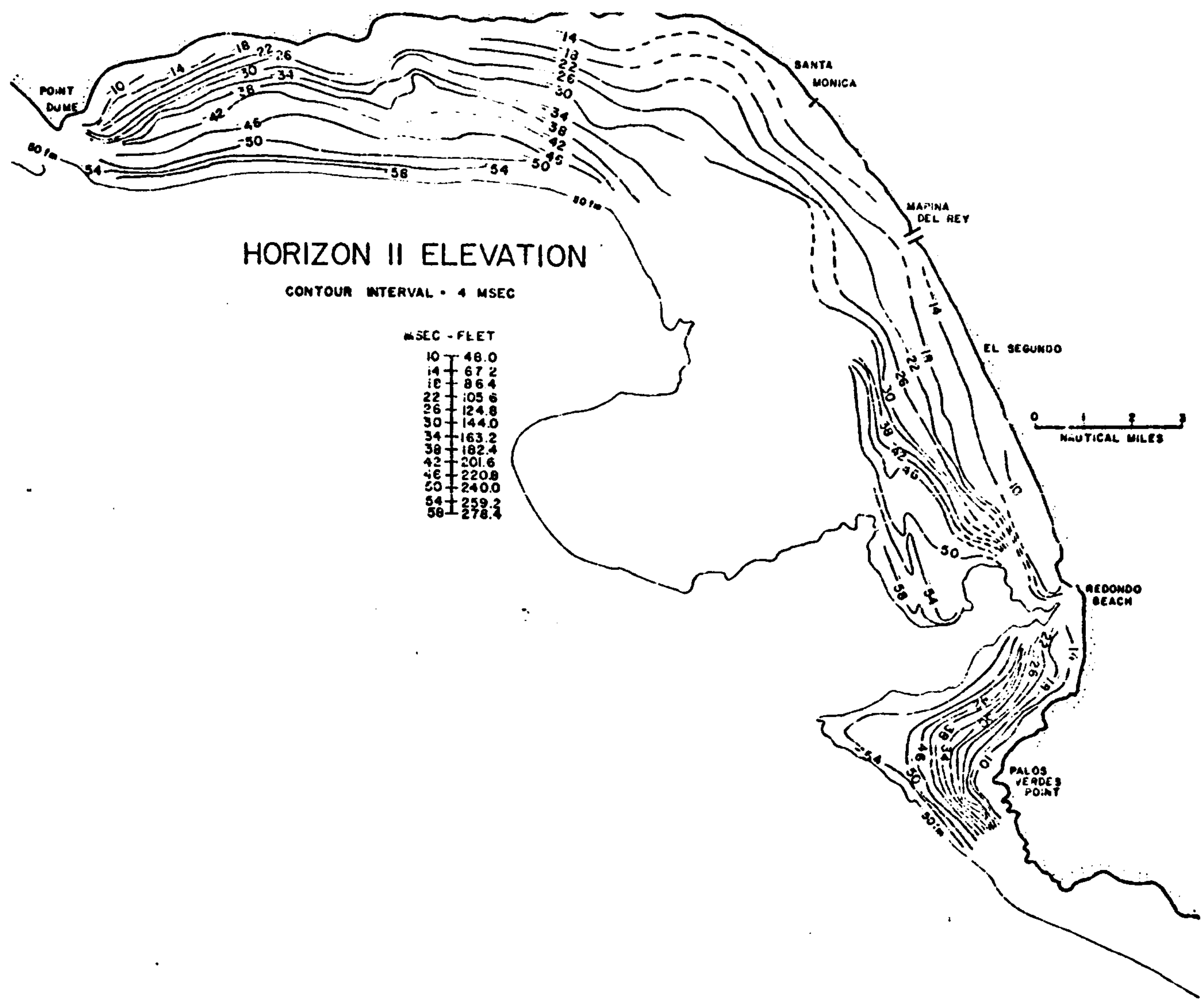
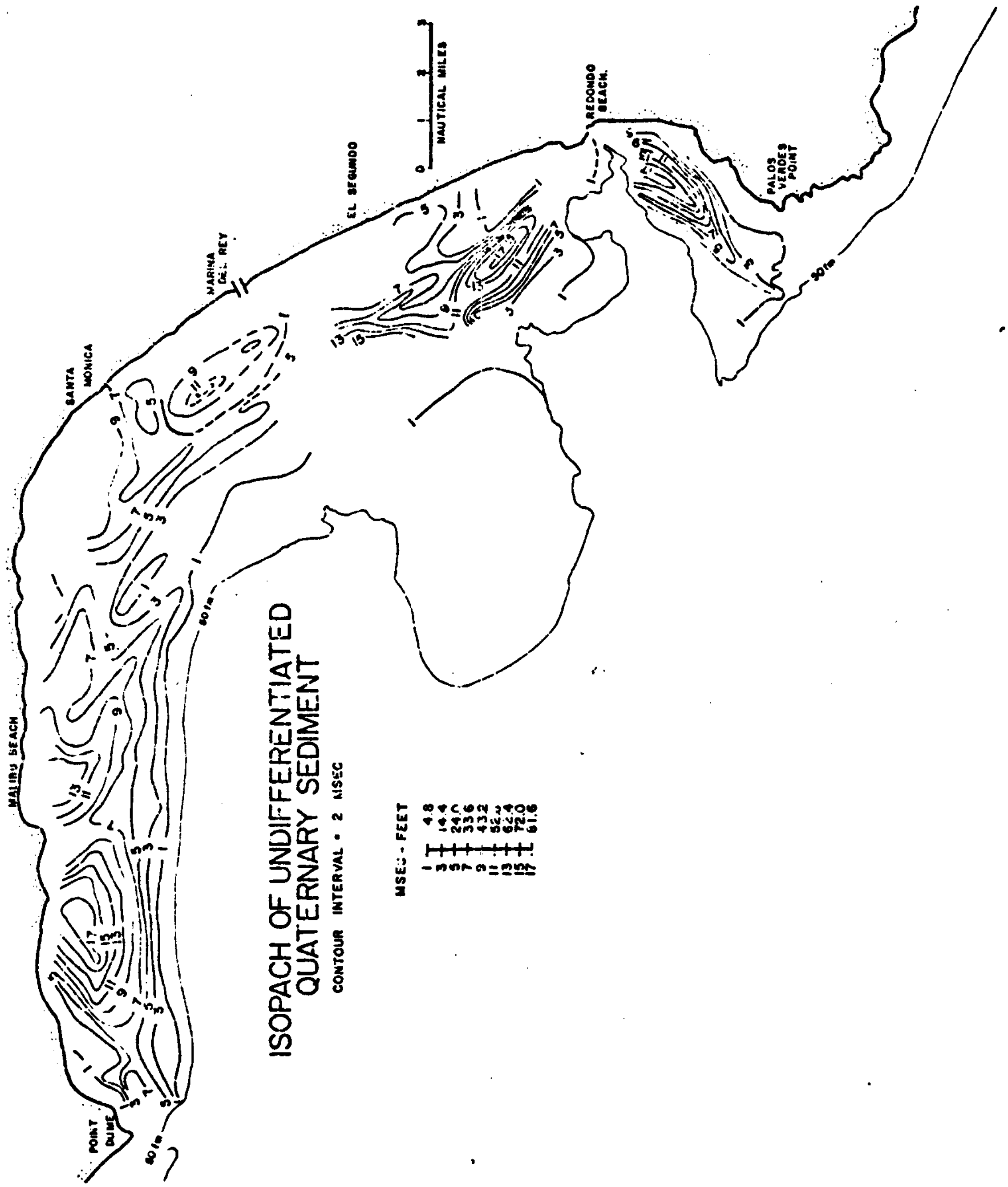

HORIZON II ELEVATION
CONTOUR INTERVAL - 4 MSEC
MSEC - FEET
10 48.0
14 67.2
18 86.4
22 105.6
26 124.8
30 144.0
34 163.2
38 182.4
42 201.6
46 220.8
50 240.0
54 259.2
58 278.4
POINT DUME
SANTA MONICA
MARINA DEL REY
EL SEGUNDO
REDONDO BEACH
PALOS VERDES POINT
0 1 2 3
NAUTICAL MILES
50 fm

Figure 29. Isopach of undifferentiated Upper Quaternary sediments overlying horizon II. Conversion table provides minimum thicknesses.

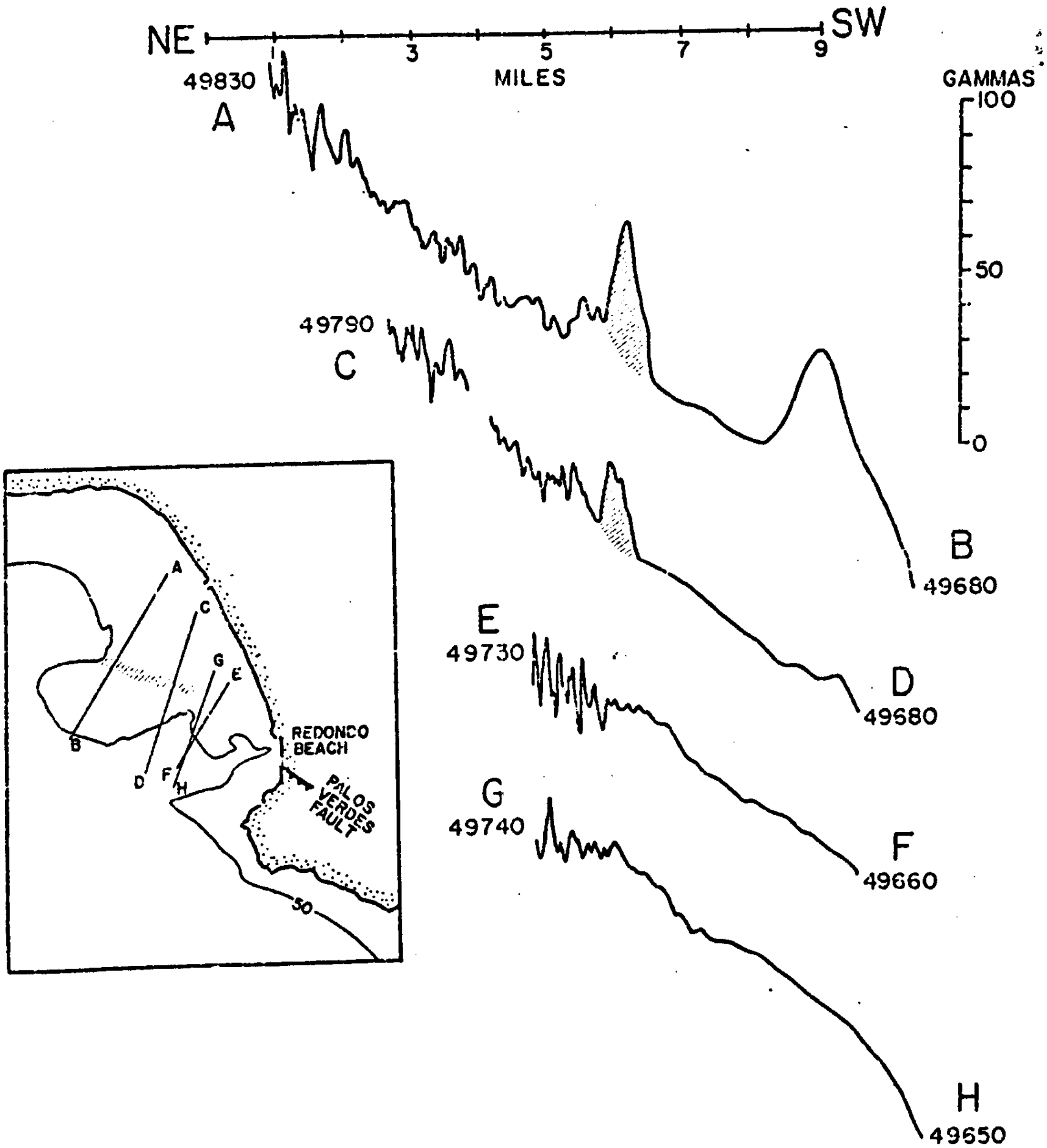

ISOPACH OF UNDIFFERENTIATED
QUATERNARY SEDIMENT
CONTOUR INTERVAL • 2 MSEC
MSEC - FEET
1 4.8
3 14.4
5 24.0
7 33.6
9 43.2
15 72.0
17 81.6
POINT DUME
MALIBU BEACH
SANTA MONICA
MARINA DEL REY
EL SEGUNDO
REDONDO BEACH
PALOS VERDES POINT
0 1 2 3
NAUTICAL MILES
50 fm

formity (Figs. A3, A4, and A5). The upper unit is identified by its acoustic transparency and lack of detail, features commonly considered to be representative of Holocene sediments (for example, Moore, 1960). The unconformity separating the upper and lower parts of the unit was probably formed during the Holocene transgression. Therefore, displacement of the upper unit or the unconformity suggests faulting within the last 18,000 years. The lower unit exhibits large lateral changes in acoustic signature. For example, along the inner shelf the unit is often characterized by low angle cross-stratification suggestive of a prograding beach (Figs. A3 and A4). In contrast, south of the Santa Monica Mountains the profiles reveal that it consists of numerous discontinuous horizontal reflecting surfaces and may be lithologically more variable (Figs. A10 and A11). No absolute dates are available for this unit but it follows from coastal stratigraphic relationships that it is probably equivalent to, or younger than, the Palos Verdes Sand. Faults displacing the lower unit or horizon II are therefore considered to have been active during Late Quaternary time (probably within the last 100,000 years). Except in the case of the Palos Verdes fault, more recent activity than that proposed in earlier investigations (Ziony and others, 1974; Vedder and others, 1974) is suggested for each fault described below.

Examination of air gun records indicate that the northwest extension of the Palos Verdes fault as mapped by previous investigators (Figs. 8 through 11) has not been appreciably active since the deposition of at least the upper 1000 ft of postorogenic strata. Evidence that the Palos Verdes fault once extended across the area now occupied by the shelf, however, is observed in both seismic-reflection and magnetometer profiles. Specifically, near the head of Redondo Submarine Canyon a wide, acoustically chaotic but sharply defined zone appears to mark the location of the fault as mapped by Ziony and others (1974) and Vedder and others (1974)(Figs. A16, A17, 10, 11, and 25). Although mildly deformed postorogenic reflectors can be traced across the zone, the preorogenic unit is not observed on the profiles northeast of the zone and often appears to be truncated by it. Similarly, a short northwest-trending fault near the head of Santa Monica Canyon is recognized only by the apparent truncation of preorogenic strata against postorogenic strata in the lower half of the record (Fig. A18). The fault apparently does not displace postorogenic reflectors, however. Therefore, within the postorogenic section observed on 250 msec seismic-reflection records, the discontinuity between preorogenic and postorogenic strata along the proposed Palos Verdes fault trend is not a fault contact but rather is an unconformity. Figure A25 is a profile across the Palos Verdes fault in San Pedro Bay. Comparison between this profile and profile M-M' (Fig. A15) shows the marked contrast in the acoustic definition of the two types of discontinuities. Further, magnetometer profiles across the shelf projection reveal a distinct positive anomaly over the pre-orogenic-postorogenic discontinuity (Fig. 30). This anomaly diminishes in amplitude to the southeast and disappears near the head of Redondo Submarine Canyon. Although a quantitative interpretation has not been attempted, visual inspection of the anomaly suggests its similarity to theoretical anomalies produced by both step (fault) models and ribbon (dike) models (for example, Grant and West, 1965). It is interesting to note that a significant change in magnetic signature also occurs along these profiles. A relatively subdued signature is present seaward of the positive anomaly and an erratic signature landward. The wavelengths of the signal anomalies over the inner shelf are sufficiently short to require that the sources be contained within the Quaternary section. These anomalies may be associated with either heavy minerals or chemical alterations along one or more of the Quaternary unconformities (Fig. A4).

The previously mapped more westerly-trending branch of the Palos Verdes fault near Santa Monica Submarine Canyon also appears to be absent in upper parts of the post-orogenic section (Ziony and others, 1974). A fault whose

Figure 30. Magnetometer profiles across the shelf projection and inner shelf. The gradient of these profiles would approach zero if the regional gradient had been subtracted.



NE
SW
1
3
5
7
9
MILES
GAMMAS
100
50
0
49830
A
B
49680
49790
C
D
49680
E
49730
F
49660
G
49740
H
49650
A
C
G
E
B
D
F
H
REDONDO BEACH
PALOS VERDES FAULT
50

trend is similar, however, has been mapped farther south near the axis of Santa Monica Submarine Canyon. This fault is observed to drop postorogenic strata to the north along a prominent scarp suggesting activity during Late Quaternary time (Fig. A23). Profile U-U' also depicts a rare instance when the fault plane is visible on a record that has not been migrated. It follows that the fault, which shows normal displacement, must be dipping at a lot angle. It should be noted that these are not features expected of a fault belonging to the Palos Verdes system. The fault may, instead, be a segment of the Santa Monica Canyon fault hypothesized by Terry and others (1956). If it is, its trend as well as air gun records demonstrate that it does not connect with faults along Ballona Creek as Terry and others proposed. Alternatively, since the magnitude of the displacement cannot be determined from the data, it is possible that the fault is a glide plane associated with large-scale low angle slumping similar to the type described by Lewis (1971) along the upper continental slope of New Zealand.

Interpretation of air gun records suggest that a short northwest-trending fault exists southwest of the city of Santa Monica. Because the fault cannot be traced farther south, it is not probable that it is a direct continuation of the Palos Verdes fault. Rather it may be associated with the fault mapped by Ziony and others (1974) but omitted in later interpretations by Vedder and others. Although the strata north of the fault are tilted toward the southwest, the visible portion of the fault is considered entirely contained within the postorogenic unit. High resolution profiles indicate hydrocarbon seepage is associated with the fault (Fig. 32).

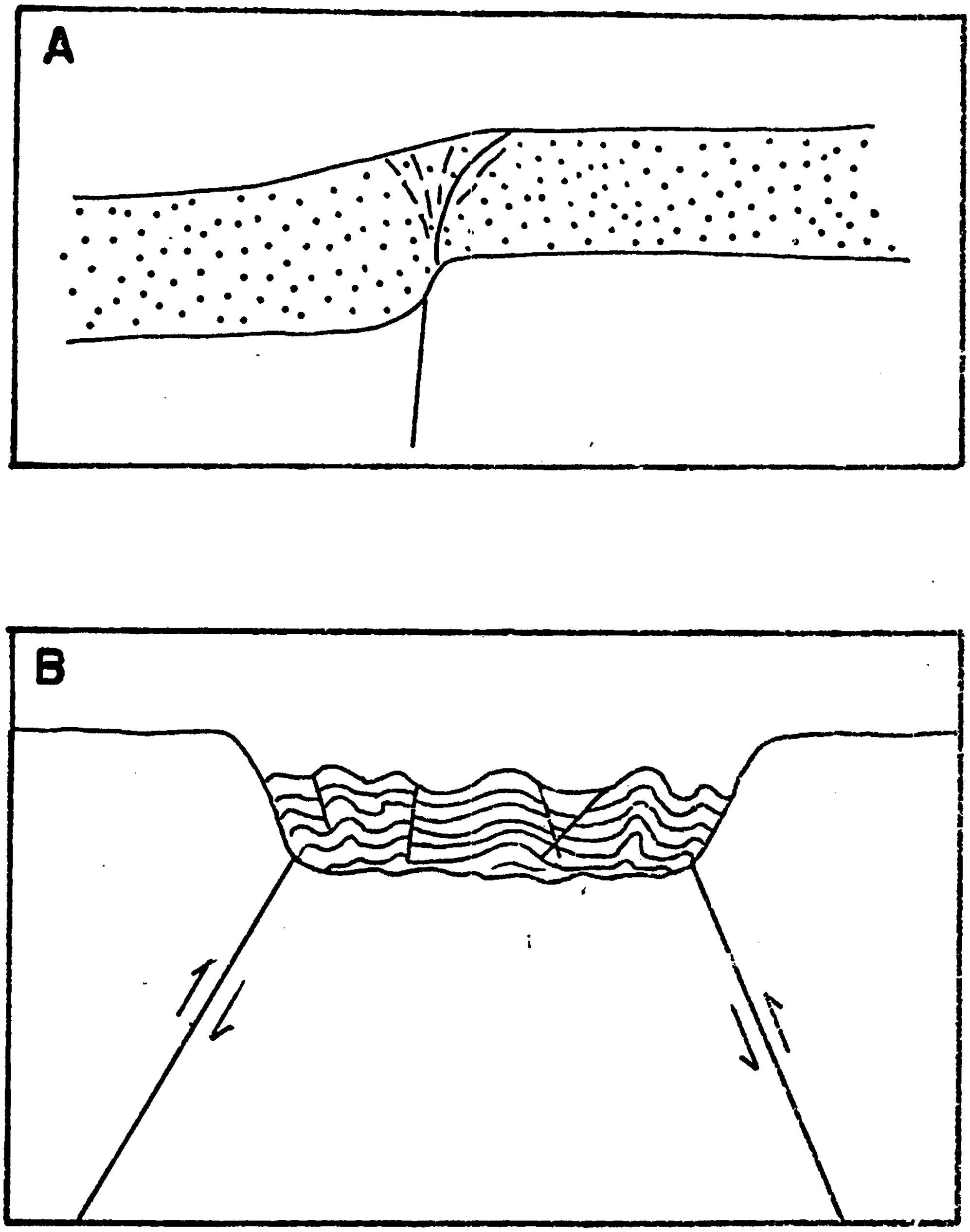
The Redondo Canyon fault first proposed by Yerkes and others (1967) is clearly present on both high resolution and air gun records. The fault, however, does not follow the trend of the canyon's axis for its entire length as suggested by Yerkes and others. Instead the fault cuts the Redondo submarine fan, the south wall of the canyon, and the narrow shelf adjacent to the Palos Verdes Hills, and may merge with the Palos Verdes fault onshore (Figs. A8, A16, A19 and 25). The position of profile Q-Q' over the submarine fan is near northwest-trending faults proposed by Ziony and others (1974), Vedder and others (1974), and Hackett (1970), but the fault observed on the profile is probably the Redondo Canyon fault as its sense of displacement and time of latest movement do not correlate with those of the northwest-trending faults. The large throw of the Redondo Canyon fault is evidenced by the displacement of preorogenic strata along the south wall of the canyon. Although side echoes obscure the postorogenic detail in this area, postorogenic strata appear to be dragged along the fault. Figures A16 and 27 show apparent structural and stratigraphic continuity across the axis of the canyon north of the fault in this region. Displacement of strata and the scarp across the submarine fan attest to Late Quaternary movement along the fault in the basin (Fig. A19). Another prominent scarp in the acoustically transparent unconsolidated overburden evidences Holocene displacements along the shelf portion of the fault (Fig. A8). Examination of jet core data reveal that middle Miocene shale occurs beneath the shelf south of the fault and post-orogenic sands and silts north of the fault. Samples of shale near the fault also show fractures and slickensides.

Another southwest-trending fault, associated with Redondo Submarine Canyon, is evidenced by displacement of preorogenic strata along the canyon's north wall (Fig. A20). In future discussions this fault is termed the North Redondo Canyon fault. The throw of the fault diminishes toward the west; thus, the fault appears to be hinged in the vicinity of profile T-T' (Fig. A22). This profile also exhibits numerous small fault splinters which pass into shear flexures near the surface. Figure 31a is a model illustrating the common phenomenon of splintering near the hinged end of a fault (Hill, 1963).

Northwest-trending faults along the San Pedro Escarpment and the basin slope adjacent to the shelf projection are accompanied by reverse drag folding, noted also by Moore (1969 ; for example, Plate 6, Fig. 1) along

Figure 31a. Diagram showing splintering of fault near its hinged end (after Hill, 1963).

Figure 31b. Graben bounded by reverse faults and containing laterally compressed sediments.


A
B

many prominent faults in the western third of the Borderland (Fig. A21). Reverse drag is a much larger feature than normal drag, and is often associated with normal faults in regions of minor deformation and gentle dip (Russell, 1955). These faults are probably part of a fault zone (other members mapped by Moore, 1969; Hackett, 1970; Ziony and others, 1974; and Vedder and others, 1974) that constitute the northeast boundary of San Pedro and Santa Monica Basins. The strata on the downthrown side of the San Pedro fault, although deformed have the appearance of postorogenic strata. Late Quaternary displacements have probably occurred as it seems likely that the fault participated in the uplift of the Palos Verdes Hills.

A fault trending west-southwest across the shelf and slope adjacent to the Santa Monica Mountains (Fig. 25) has been mapped essentially as proposed by Ziony and others (1974) and Vedder and others (1974). Along the slope, the fault is associated with apparent reverse drag characteristic of normal displacement (Fig. A24) and can be recognized in air gun records taken across the shelf by the displacement of distinctive reflecting surfaces within the preorogenic unit. North of the fault these surfaces approach the seafloor but are replaced by more acoustically transparent strata to the south. In addition, the fault appears to separate an area of folding on the north from an area of purely homoclinal dip on the south (Fig.

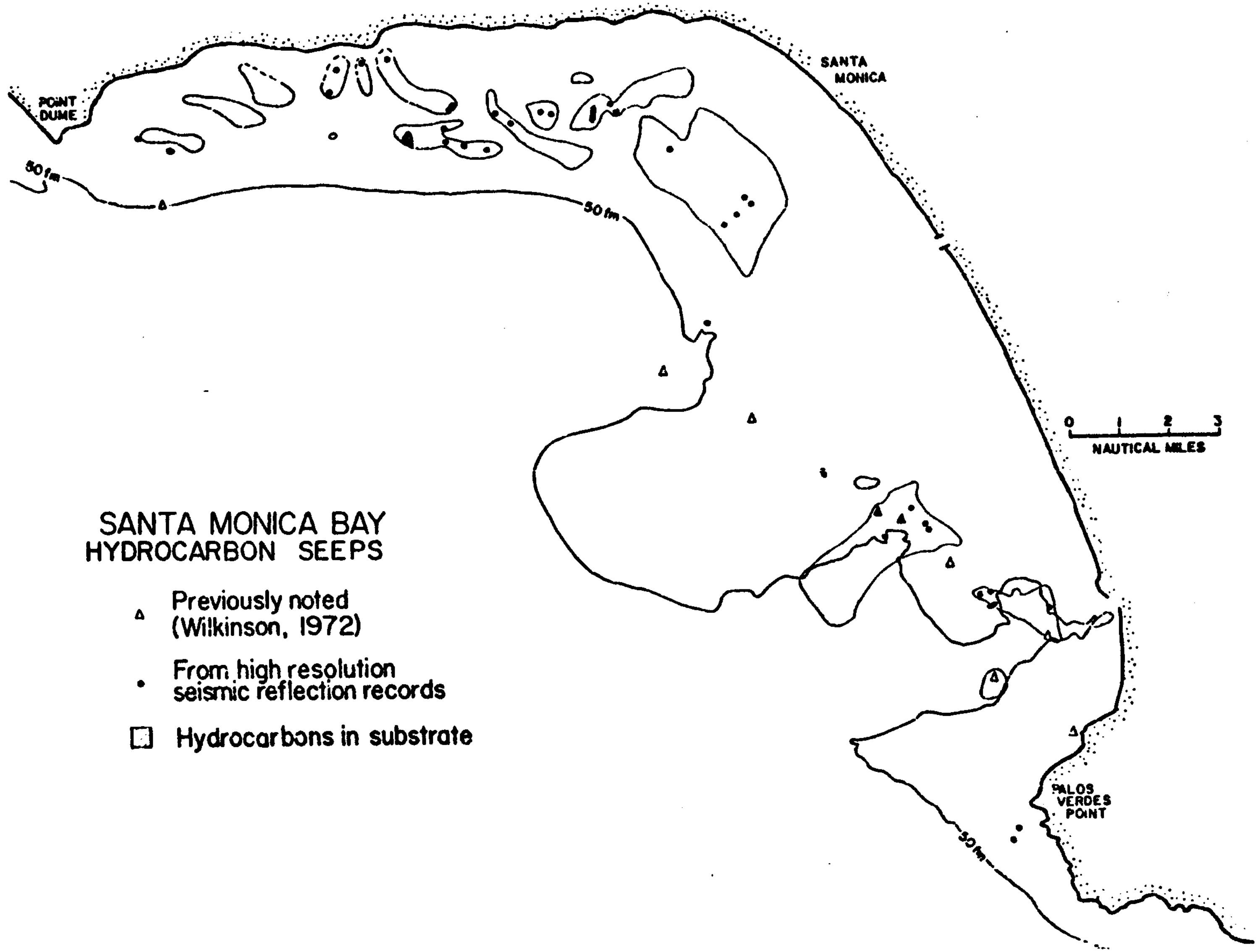
25). Because tilted strata occur on both sides of the fault beneath the shelf, the fault, however, may not separate Miocene and post-Miocene strata everywhere along its length as the geologic map of Vedder and others suggests. Profile H-H' (Fig. A10) reveals that the unconformity but not the overburden has been displaced along the fault. Therefore, the latest recognizable movement occurred late in Pleistocene time (post 100,000 y.b.p.). Profile H-H' also reveals that hydrocarbon seepage is associated with the fault (Fig. 32).

Hydrocarbon Seeps

General Statement

Link (1952) summarized the types of geologic settings commonly associated with hydrocarbon seepage. If source rocks are present, geologic discontinuities such as unconformities, sedimentary layers, and faults may act as avenues through which hydrocarbon may migrate toward the surface. Vernon and Slater (1963) and Fischer (1974) investigated hydrocarbon seepage in this context in the Santa Barbara region and correlated seepage patterns with geologic structures beneath the shelf. In Santa Monica Bay correlation between zones of seepage and structure also has been established.

Figure 32. Location of hydrocarbon seeps and areas where hydrocarbons appear in the substrate.


SANTA MONICA BAY
HYDROCARBON SEEPS
Previously noted (Wilkinson, 1972)
From high resolution seismic reflection records
Hydrocarbons in substrate
POINT DUME
SANTA MONICA
PALOS VERDES POINT
50 fm
0 1 2 3
NAUTICAL MILES

Detection

Until a few years ago natural hydrocarbon seepage was detected solely by observation of oil slicks or gas bubbles on the sea surface. The disadvantage of this technique is that owing to currents, oil or gas bubbles may surface at considerable distances from seafloor emanations. Accurate locations could only be achieved by diving and following a rising train of bubbles to the bottom. Wilkinson (1972) reported the presence of 9 seeps detected in this manner in Santa Monica Bay. Subsequently, it was learned that hydrocarbon seeps could be detected using high resolution (greater than 3.5 kHz) profiling systems (Sweet, 1972). Due to the contrast in acoustic impedance between seawater and hydrocarbons, seeps can be easily recognized from acoustic scattering within the water column. Many profiles illustrating their distinctive acoustic signature were published (for example, Sweet, 1974; Tinkle and others, 1973; Fischer and Stevenson, 1973). In Santa Monica Bay, oil and gas seeps in addition to those reported by Wilkinson (1972) were detected using this technique (Fig. 32). In many instances, as seeps were being recorded, the profiles were correlated with surface observations of rising gas bubbles and slicks. The large number of additional seeps discovered during this investigation could be anticipated because the source rocks (chiefly the Monterey Shale) of one of the world's most prolific oil producing regions, the Los Angeles Basin, crop out in the bay. Because it has experienced recent structural deformation, Wilson and others (1974) rated offshore southern California as a potentially high seepage area.

Both oil and gas seeps occur near Redondo Submarine Canyon but, in contrast, only gas seeps were noted between Point Dume and Santa Monica. In only two instances were seeps recorded at the locations reported by Wilkinson (1972). It appears that at least some of the previously reported seeps were either inactive at the time or the survey or they were located incorrectly with respect to the seafloor emanation. Fischer (1974) found that 75 percent of the seeps along the Santa Barbara Shelf occurred in areas covered by less than 6 feet of Quaternary sediment. In sharp contrast, a comparison between areas of seepage and an isopach map of the unconsolidated Late Quaternary overburden in Santa Monica Bay (Fig. 29) shows no correlation between seepage and sediment thickness. It is possible, however, that the thick sequence of sediments along the shelf adjacent to the Santa Monica Mountains has trapped the oil and tar and permitted only gas to escape to the surface.

A secondary manifestation, usually present but observed on a broader scale, is a distinct acoustic signature within the Late Quaternary sediments themselves as depicted for example in Figures A5, A10, A11, and A12. Tinkle and others (1973), Sieck (1973), and Sweet and Geyer (1972) observed and attempted to explain the origin of similar features on high resolution records from the Gulf of Mexico. The records show that the areas immediately below a seep are darkened and below that sometimes lightened again. In layered sediments the darkened area often appears as a local enhancement of a reflecting surface (Figs. A5, A11, and A12). In much the same way as bubbles are detected in the water column, the acoustic impedance contrast between hydrocarbons and water-laden sediment may permit their detection in the substrate. Therefore, these acoustically opaque areas are thought to represent reflections and internal backscatter due to the presence of hydrocarbons in the sediments. The acoustic void below an opaque area may be a shadow zone of reduced seismic penetration. Alternatively, Sieck (1973) hypothesized that the voids themselves were charged with gas. Similarly, the void could be caused by gas moving toward the surface and the subsequent homogenization of sediment (Tinkle and others, 1973). Rising gas bubbles are also considered to be responsible for the formation of crater-like depressions as much as 150 ft in diameter and 30 ft deep in the sediments of the Scotian Shelf (King and MacLean, 1970). These features, termed pockmarks, are observed at several locations along the shelf adjacent to the

Santa Monica Mountains and occur below active gas seeps and above opaque areas (Figs. A10 and A11).

High resolution seismic-reflection coverage is sufficiently dense that the opaque areas can be mapped into zones as shown in Figure 32. Although not all opaque areas are associated with active seeps, it should be noted that, where there are Late Quaternary sediments, seeps occur above opaque areas. Opaque zones not associated with active seeps probably represent areas of previous or intermittent seepage. The elongate shape of many of the zones suggests that some seeps may not originate from point sources but rather from linear sources.

Association with Geologic Structure

Seeps along the shelf adjacent to the Santa Monica Mountains are undoubtedly associated with the homoclinal strata truncated by the Late Quaternary unconformity (horizon II). The pattern of seepage suggests that the avenue of migration for much of the hydrocarbons is the west-southwest-trending fault which divides the shelf into folded and unfolded areas (Fig. 25). It is evident that most of the seeps occur north of the fault in the folded area, but consistent correlation between anticlinal axes and seeps has not been established.

Results presented on Figures 25 and 32 also suggest that seeps are associated with the northwest-trending fault immediately southwest of Santa Monica although the fault is not observed on the high resolution profiles. Beds exhibiting original depositional dip locally are enhanced by hydrocarbons migrating updip (Fig. 21). It is apparent that although many of the seeps are associated with faults, in some cases lateral migration of hydrocarbons in near-surface strata results in opaque zones that are broad rather than narrow and linear.

Previous investigators proposed that the northwest-trending line of seeps in the southern one-half of the bay is associated with the offshore extension of Palos Verdes fault. Evidence presented in this study indicate a more complex origin. Although the Palos Verdes fault may exist at depth, the avenue for hydrocarbons close to the surface is an unconformity near the shelf projection. Interestingly, the acoustically chaotic zone which marks the extension of the fault near the head of Redondo Submarine Canyon does not seem to be associated with active seeps or opaque areas. Near the eastern tributary of the canyon, hydrocarbons appear to have migrated to the surface, again through permeable strata exhibiting original depositional dip. These strata overlie preorogenic strata folded into an anticline, the possible source of hydrocarbon seeps in this area.

The southwest trend of the opaque zone near the head of the western tributary of Redondo Submarine Canyon suggests that at least a portion of the hydrocarbon contribution in this area is from the North Redondo Canyon fault. Notably, nearby jet core samples were discovered to contain tar. A seep and opaque area (Wilkinson's (1972) seep #7, or the Redondo Beach seep) along the south wall of the canyon is probably associated with Redondo Canyon fault.

It is interesting to note that the air gun records gathered over the Redondo platform contain large areas which are lighter than the surrounding record (Figs. A14 and A17). Upon close examination the light areas are composed of many small discontinuities or breaks in the recordings. Light areas can be observed at similar positions in different records and therefore are probably not the result of equipment failure or gain changes during recording. The pattern of the light areas suggests that they represent hydrocarbons emanating from preorogenic strata and migrating vertically and laterally through permeable postorogenic sands and silts. The difference between the acoustic signatures of hydrocarbons in high resolution records and air gun records may be a result of compaction and loss of water in the more deeply buried strata and the consequent reversal in acoustic impedance contrast.

DISCUSSION

Palos Verdes Fault

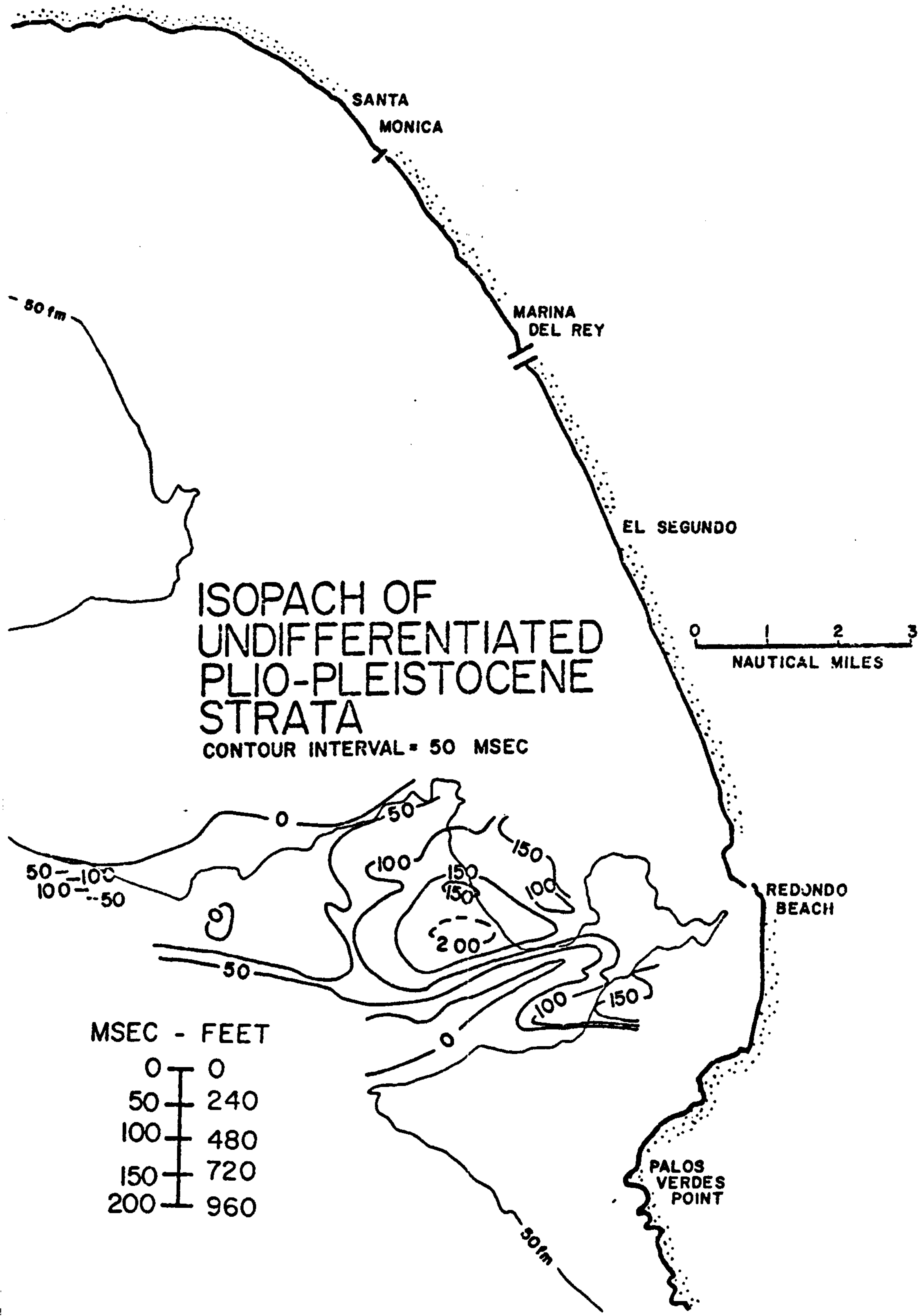
It has been shown that if the Palos Verdes fault extends across the shelf as proposed by previous investigators, large displacements must be confined to strata below those visible on 250 msec seismic-reflection records. Therefore, vertical displacement along the seaward extension of the Palos Verdes fault has been negligible since at least latest Pliocene time. This infers that the Late Quaternary uplift of the Palos Verdes Hills occurred along the Redondo Canyon fault as Yerkes and others (1967) proposed. Also it is apparent that much of the seismic activity near the head of Redondo Submarine Canyon (Fig. 13) may be due to movement along the Redondo Canyon fault. This is not consistent with the composite fault plane solution of Teng and Henyey (1975) and may thus invalidate the application of composite seismic solutions in this region. In the absence of an active extension of the Palos Verdes fault, the pattern of inner shelf seismicity, if accurate, is difficult to explain. It may be due to displacements at depth not transmitted to near-surface strata.

Because the preorogenic-postorogenic discontinuity observed on the records is an unconformity, the shelf projection anticlinorium was formed prior to the deposition of the lowest observable reflecting surfaces. That is, folding of the shelf projection anticlinorium and significant displacement along the shelf segment of the Palos Verdes fault occurred before latest Pliocene time. Woodring and others (1946), in their study of the geology of the Palos Verdes Hills, as well as the seismic-reflection data from the San Pedro shelf discussed in this report, suggest that displacement occurred after the deposition of the Repetto Siltstone. Therefore, a middle to early late Pliocene diastrophism is indicated. This time corresponds approximately to the time of localization of lateral strain along the Newport-Inglewood zone (Yeats, 1973) suggesting that the folding of the en echelon anticlinoria may have been caused by dextral shear along the Palos Verdes fault. However, since that time, the area now occupied by the shelf projection appears to have been coupled to the remainder of the southwestern block. Thus, the Quaternary dextral offset of the onshore segment of the Palos Verdes fault proposed by previous investigators is unlikely. Instead, abrupt contrasts in late Pliocene through Pleistocene sediment thicknesses across the fault near the peninsula are probably due to vertical movements. During late Pliocene and Quaternary time the shelf projection acted as a local dam trapping Los Angeles Basin sediments.

Redondo Graben

High resolution profiles (Fig. A8) demonstrates that, although the shelf projection suffered extensive erosion, preorogenic strata beneath the Redondo platform were not exposed to appreciable erosion since the folding of the anticlinorium. Therefore, if the major period of deformation occurred in middle to early late Pliocene time, the absence of upper Miocene and lower Pliocene strata on the shelf projection (assuming they were ever deposited there) indicates that as much as 950 ft of displacement occurred along the eastern segment of the North Redondo Canyon fault. Similarly, significant displacement along the Redondo Canyon fault is demonstrated in profile I-I' (Fig. A11). Thus, displacement has been large enough to support the Yerkes' and others (1967) proposal that the fault forms the northwest boundary of the Palos Verdes Hills uplift. It is suggested that these faults form the boundaries of a graben in which the Redondo platform anticlinorium was dropped and tilted toward the east. Profiles parallel to the plunge of the anticlinorium show nearly horizontal sequences of postorogenic sediments preserved in the graben (Figs. A14 and A17). Therefore, it is likely that most of the tilting occurred before the deposition of these sediments and that faulting was initiated at the same time as the formation of the anticlinorium or soon afterward. Thickness of postorogenic strata in the graben is shown in Figure 33. Both high resolution and air gun profiles demonstrate appreciable Late Quaternary and possibly Holocene tectonic activity in the graben (Figs. A9 and A18). Since the attitude of the fault planes cannot be determined from the records, the stress regime responsible for continuing deformation is difficult to ascertain. If the graben is bounded by reverse faults, then the folding of postorogenic strata over the crests of some of the anticlines may be due to compressional stresses (Fig. 31b). Movement along flanking subsidiary or antithetic faults in a graben bounded by normal faults, however, could produce the same effect. Similarly, either type of fault could have been produced during the Late Cenozoic tectonic development of the southwestern block. For example, several thousand feet of uplift of the area now occupied by the San Pedro Shelf, the Palos Verdes Hills,and the Santa Monica Shelf is postulated to have occurred between early and late Pliocene time. Assuming that fault trends in the Los Angeles Basin are influenced by basement anisotropies (Yeats, 1973), then westward-trending faults could be reactivated, with normal displacements, along a ridge striking northwest. It should be recalled that the existence of westward-trending basement anisotropies is suggested by the pattern of the long

Figure 33. Isopach of undifferentiated Pliocene and Pleistocene strata in Redondo graben. Conversion table provides minimum thicknesses.


ISOPACH OF UNDIFFERENTIATED PLIO-PLEISTOCENE STRATA
CONTOUR INTERVAL = 50 MSEC
SANTA MONICA
MARINA DEL REY
EL SEGUNDO
REDONDO BEACH
PALOS VERDES POINT
0 1 2 3
NAUTICAL MILES
50 fm
MSEC - FEET
0 0
50 240
100 480
150 720
200 960

wavelength component of Bouguer gravity (Harrison and others, 1966). Alternatively, the simple shear model depicted in Figure 34 demonstrates that dextral shear along the Palos Verdes fault could have reactivated the same basement anisotropies to produce westward-trending reverse faults. Although dextral offset along northwest-trending faults was initiated as early as late Miocene time, it did not become localized along the Newport-Inglewood zone until late Pliocene time. Because it has already been proposed that the *en echelon* anticlinoria were folded in middle to early late Pliocene time owing to dextral shear, the second solution is preferred.

The origin of Redondo Submarine Canyon is closely linked to the graben. In addition to having been a topographically low area, the graben constituted a zone of weakness because it was filled with easily erodable post-orogenic sands and silts. Formation of the canyon could have been initiated as soon as the Los Angeles Basin had completely filled and large quantities of sediment began to be delivered to the area by way of an ancestral Los Angeles River system. Ages proposed for Palos Verdes Hills marine terrace deposits (Fanale and Schaeffer, 1965) and stratigraphically equivalent nearshore and continental deposits beneath the coast (Poland and others, 1959) suggest that this may have occurred as recently as 330,000 ± 50,000 to 420,000 ± 60,000 y.b.p. Subsequent glacially

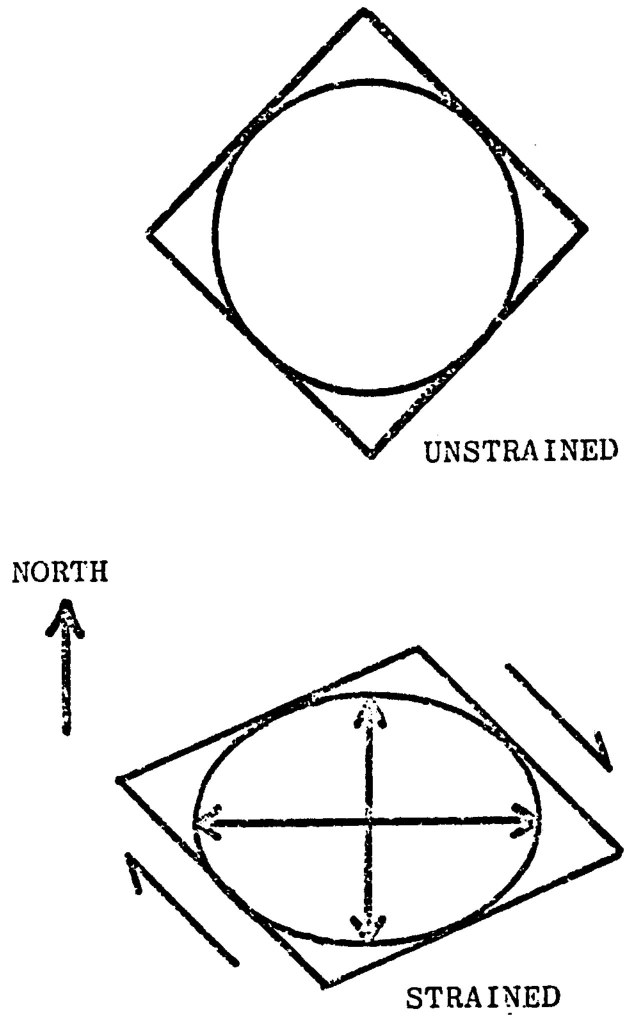


Figure 34. Distortion of circle by simple dextral shear (after Ramsey, 1967). North-south compression and east-west extension are produced if shearing direction is northwest-southeast.

lowered sea levels resulted in erosion of the canyon and accelerated the sediment contributions to the basin. The rate of sediment influx may have been at its highest when the Gardena River began to discharge near the head of the canyon approximately 100,000 y.b.p. According to this model, the large prism of sediment that makes up the Redondo submarine fan is quite young.

Santa Monica Submarine Canyon

The transition between the northwest-trending anticlinorium and the west-trending homocline remains unknown. The contrast in Miocene lithologies north and south of Santa Monica Submarine Canyon could represent either a facies change or tectonic juxtaposition. Unfortunately, seismic-reflection records across the canyon do not provide information about tectonic events occurring earlier than latest Pliocene time. It is possible that preorogenic strata on either side of the canyon are separated by a single fault at depth and the fault has not been significantly active since late Pliocene time. West-trending faults along both sides of the canyon, however, suggest that the canyon may be a graben similar to the Redondo graben. The fault along the north wall of the canyon and the shelf adjacent to the mountains may be responsible for much of the seismicity in the canyon. A third possibility is that the canyon simply reflects a large asymmetrical synclinal structure plunging toward the west.

SUMMARY AND CONCLUSIONS

Air gun records reveal that Late Cenozoic strata can be divided conveniently into preorogenic and postorogenic units. The preorogenic unit in the southern one-half of the bay, where predominantly northwest-trending structures belonging to the Peninsular Range Province occur, is characterized by folded, well-defined reflecting surfaces. Jet core and dredge samples, in addition to the geology in the Palos Verdes Hills and the San Pedro Shelf, suggest that these preorogenic strata consist of the Monterey Shale and Repetto Siltstone. Coastal plain stratigraphy demonstrates that the relatively undeformed postorogenic strata beneath the inner shelf consist of siltstone and sandstone belonging to the upper part of the upper Pliocene Pico Formation and the entire preserved Quaternary section. Therefore, the deformation of the preorogenic strata occurred in middle to early late Pliocene time. Within the visible portion of the postorogenic section the contact between postorogenic and preorogenic strata is an unconformity, not the Palos Verdes fault as previously proposed. The Palos Verdes fault, however, is believed to exist at depth and was probably active in the area of Santa Monica Bay prior to latest Pliocene time. Preorogenic strata have been folded into at least three northwest-trending anticlinoria arranged _en echelon_: the shelf projection anticlinorium, the Redondo platform anticlinorium, and the Palos Verdes Hills anticlinorium. Dextral shear along the Palos Verdes fault is postulated to be responsible for the formation of the _en echelon_ anticlinoria, and in this respect is similar to the Newport-Inglewood zone of deformation. This conclusion has significance in the context of the increasing recognition of strike-slip movement, particularly along _en echelon_ fault systems, as an important structural feature in the California Continental Borderland (for examples see Moore, 1969; and Vedder and others, 1974).

The platform anticlinorium was dropped in a graben bounded by west-southwest-trending faults: the Redondo Canyon fault and the North Redondo Canyon fault. Thick sequences of postorogenic strata have been preserved in the graben which facilitated the development of the Redondo Submarine Canyon during Late Pleistocene time. Interpretation of profiles suggest that the graben was initiated along with the formation of the anticlinoria. Although the attitude of boundary faults cannot be determined directly for the seismic-reflection records, proposed dextral offset along the Palos Verdes fault, responsible for _en echelon_ folding, also may be responsible for the reactivation of west-trending basement anistropies. If this is the case, a simple shear model predicts that they would be reverse faults. Inasmuch as the Palos Verdes fault has not been active in the bay since latest Pliocene time, Late Quaternary uplift of the Palos Verdes Hills has occurred along the Redondo Canyon fault. Quaternary displacement along the San Pedro fault zone is also indicated.

The preorogenic unit along the shelf between Point Dume and Santa Monica is lithologically variable and similar to the middle and upper Miocene strata south of the Malibu Coast fault in the Santa Monica Mountains. These strata form a southward dipping homocline transected by a west-southwest-trending normal fault. The structural transition across the Santa Monica Submarine Canyon between northwest-trending and west-trending structural elements is as yet unknown.

Late Quaternary (younger than 100,000 years) movement along the North Redondo Canyon fault, the San Pedro fault zone, and the faults bounding the Santa Monica Submarine Canyon is believed to have taken place. Holocene displacements occurred along the Redondo Canyon fault and possibly the North Redondo Canyon fault.

High resolution profiling has proven to be an excellent method of determining the locations of hydrocarbon seeps. In addition to the 9 seeps previously reported in Santa Monica Bay, several times that number were detected in this study. Seeps are recognized primarily by acoustic scattering from hydrocarbon emanations in the water column. Further, distinct acoustic signature within the Late Quaternary sediments themselves indicates the presence of hydrocarbons in the substrate. Seeps are primarily associated with (1) the homoclinal structure and normal fault in the shelf adjacent to the Santa Monica Mountains, (2) a short fault segment immediately southwest of Santa Monica, (3) the Redondo Canyon fault, (4) the North Redondo Canyon fault, and (5) the postorogenic-preorogenic unconformities.

Although Late Quaternary geology was not emphasized in this report, the high resolution provided by the seismic-reflection data and the current interest in paleoclimates suggest that a logical extension of this investigation would be the study of the Late Quaternary sedimentological, structural, and morphological evolution of Borderland shelves and banks and its relationship to eustatic sea level fluctuations.

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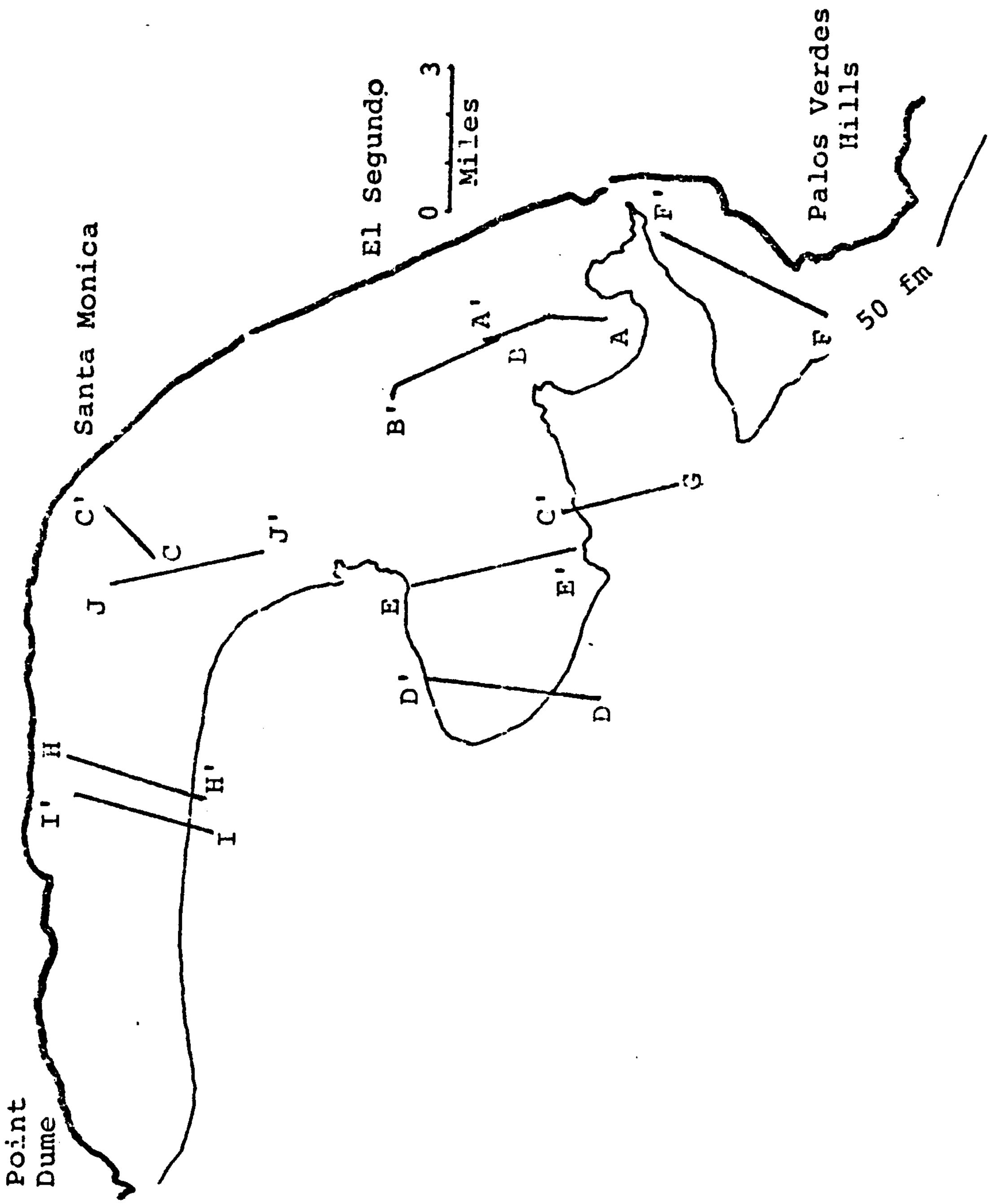
APPENDIX


Point Dume
Santa Monica
El Segundo
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Palos Verdes Hills
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D D'
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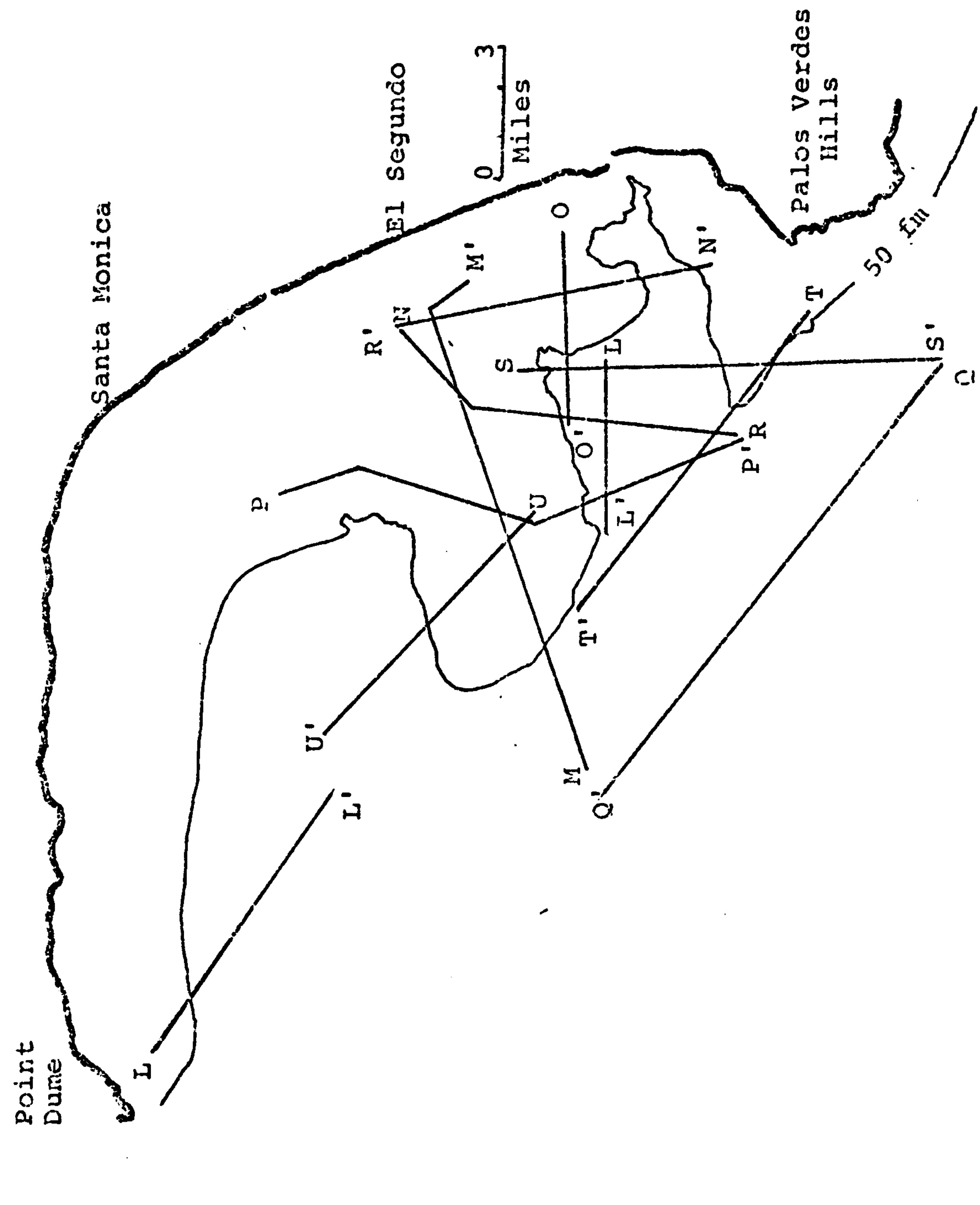
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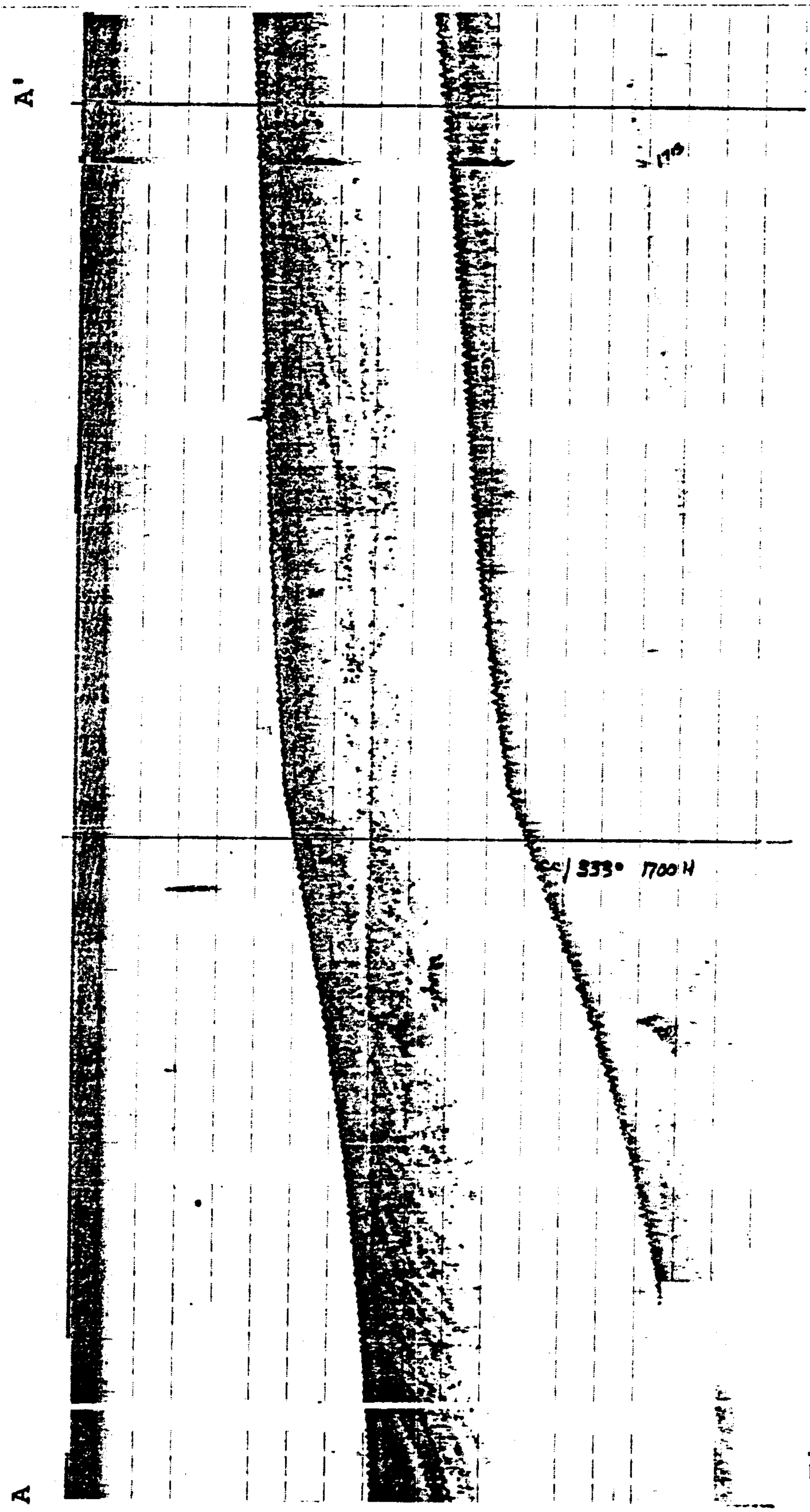

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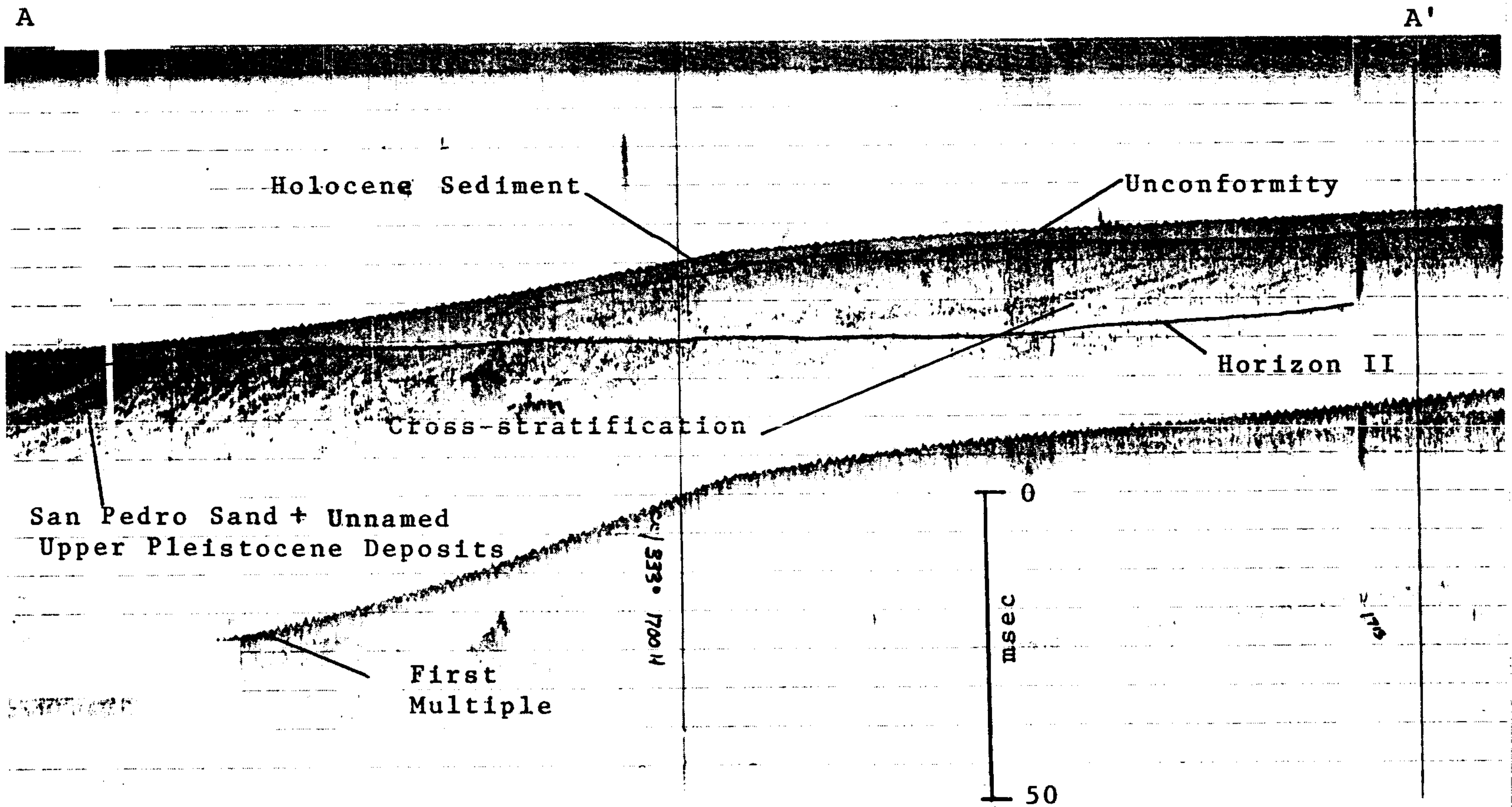

A
A'
Holocene Sediment
Unconformity
Horizon II
Cross-stratification
San Pedro Sand + Unnamed
Upper Pleistocene Deposits
First
Multiple
0
msec
50
333° 1700 H

Figure A3

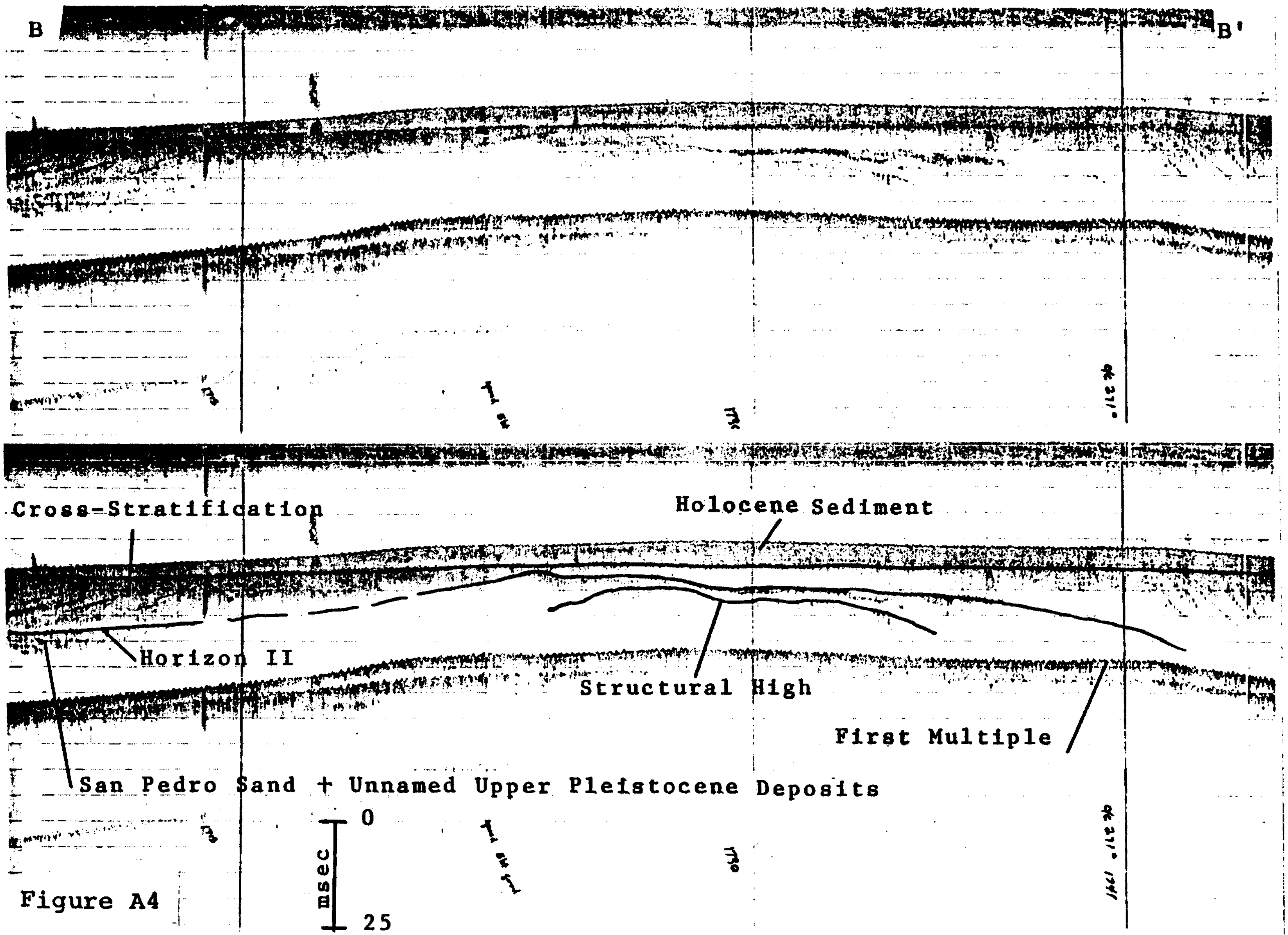
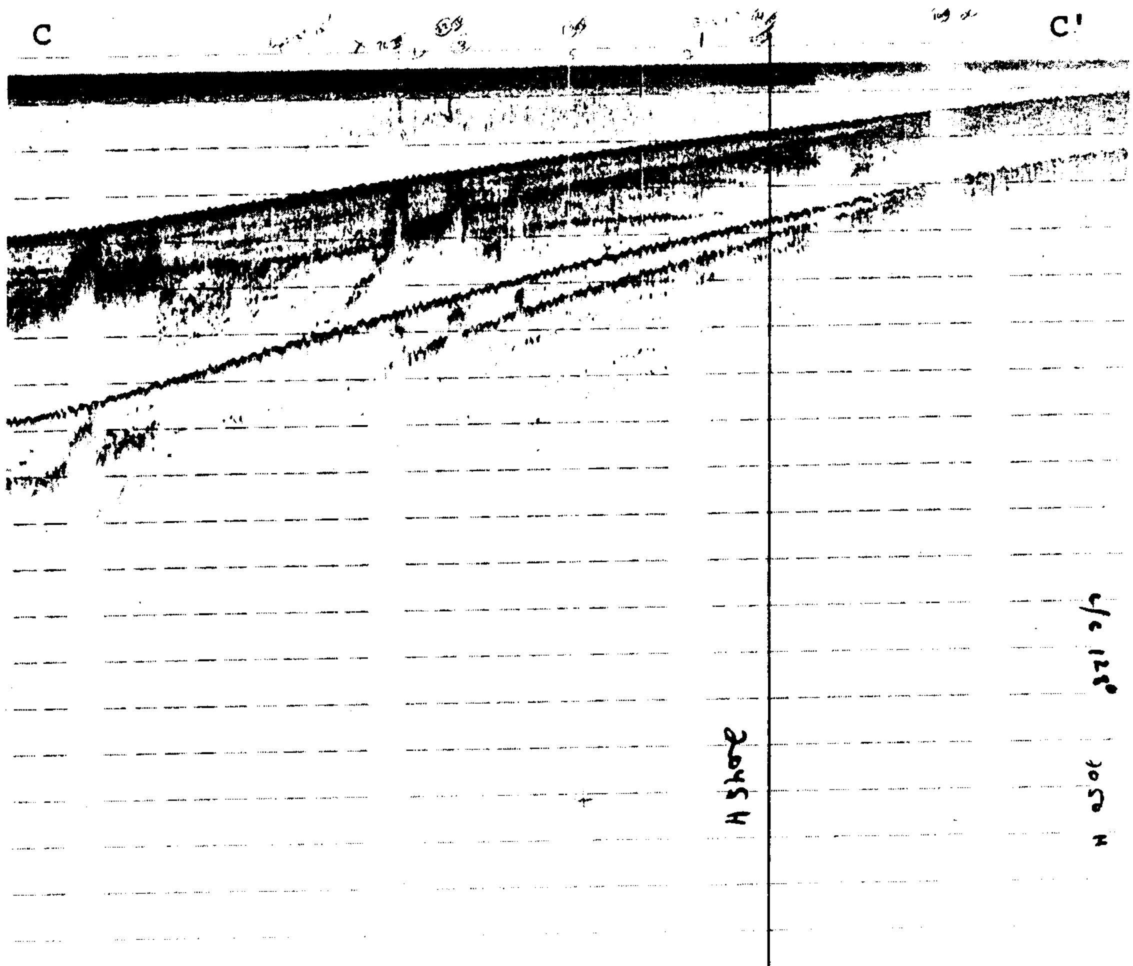

B
B'
Cross-Stratification
Holocene Sediment
Horizon II
Structural High
First Multiple
San Pedro Sand + Unnamed Upper Pleistocene Deposits
0
msec
25

Figure A4



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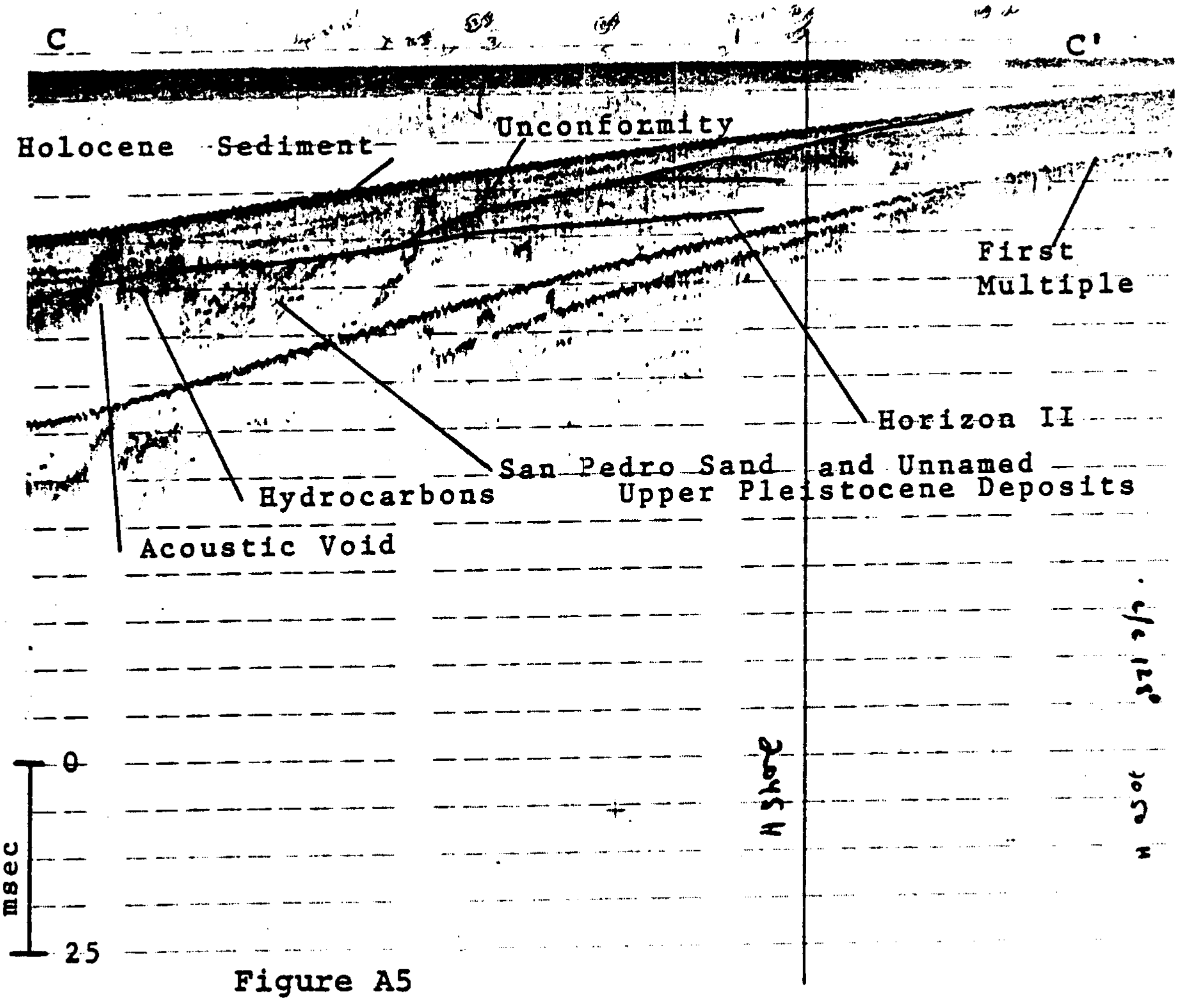
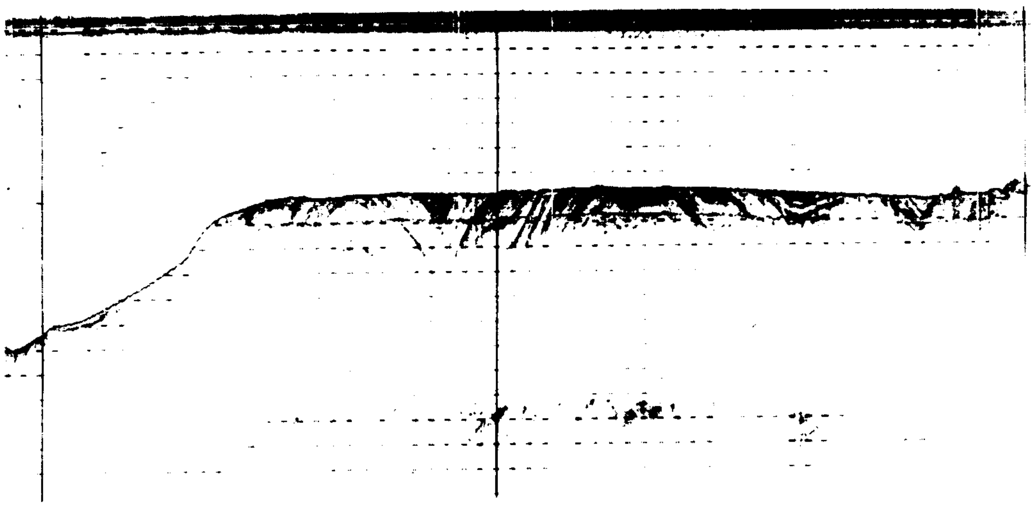

C
C'
Holocene Sediment
Unconformity
First Multiple
Horizon II
San Pedro Sand and Unnamed Upper Pleistocene Deposits
Hydrocarbons
Acoustic Void
0
msec
25

Figure A5



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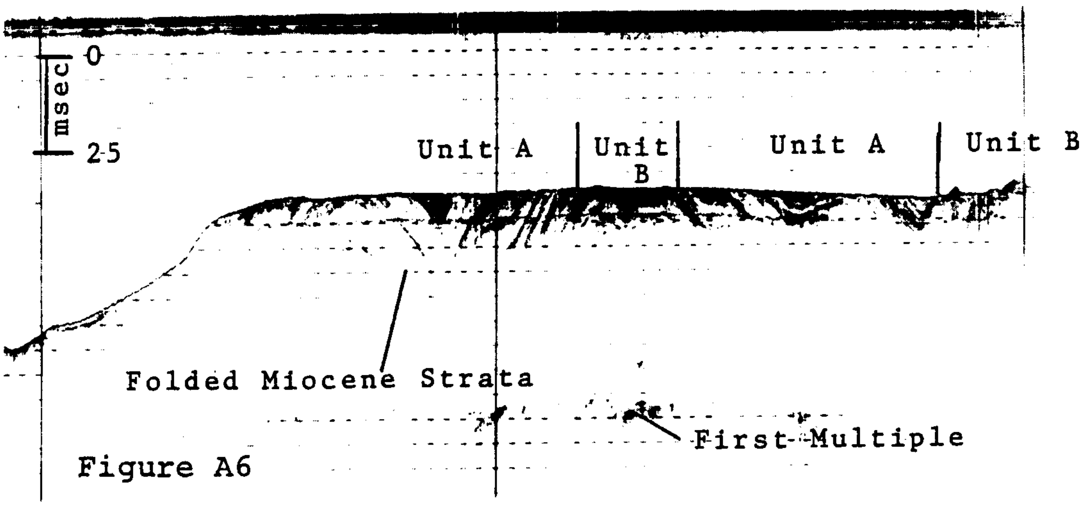

msec
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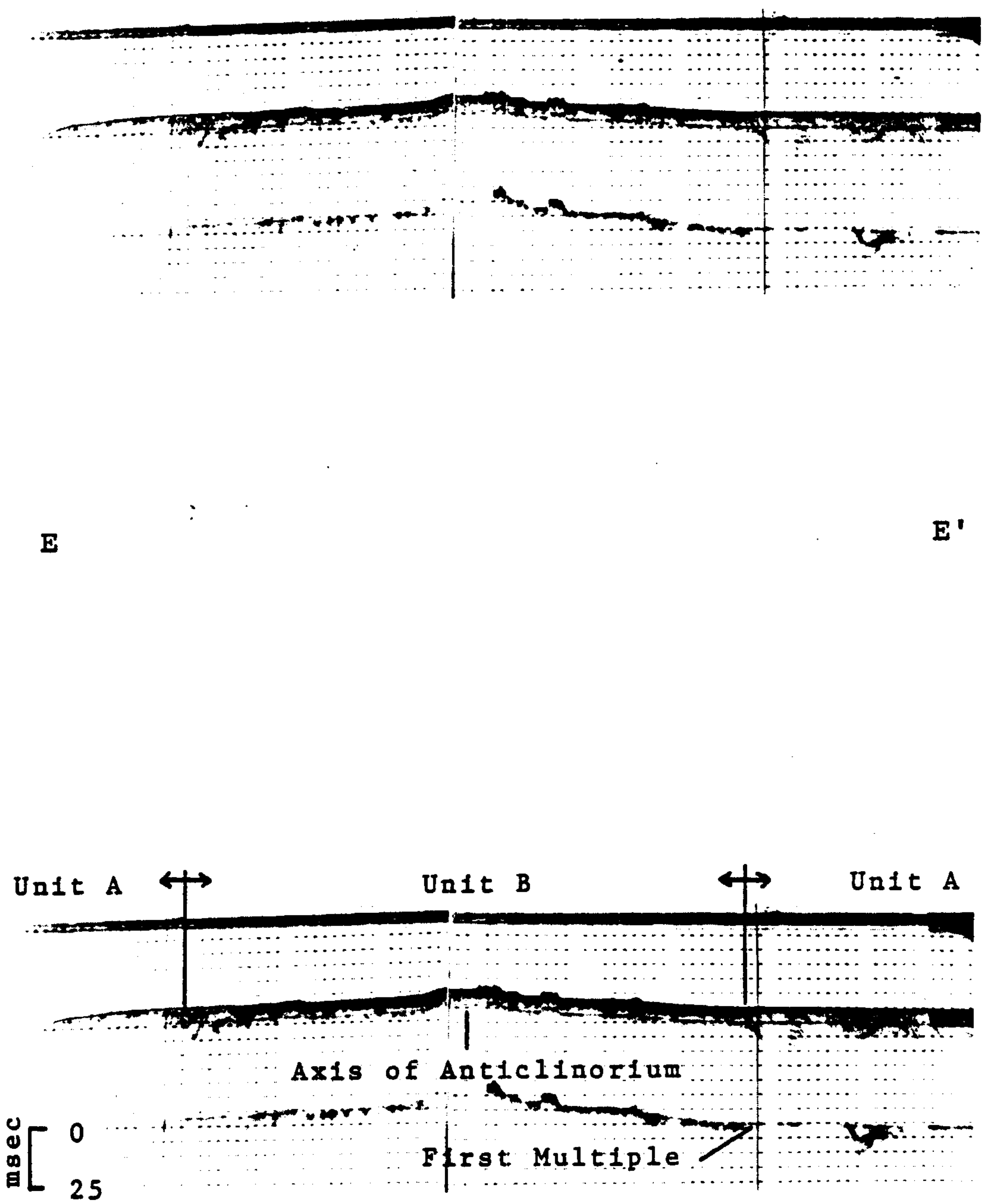
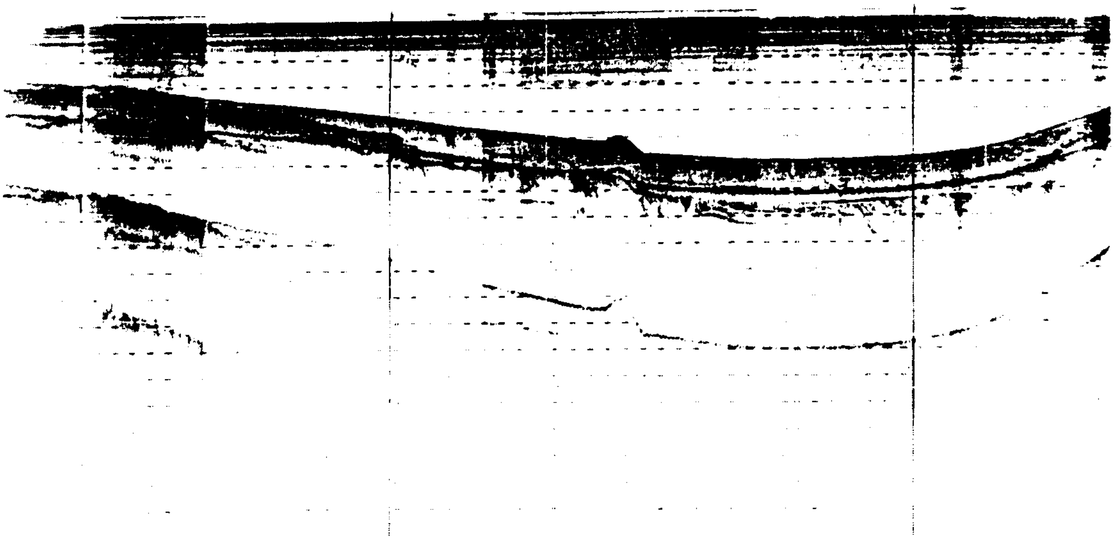
25
Unit A
Unit B
Unit A
Unit B
Folded Miocene Strata
First Multiple

Figure A6

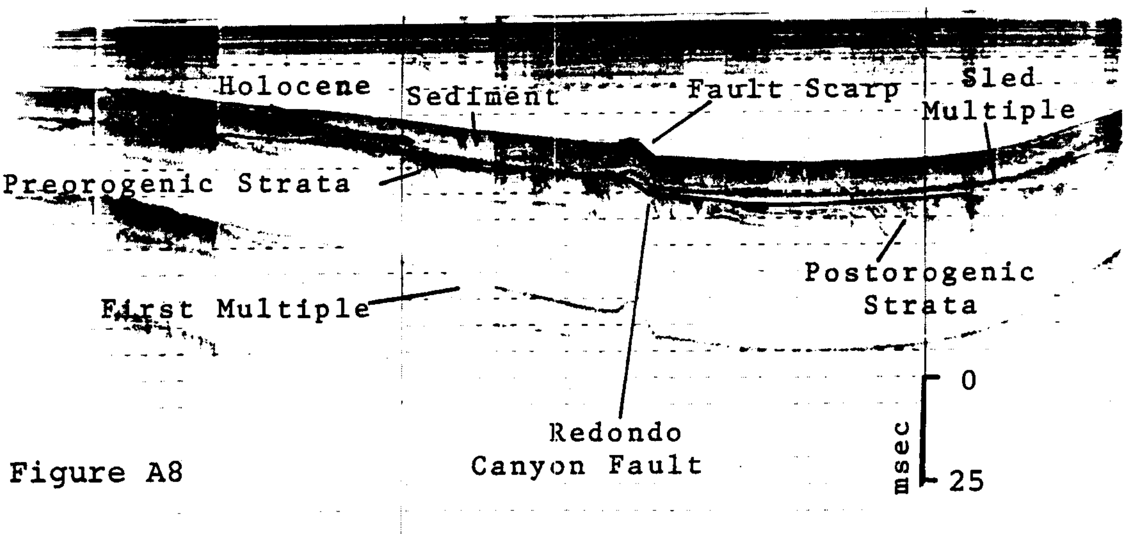
Figure A7


E
E'
Unit A
Unit B
Unit A
Axis of Anticlinorium
msec
0
25
First Multiple



F

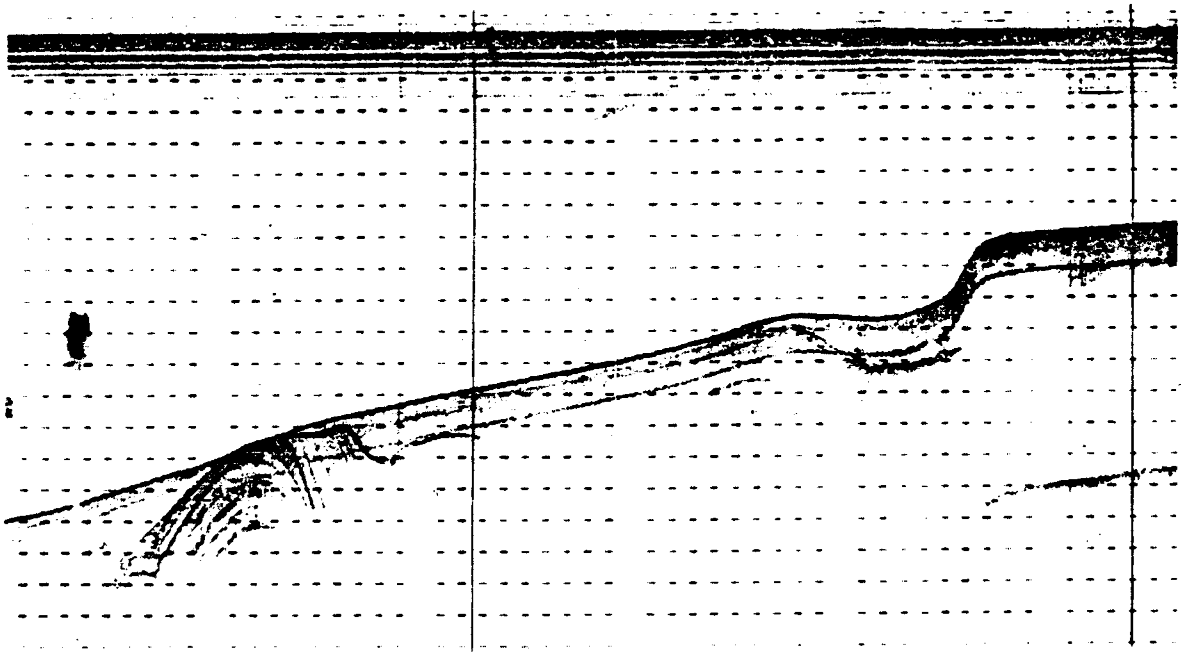
F'

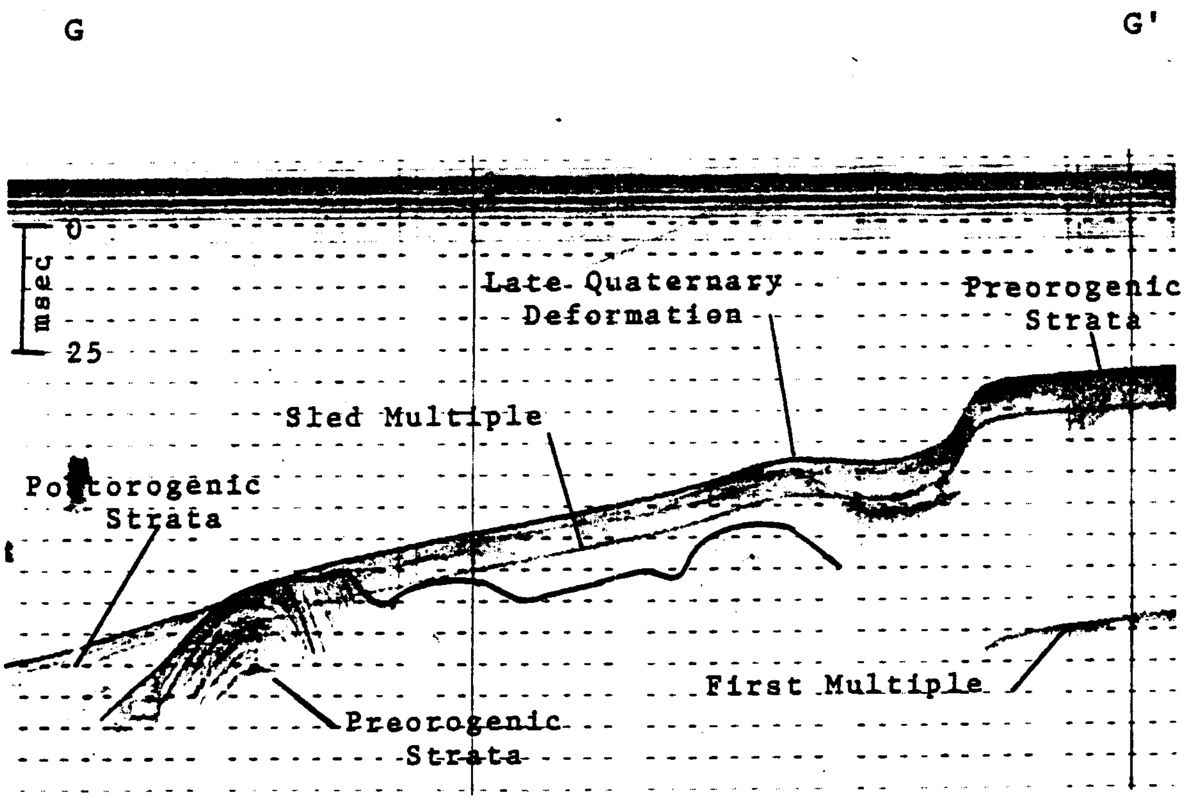


Holocene
Sediment
Fault Scarp
Sled
Multiple
Preorogenic Strata
Postorogenic
Strata
First Multiple
0
msec
25
Redondo
Canyon Fault

Figure A8

Figure A9




G
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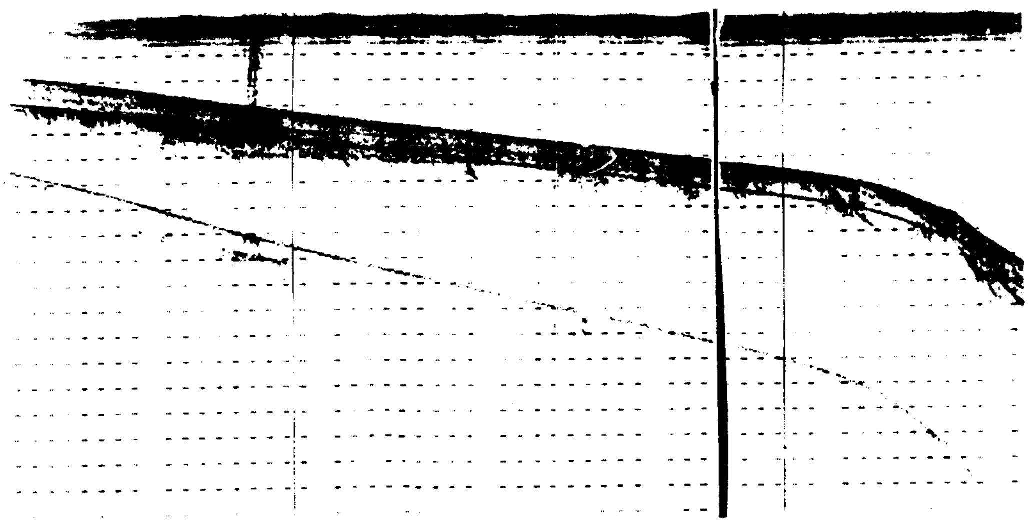
Late Quaternary
Deformation
Preorogenic
Strata
Sled Multiple
Postorogenic
Strata
First Multiple
Preorogenic
Strata



H

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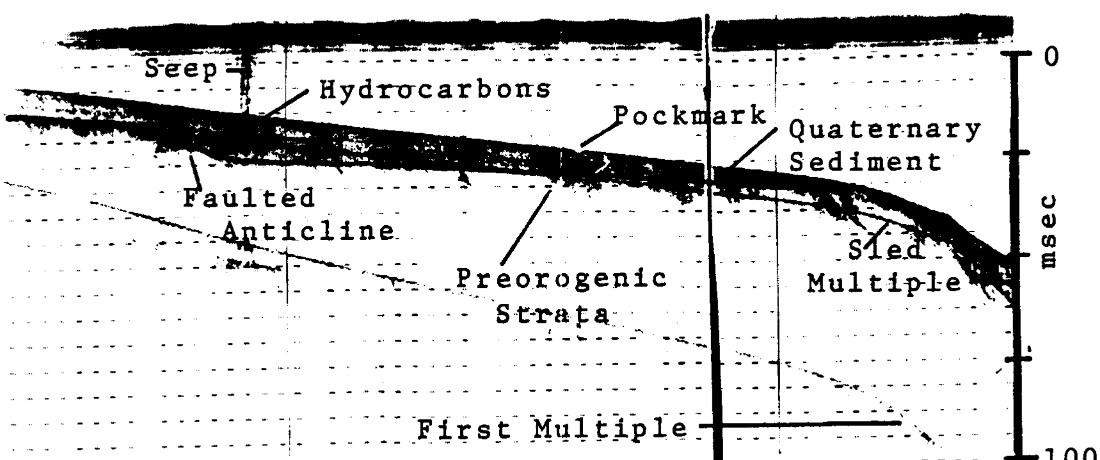


Figure A10

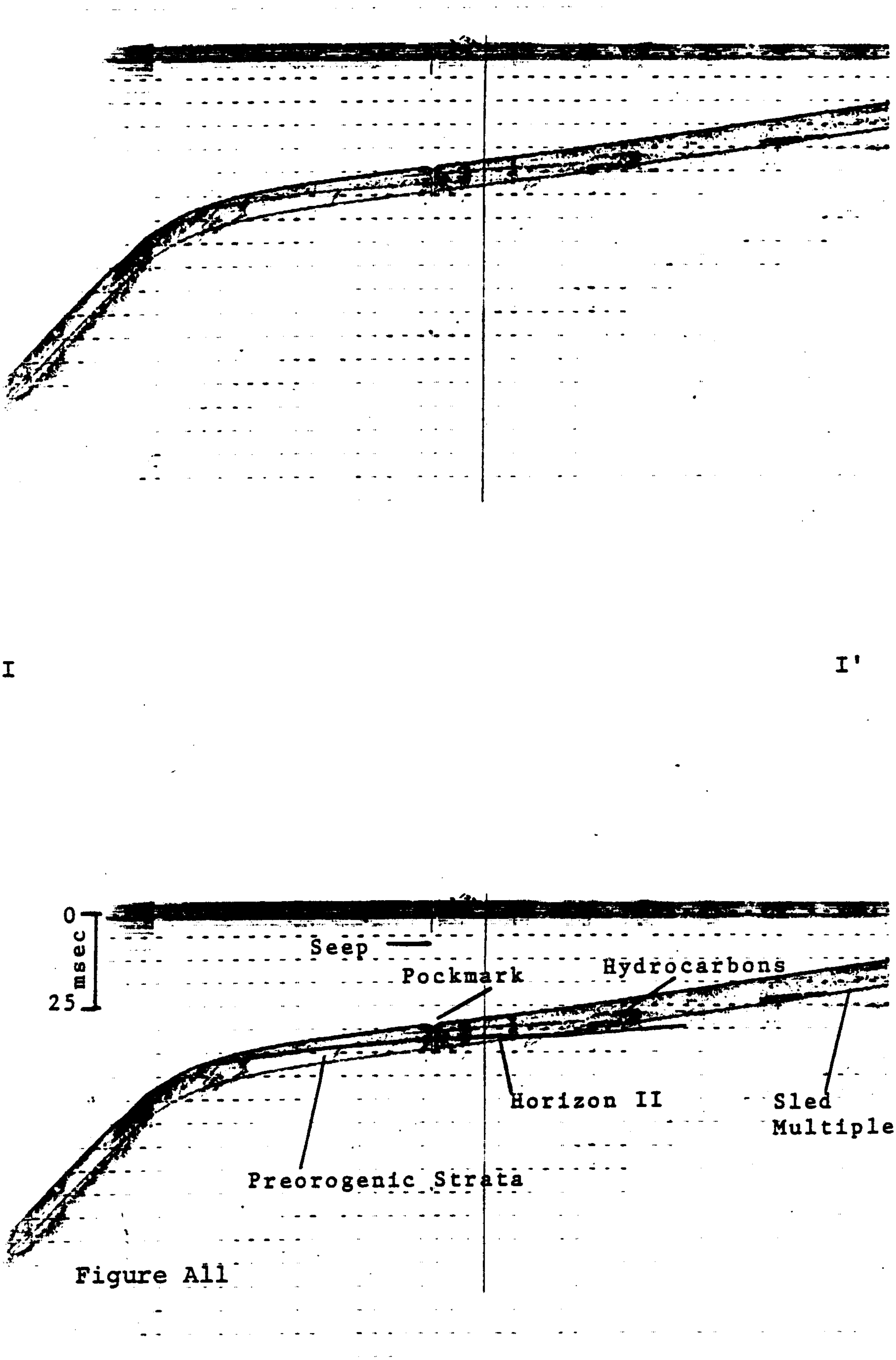
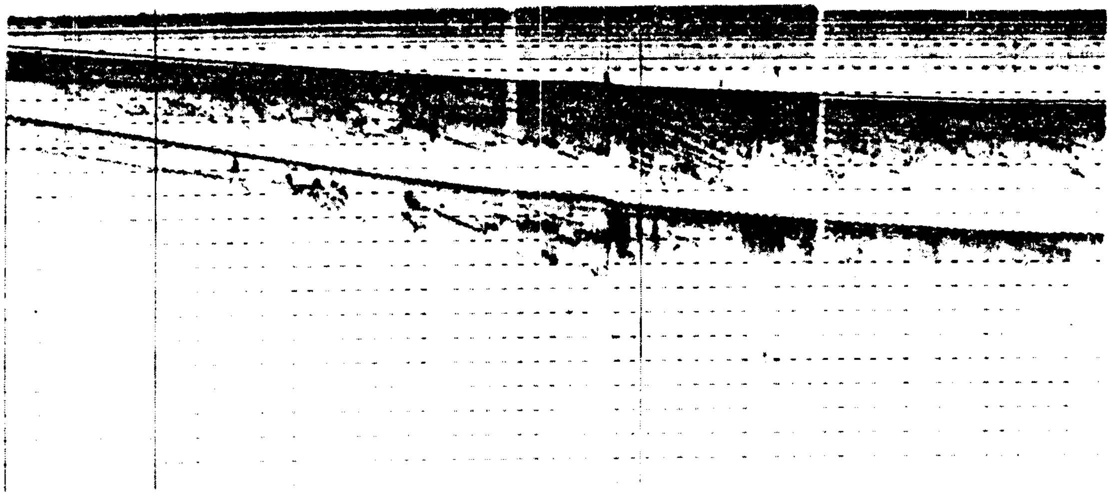

I
I'
0
msec
25
Seep
Pockmark
Hydrocarbons
Horizon II
Sled Multiple
Preorogenic Strata

Figure A11

Figure A12



J J'

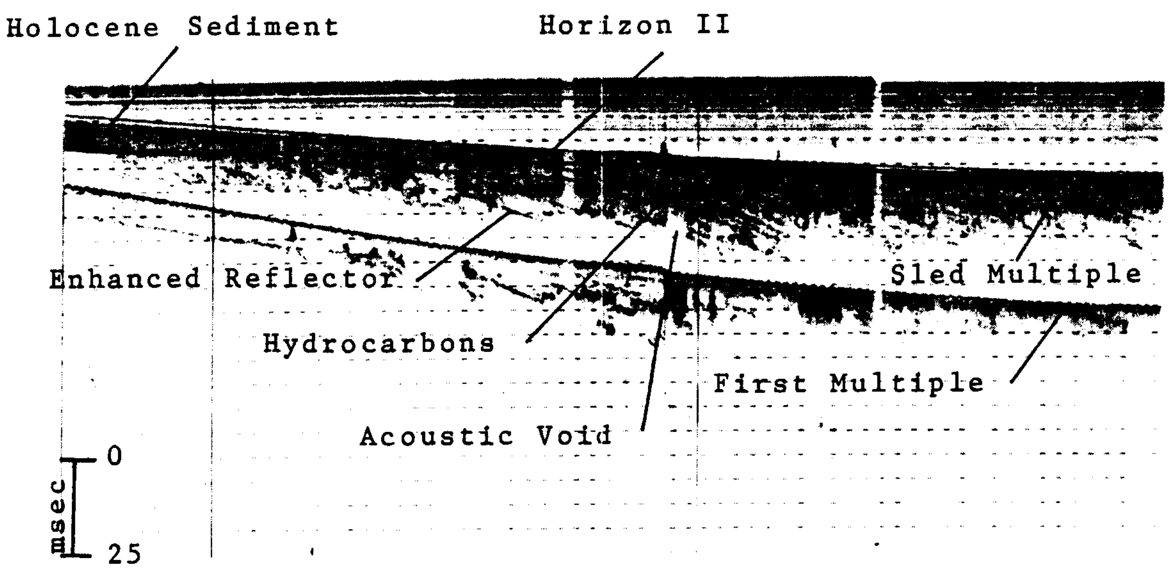
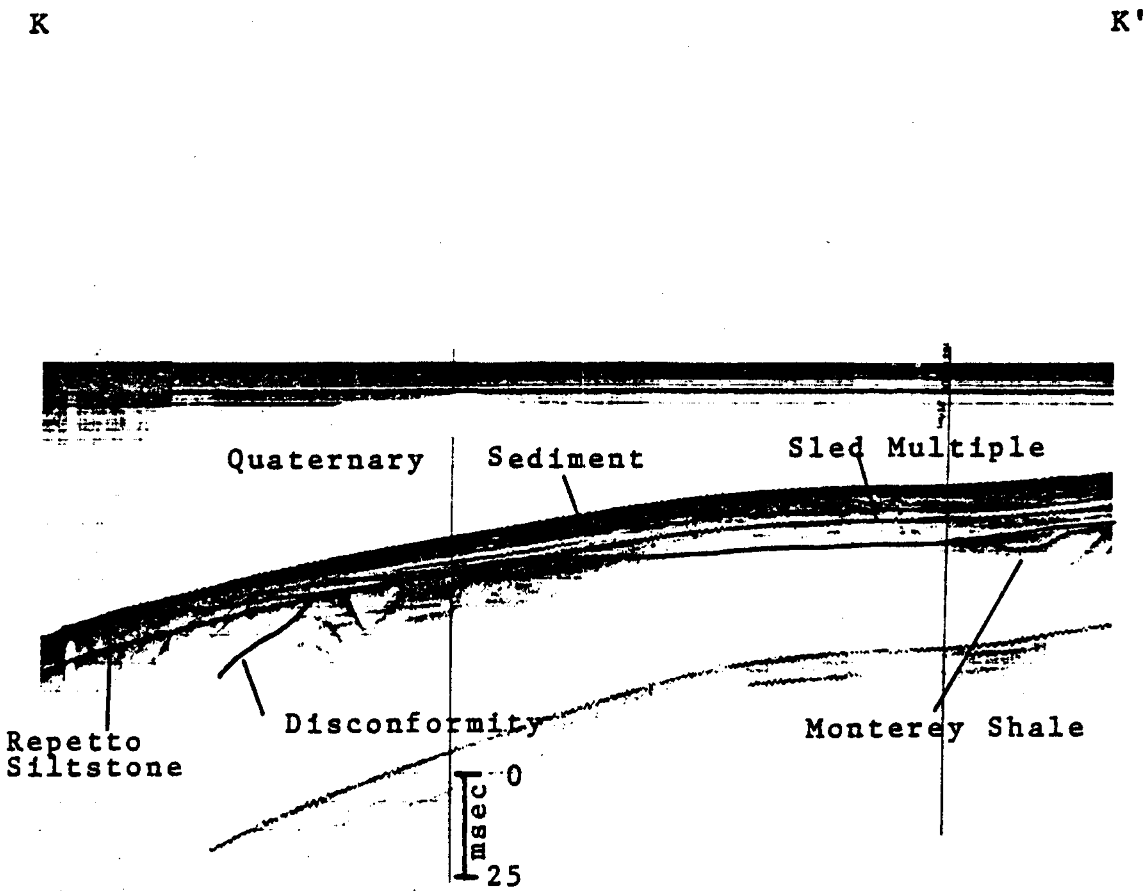
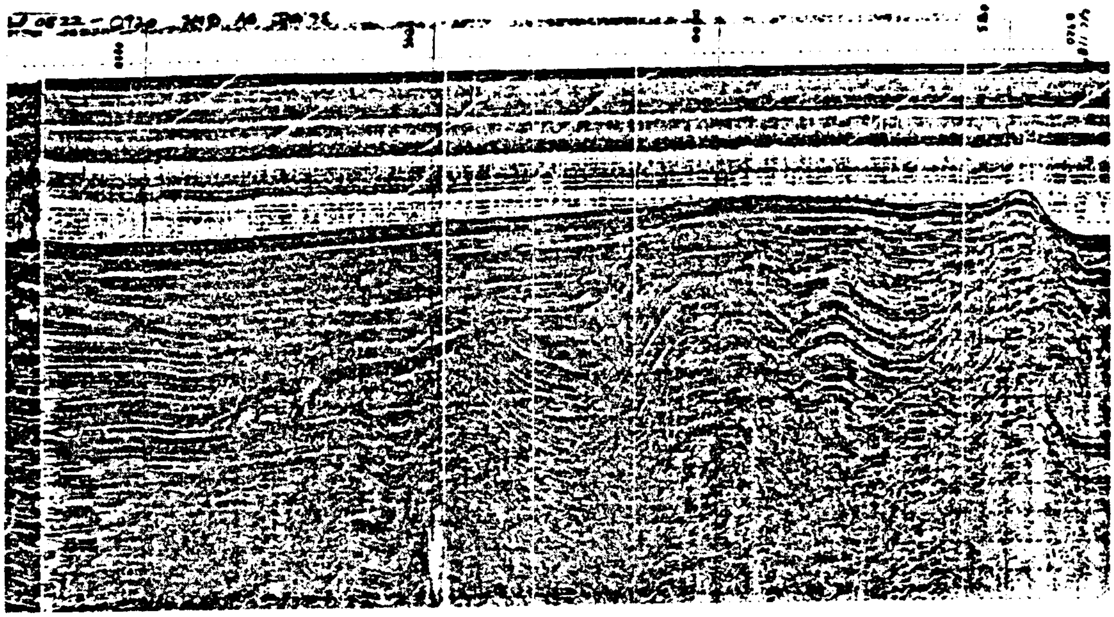


Figure A13


K
K'
Quaternary Sediment
Sled Multiple
Repetto Siltstone
Disconformity
Monterey Shale
0
msec
25



L L'

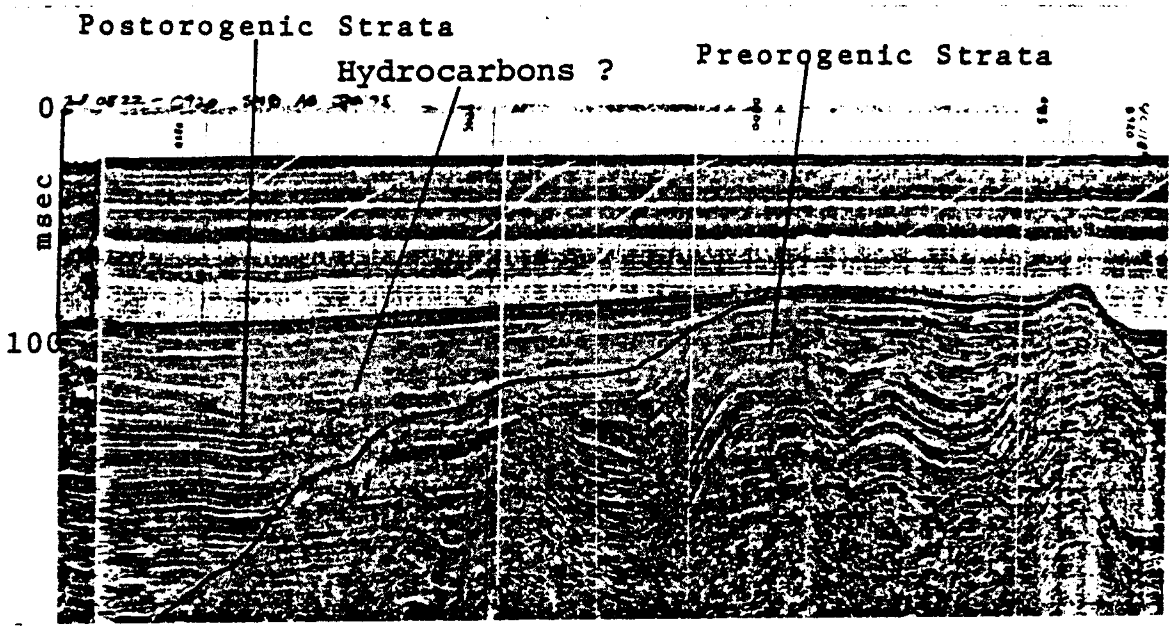
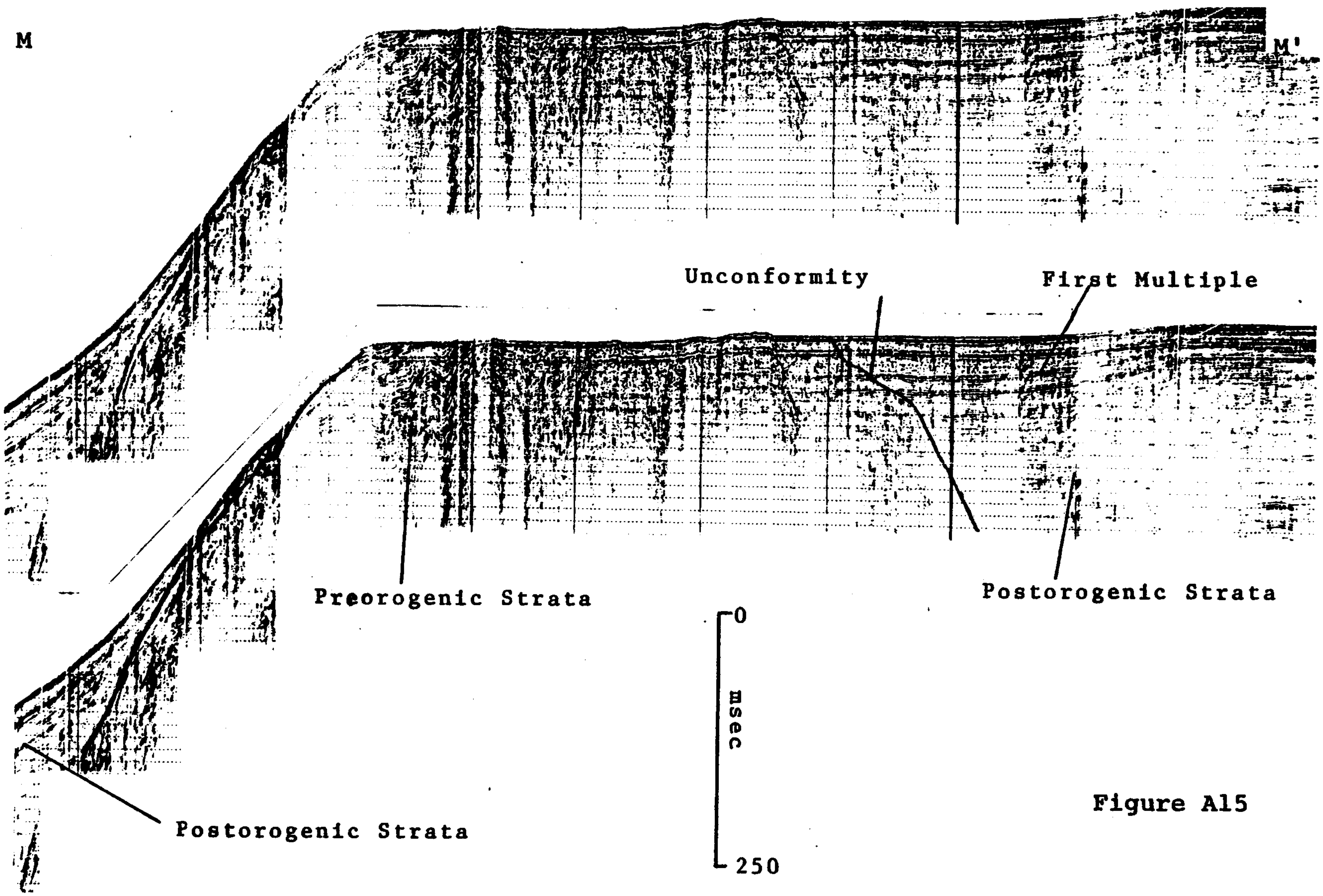


Figure A14



M
M'
Unconformity
First Multiple
Preorogenic Strata
Postorogenic Strata
0
msec
250
Postorogenic Strata

Figure A15

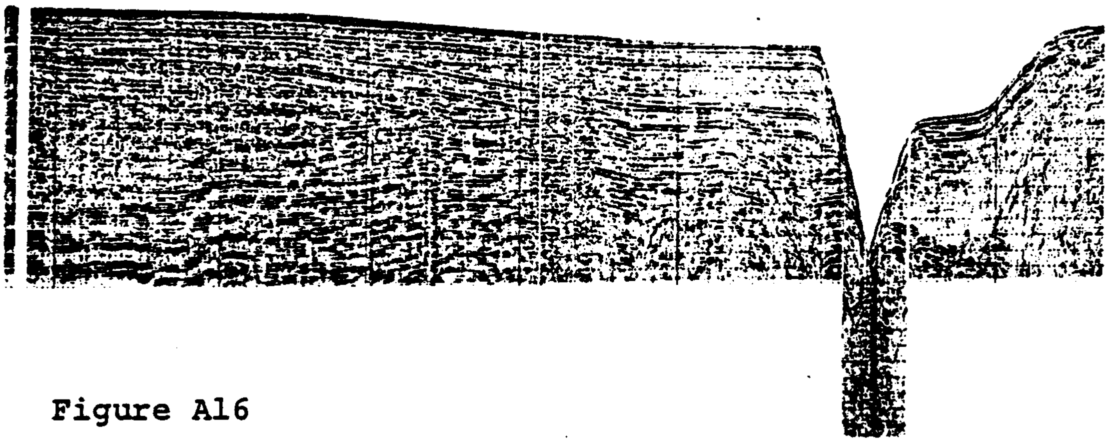
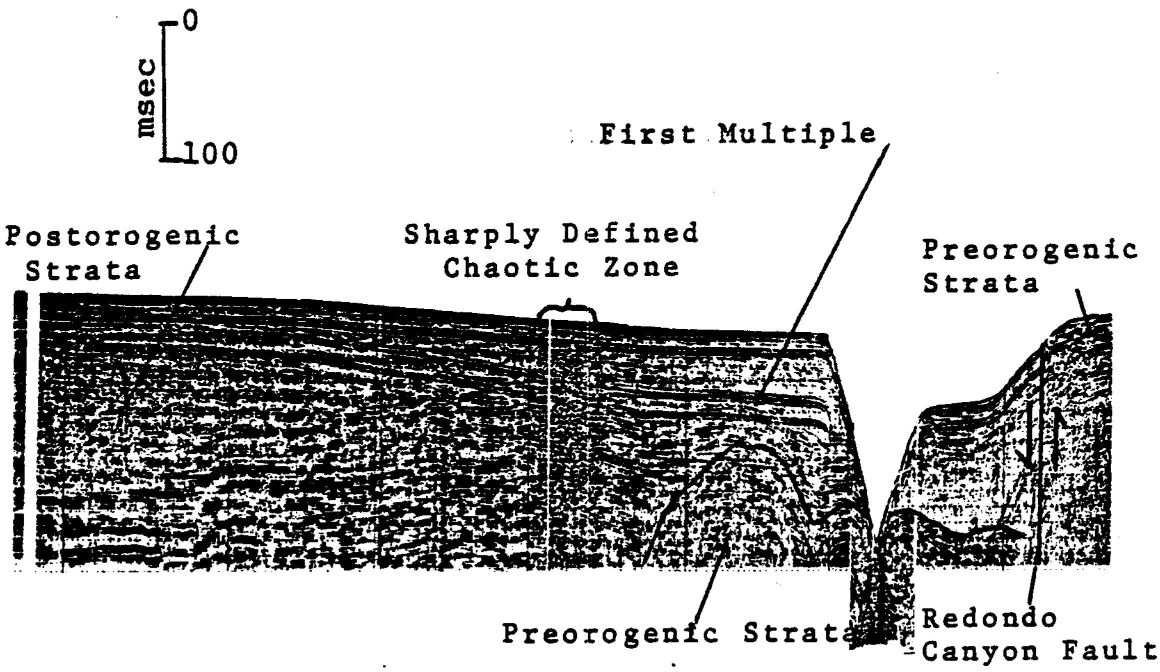
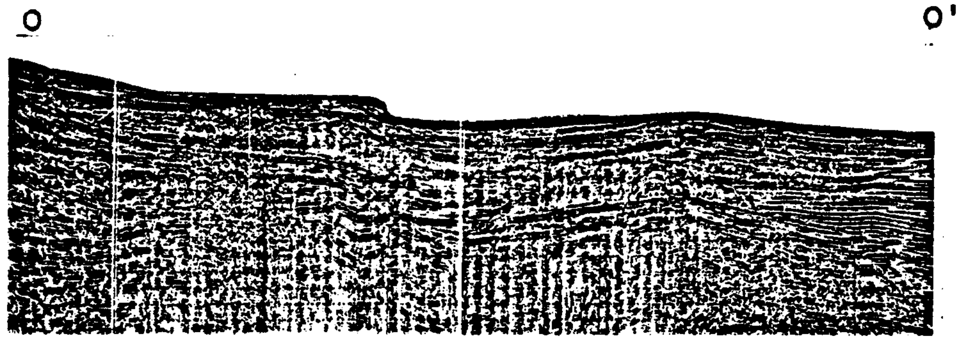


Figure A16

N

N'




O
O'

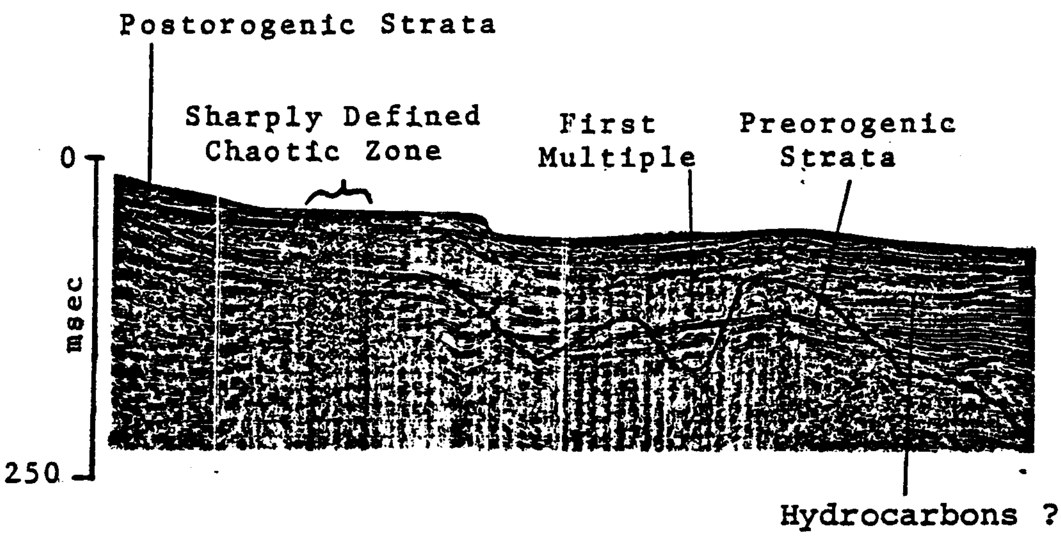

Postorogenic Strata
Sharply Defined
Chaotic Zone
First
Multiple
Preorogenic
Strata
0
msec
250
Hydrocarbons ?

Figure A17

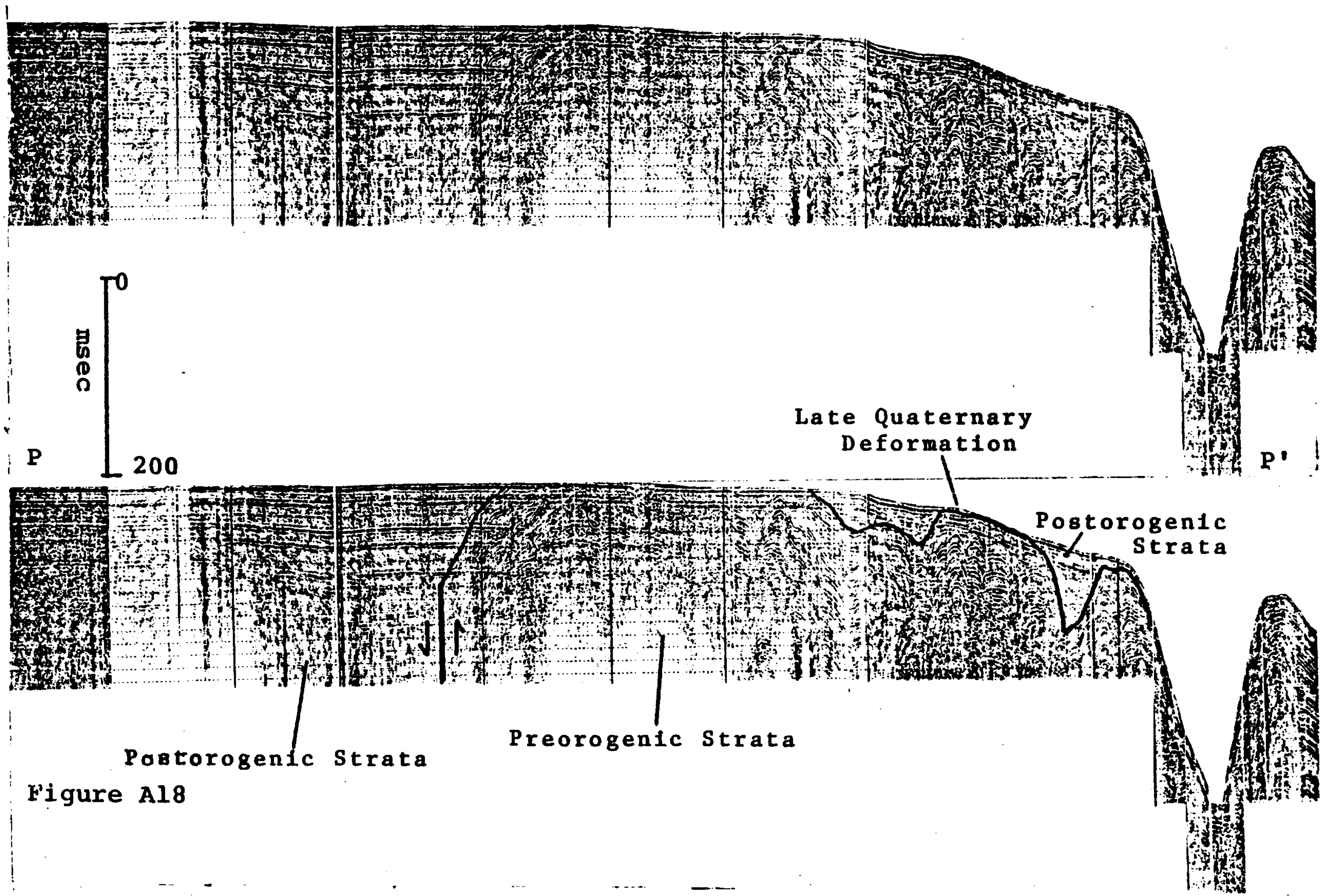

P
P'
0
msec
200
Late Quaternary
Deformation
Postorogenic
Strata
Preorogenic Strata
Postorogenic Strata

Figure A18

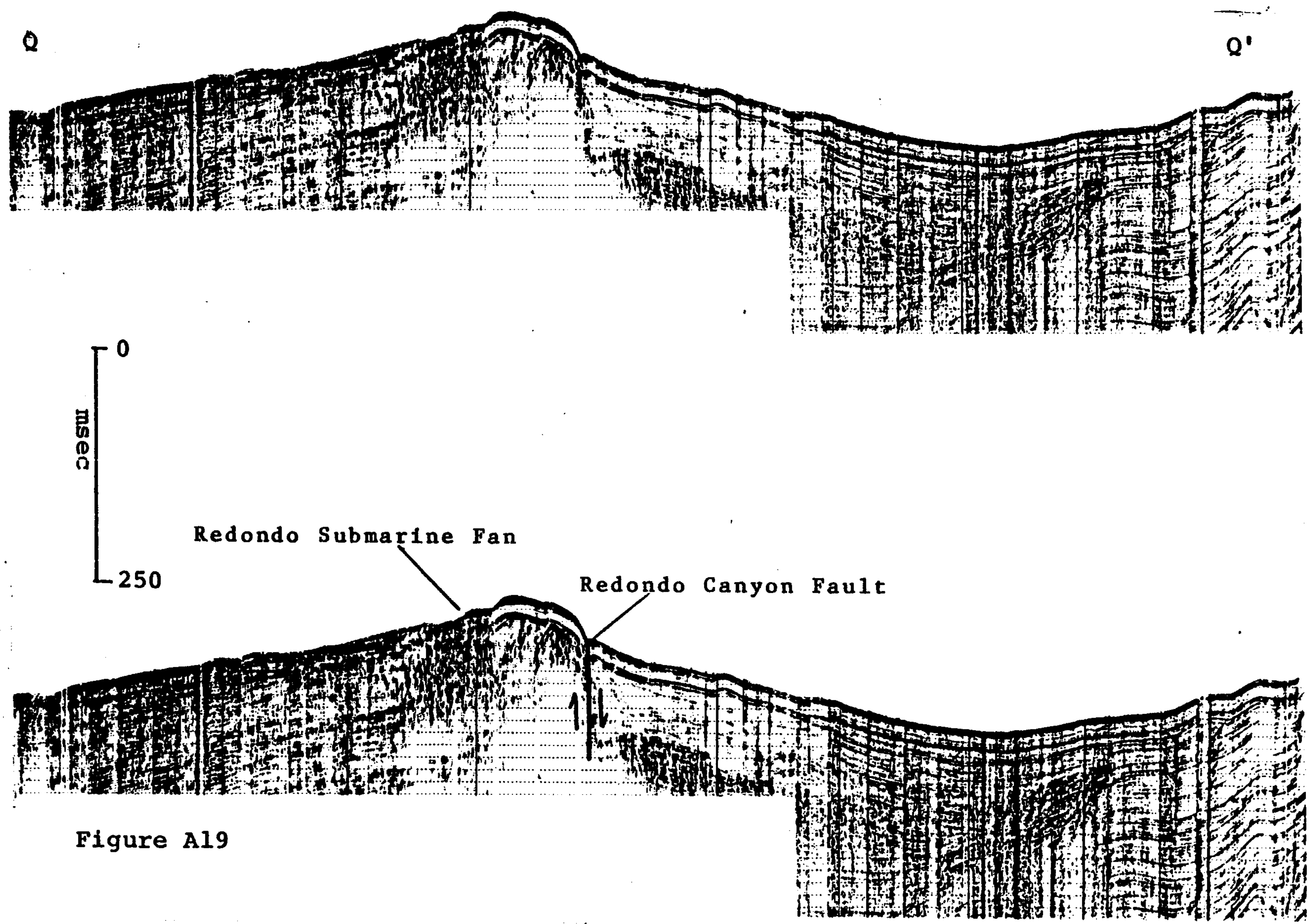


Figure A19

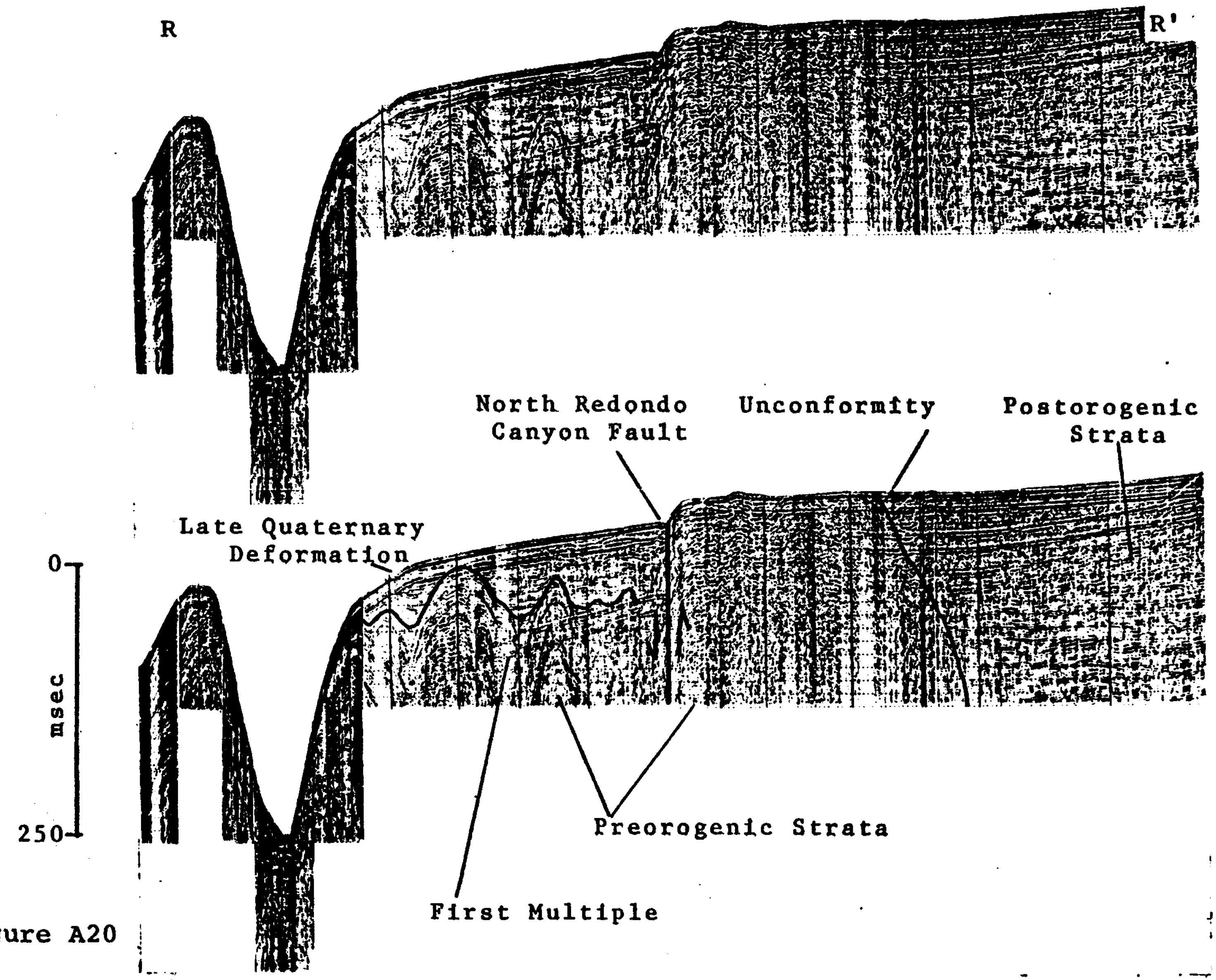

R
R'
North Redondo
Canyon Fault
Unconformity
Postorogenic
Strata
Late Quaternary
Deformation
0
msec
250
Preorogenic Strata
First Multiple

Figure A20

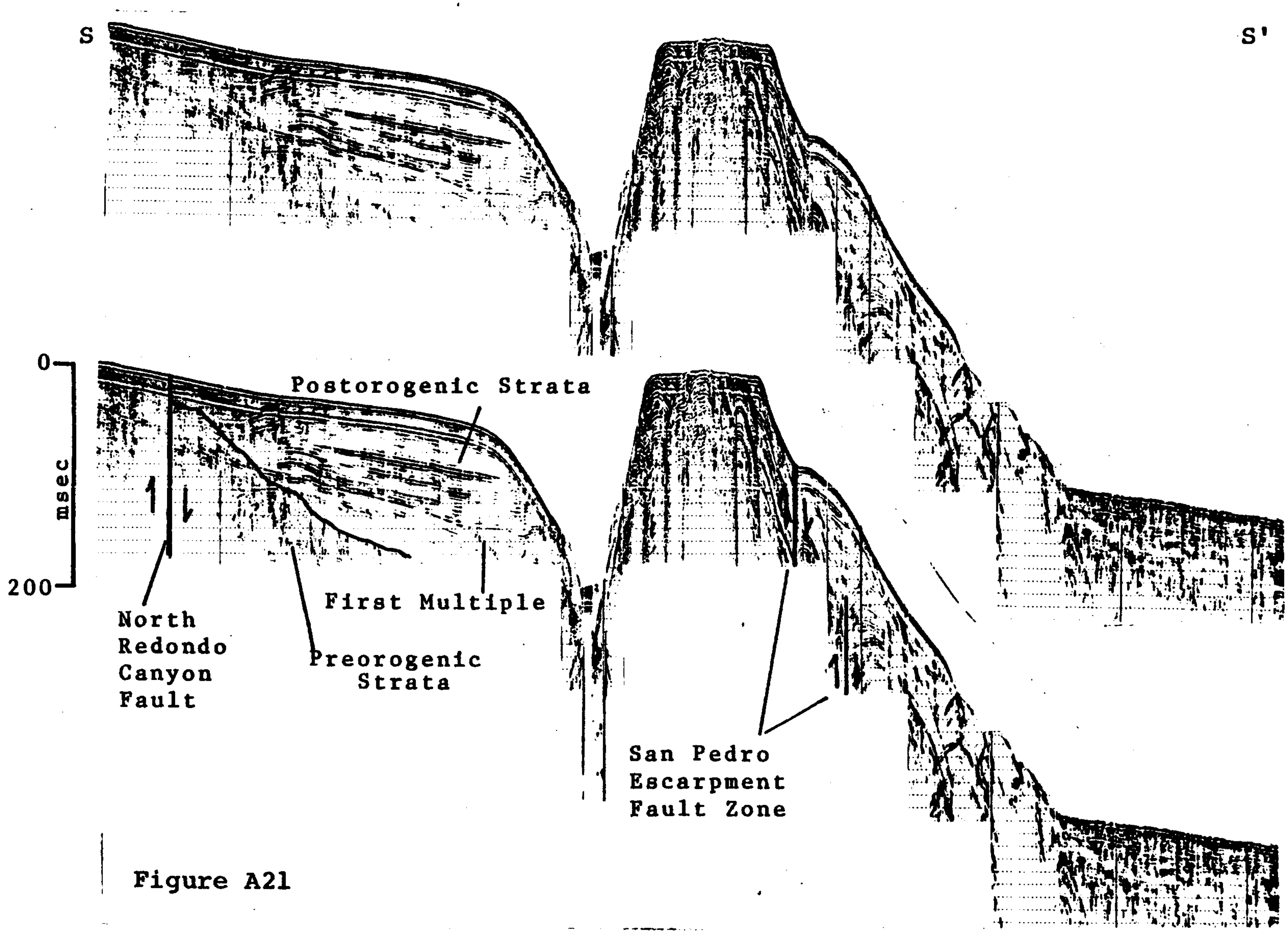

S
S'
0
200
msec
Postorogenic Strata
First Multiple
North Redondo Canyon Fault
Preorogenic Strata
San Pedro Escarpment Fault Zone

Figure A21

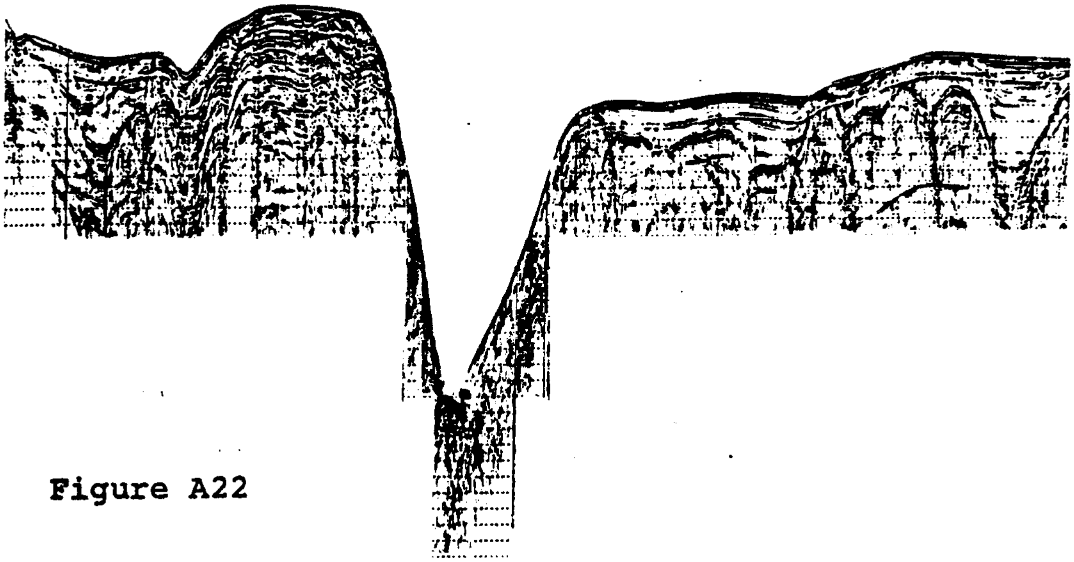
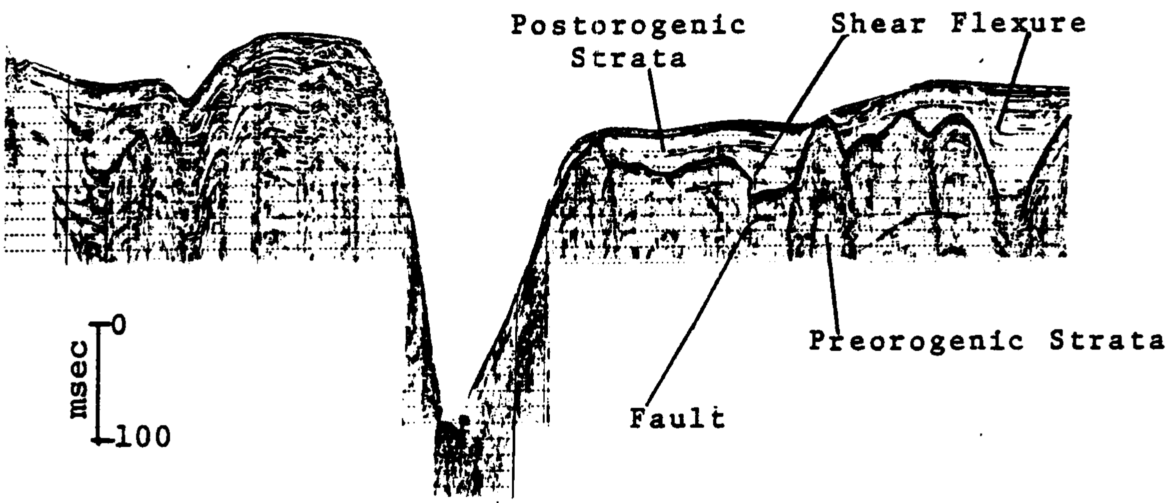


Figure A22

T T'



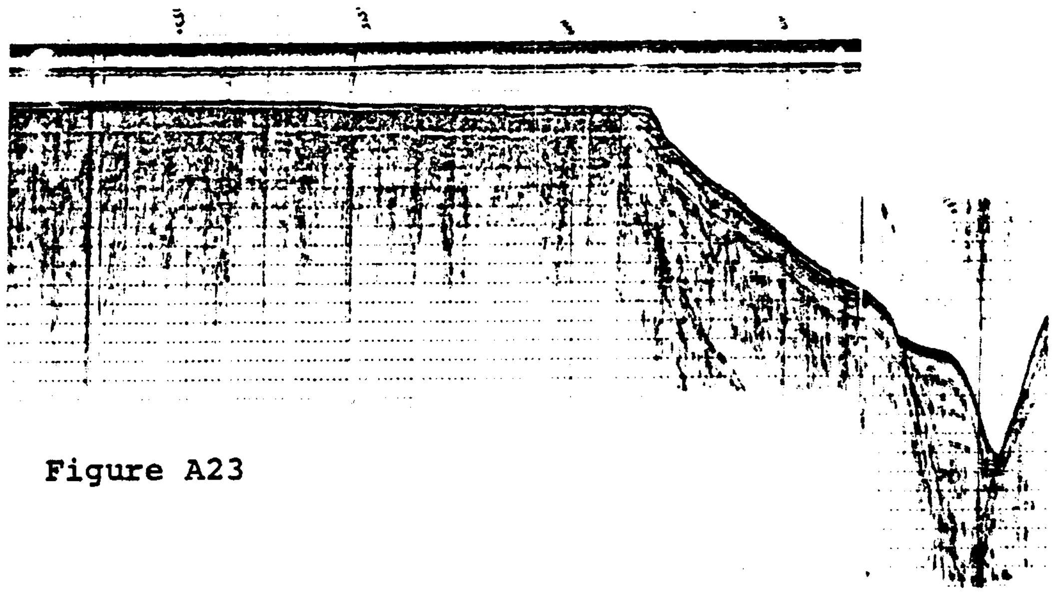
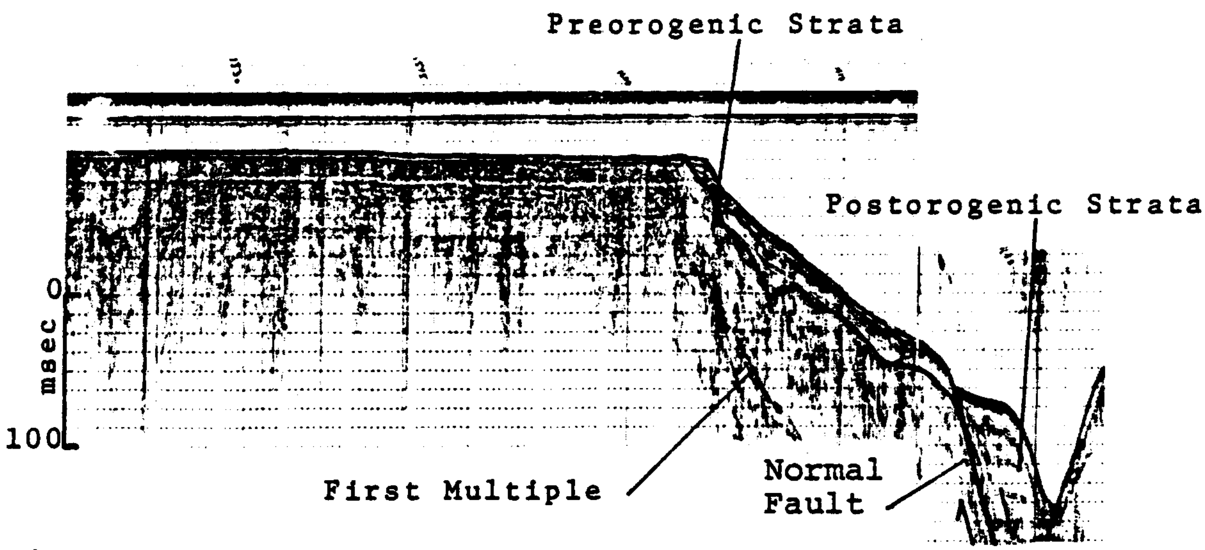


Figure A23

U

U'



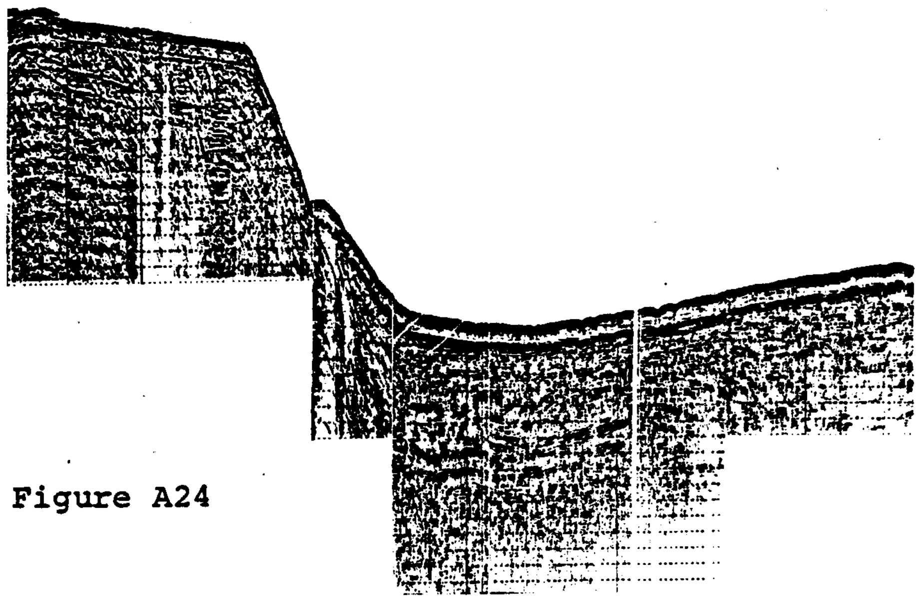
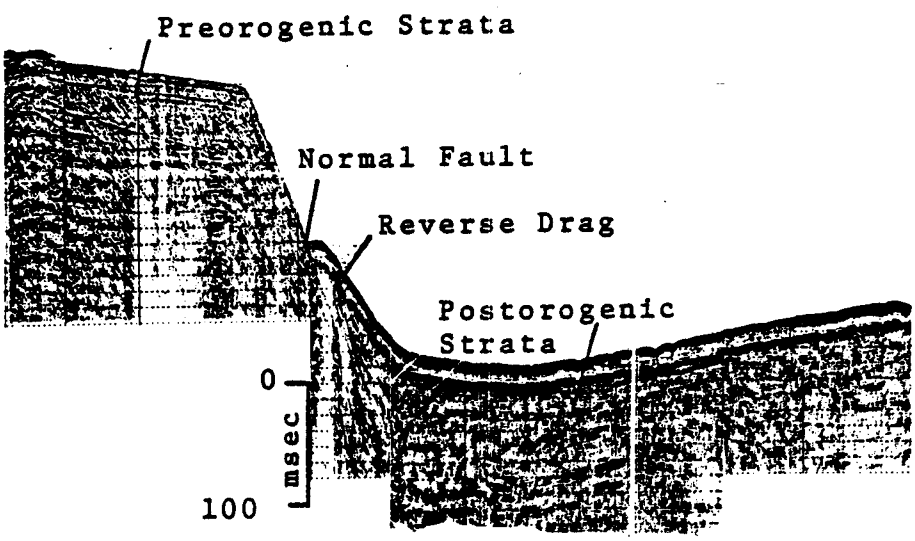


Figure A24

V

V'



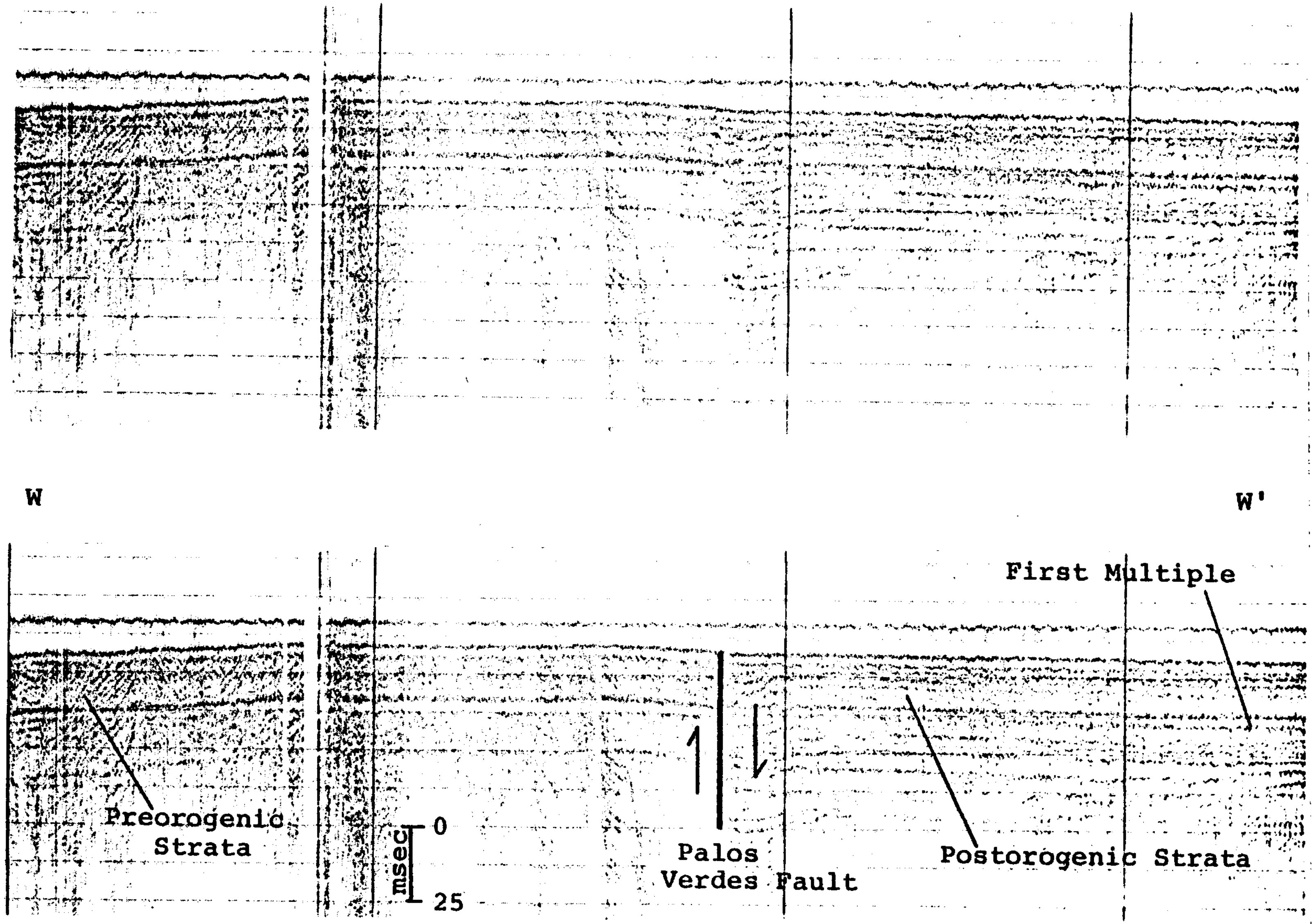

W
W'
First Multiple
Preorogenic
Strata
Palos
Verdes Fault
Postorogenic Strata
msec
0
25

Figure A25