CALIFORNIA STATE UNIVERSITY, NORTHRIDGE

GEOLOGY OF THE INNER BASIN MARGIN:

DANA POINT TO SAN ONOFRE, CALIFORNIA

A thesis submitted in partial satisfaction of the requirements for the degree of Master of Science in

Geology

by

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

ABSTRACT

GEOLOGY OF THE INNER BASIN MARGIN

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Acoustic subbottom profiles, in conjunction with onshore geological data and limited bottom samples were analyzed to determine the geology and Quaternary evolution of the inner basin margin between Dana Point and San Onofre, California.

Structural features are characterized by the typical northwest trends of the Peninsular Range Province and the Southern California Continental Borderland. The major structural element of the study area is the offshore Newport-Inglewood fault zone. Activity has not been continuous over the length of the offshore Newport-Inglewood fault zone. Within the study area, sea floor scarps and offset Holocene sediments are evidence of Holocene activity south of San Mateo Point.

Subbottom profiles, dart cores and vibro-cores were correlated with the onshore data to map the offshore geology. Exposed units range in age from the mid-Miocene San Onofre Breccia to Holocene sediments. The San Onofre Breccia unconformably overlies the basement unit which is Catalina Schist. The deep water Monterey and Capistrano Formations overlie the San Onofre Breccia.

During the last low stand of sea level (20,000 years b.p.) a bedrock erosional shelf surface was cut. Three units of late Pleistocene age unconformably overlie this erosional surface.

At least two buried offshore terraces, which are incised into late Pleistocene sediments, have been mapped within the study area. In addition, nine coastal marine terraces have been identified. During periods of sea level fluctuations, uplift rates of 6 cm/1000 years to the south and 24 cm/1000 years to the north caused a regional tilt to the north and formed the marine terraces. Sea cliffs along the modern coast suggest a continuation of the process.

The modern shelf is blanketed with latest Pleistocene/Holocene sediments. Sediment volumes were calculated along the shelf from San Pedro to the Mexican border. Anomalously high volumes of sediments are present within the study area. The offshore terraces cut into the soft Pleistocene units may have acted as dams, trapping large volumes of marine sediments during the last transgression.

INTRODUCTION

During the past decade, the continental margin of California has become the site of increased geologic and economic interest. As the need for new sources of energy increases, the exploration and development of the offshore region will become more vital. Improved seismic reflection profiling systems and data processing techniques have greatly increased our understanding of the offshore geology.

This report is an investigation of the continental shelf and slope from Dana Point to San Onofre, California (Figure 1). This area is not an attractive site for petroleum exploration; however, it is a potential source of sand and gravel. The need to understand the geology and tectonic setting of this particular portion of the shelf is acute, because of the presence of the nuclear generating station at San Onofre (Figure 1). This study is based upon new high resolution seismic profiling data, which was integrated with all available seismic reflection and corehole data. The purpose of this study is to define the geology of the margin, its evolution and the activity of the Newport-Inglewood fault zone.

Previous Investigations

Early regional studies of the continental borderland by Shepard and Emery (1941) and Emery (1954, 1960) used bathymetric data and bottom samples. Moore (1960) was the first to use seismic reflection subbottom profiling as a method to investigate the geology of the continental borderland. As seismic reflection profiling equipment was improved, this technique became the primary tool for offshore investigations. A more recent study of the geology of the continental

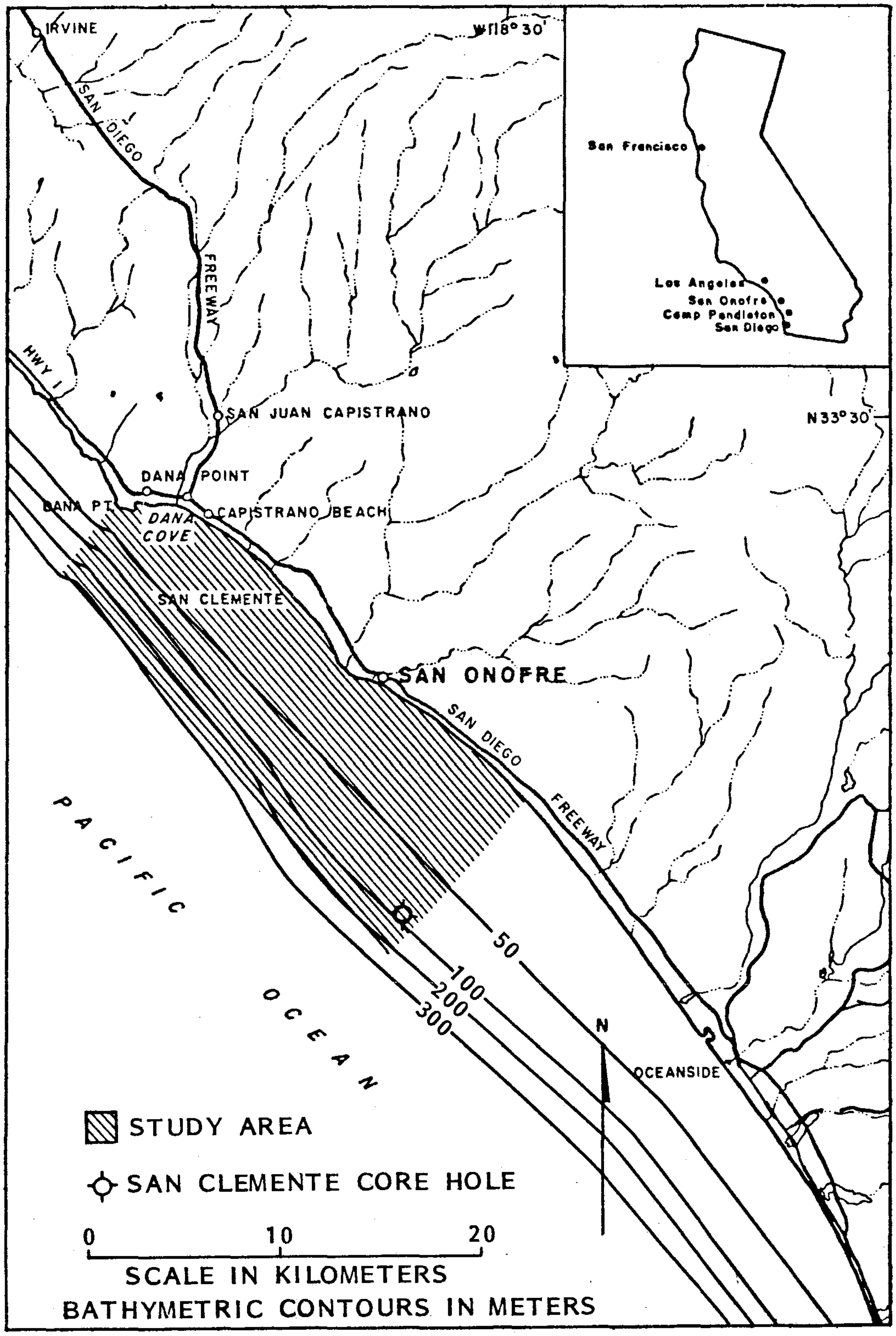

Figure 1. **LOCATION MAP**

borderland has been completed by Vedder and others (1974), and the geology of selected offshore lease tracts have been reviewed by Greene and others (1975).

Other studies are limited to specific areas of the continental borderland. Buffington and Moore (1963) completed one of the early seismic reflection surveys in the study area, concentrating on the slope gullies off San Clemente. The basin margin between Newport and La Jolla was studied by the Southern California Edison Company for the proposed expansion of the San Onofre Nuclear Generating Station. Pertinent information was provided by Intersea Research Corporation (Marine Advisors) (1970) who used sparker profiles to evaluate shallow to medium depth subsurface features and by Western Geophysical Company (1972) who collected and digitally processed common depth point (CDP) data to map the deeper structure. Jahns and others (1971) reviewed existing data and described the structure of the shelf off San Onofre. Woodward-Clyde Consultants (1978) completed a geologic evaluation of a portion of the shelf off Camp Pendleton for a proposed LNG site. Geologic investigations of the continental margin adjacent to the study area were recently completed by Young (1980) to the south and Sterling (1982) to the north.

Sediments of the continental borderland were regionally surveyed by Emery (1960). A more detailed study of the shelf sediments of southern California was completed by Wimberly (1964). Recently, Welday and Williams (1975) compiled a map of the offshore surface sediments for the entire California coast. Offshore San Diego County, sediments were mapped by Henry (1976) using seismic reflection profiling data. South of Point Conception, Quaternary sediment thickness and sediment volumes were mapped and evaluated by Fischer and others (1982) for possible beach replenishment and future sources of sand and gravel.

On land principal studies are those by Edgington (1974) in the Dana Point area, Hunt and Hawkins (1975), Ehlig (1977) and McNey (1979) in the coastal areas adjacent to the San Onofre Nuclear Generating Station. Coastal marine terraces were dated and correlated by Shlemon (1978a, 1978b) to evaluate the tectonic activity near San Onofre.

Based mainly on seismic reflection data, many hypotheses have been proposed for the formation of the southern California Continental Borderland and its topography. Originally interpreted as fault-bounded basins (Emery, 1960), the new data reveal a more complex tectonic pattern (Moore, 1969; Vedder and others, 1974; Junger and Wagner, 1977; Crouch, 1978, 1980). For example, northwest-trending faults and cross-trending folds and faults are characteristic of the borderland structural grain (Junger, 1976) while extensional tectonics (Yeats, 1968), large-scale strike-slip displacements (Howell and others, 1974), and rotational motions (Luyendyk, 1979) are proposed tectonic mechanisms. In addition, the area may be composed of a system of deep-seated microplates bounded by northwest-trending shear zones related to a broad transform fault zone (Junger, 1976; Crouch, 1978, 1980).

Regional Geology

Coastal southern California and the adjacent offshore areas are divided into three provinces: the Coast Ranges, north of 34°30'N; the Transverse Ranges, between 34°N and 34°30'N; and the Peninsular Ranges, south of 34°N (Yerkes, 1965) (Figure 2). The study area is located within the Peninsular Range Province. The northwest-trending structural features of the province terminate at the southern boundary of the Transverse Ranges Province (Jahns, 1954). Shepard and Emery (1941) termed the submerged portion of the province the "continental borderland". Vedder (1979) formalized the name to the southern California Continental Borderland. The offshore region is divided into basins and ridges resembling the Basin and Range Province (Emery, 1954).

Stratigraphic units of the region range in age from Mesozoic basement to Holocene sediments. Basement rocks of the province are divided into the eastern or granitic and the western or blueschist complexes (Woodford, 1925; Yerkes and others, 1965; Vedder and others, 1974). The area east of the Newport-Inglewood zone of deformation is probably underlain by the eastern complex (Hill, 1971; Yeats, 1973). Remnants of the Triassic and Jurassic sedimentary and volcanic rocks are interspersed with Cretaceous granitic rocks in the eastern complex (Ehlig, 1977). The continental borderland is presumably underlain by both the western complex (Vedder and others, 1974), termed Catalina Schist by Schoellhamer and Woodford (1951) and rafted blocks of the eastern complex (Crouch, 1978, 1980). Fine-grained, chlorite-quartz and glaucophane schists characterize the western basement complex (Yerkes and others, 1965) which presumably underlies the margin of the

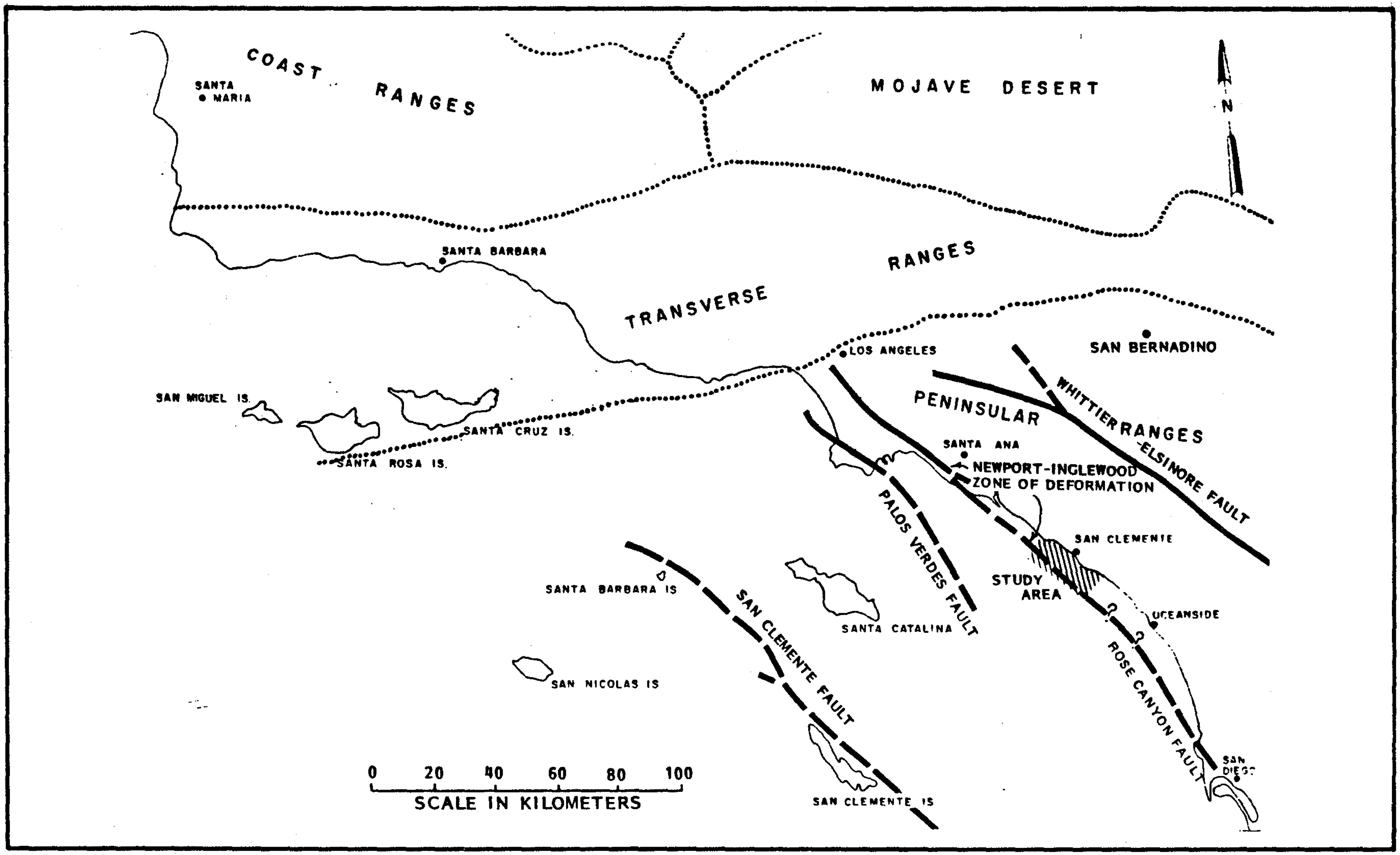

Figure 2. **SOUTHERN CALIFORNIA STRUCTURAL PROVINCES (MODIFIED FROM WOODWARD-CLYDE, 1978 AND JAHNS, 1954)**

study area. Overlying the basement rocks are predominantly marine, upper Cretaceous to Holocene deposits. Widespread Miocene strata and less common Pliocene mudstones and sandstones which are overlain by a thin veneer of upper Pleistocene and Holocene sediments, represent the bedrock of the shelf and most offshore ridges (Vedder and others, 1974).

Northwest- to west-northwest-trending fault zones divide the Peninsular Range Province into elongated blocks (Yerkes and others, 1965). Structural basins formed by block faulting are the predominant structural features of the province. On-land basins, such as the Los Angeles Basin, are completely filled with Neogene sediments, while offshore basins, such as the San Pedro Basin and San Diego Trough, are still receiving sediment (Gorsline and Emery, 1956).

Within the study area, the north-trending Capistrano Embayment is a structural trough of late Miocene to early Pliocene age formed by normal dip-slip movement along the Cristianitos fault (Ehlig, 1979) (Figure 3). This embayment, some 15 km wide near the coast, may continue offshore to or across the Newport-Inglewood fault zone (Ehlig, 1977; Sterling, 1982).

The San Joaquin Hills anticline borders the Capistrano Embayment on the east (Vedder, 1970). A basement high associated with a strong positive Bouger gravity anomaly (Western Geophysical Company, 1972) west of Dana Point may be an extension of this anticline.

The major structural feature of the region is the Newport-Inglewood zone of deformation, which extends onshore from Inglewood to Newport Bay and offshore to San Onofre. Northwest-trending en echelon faults and elongated low hills and mesas characterize this zone (Hill,

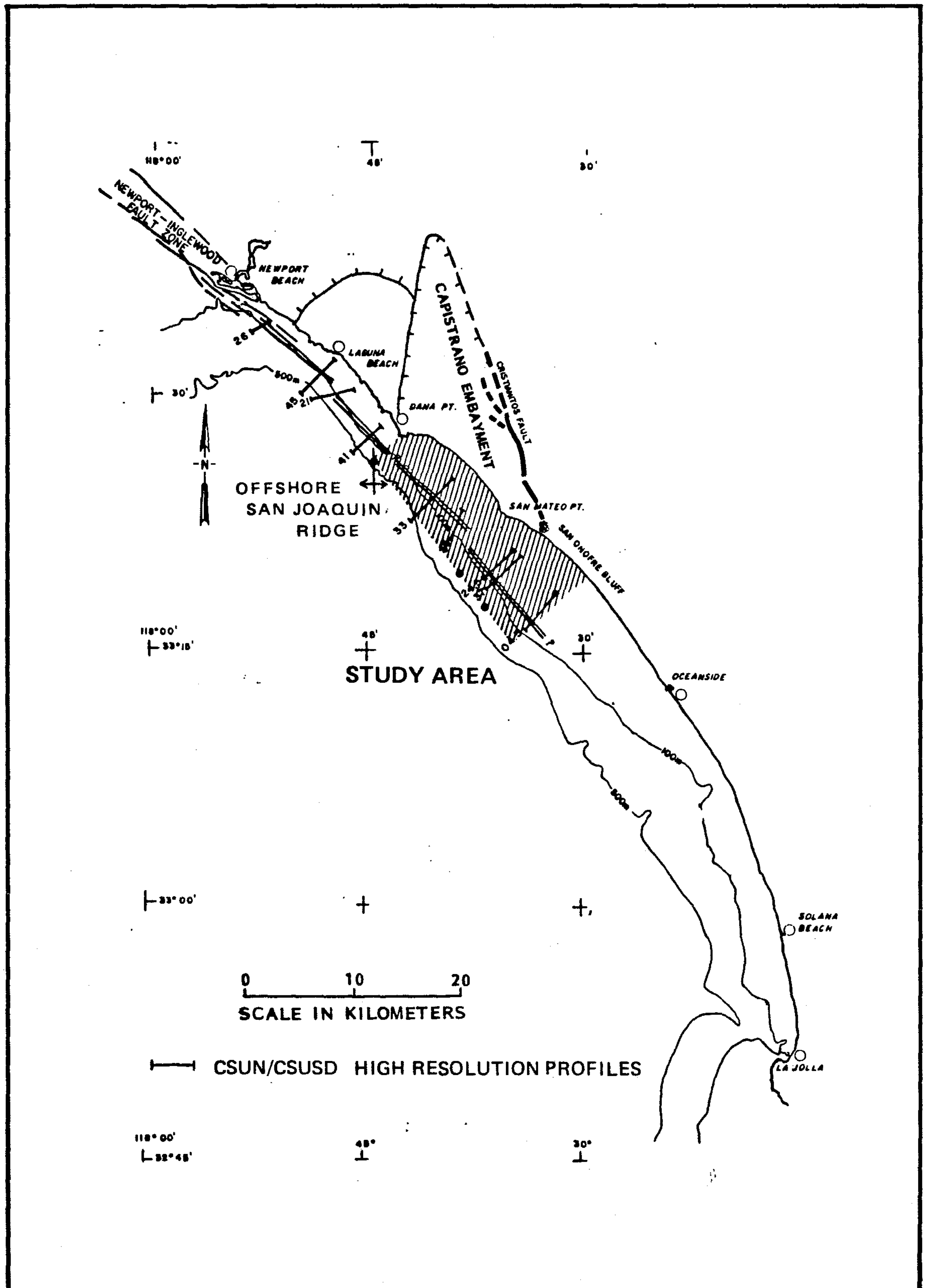

Figure 3. **STRUCTURAL FEATURES (MODIFIED FROM FISCHER AND OTHERS, 1979 AND EHLIG, 1979)**

1971). Local uplift or subsidence along a deep seated fault, inferred from local earthquake data, may produce the surface features of the zone (Barrows, 1974). The deeper basement fault developed from Mesozoic east-west compression, while the present zone formed in response to Pliocene to Holocene north-south compression (Hill, 1971). Yeats (1973), postulates a maximum of 3 km of right lateral movement along the onshore Newport-Inglewood zone. Recently, Sterling (1982) demonstrates a possible 4+ km of right-lateral separation off-shore of Laguna Beach. Seismic reflection data have been used to extend the zone to a point offshore of San Onofre Bluffs (Fischer and others, 1979) (Figure 3). Barrows (1974) and Green and others (1979) suggested the possible continuation of this zone south to San Diego, as postulated by Emery in 1960. This postulated continuation is the Rose Canyon fault.

Acknowledgements

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Other data used in this study were obtained through the cooperation of numerous agencies and personnel. The Southern California Edison Company, with Mr. Pat Hamilton acting as facilitator, contributed a major portion of the pre-existing data. Woodward-Clyde Consultants, Ertec Inc. (Fugro Inc.), and Intersea Research Inc. (Marine Advisors) supplied additional seismic reflection profiling data. The late Arne Junger provided copies of the R/V Polaris data as well as a valuable insight into the geology of the area.

Partial funding for the sediment volume phase of this project was provided by the California State Department of Boating and Waterways. Pre-1978 high resolution data were collected by California State University, San Diego, and California State University, Northridge under a National Oceanographic and Atmospheric Administration (NOAA) Sea Grant.

METHODS AND PROCEDURES

Introduction

Seismic reflection profiles provided the major portion of the data base used in this study. All available data were independently interpreted and correlated. Separate surveys employed various seismic reflection profiling techniques, making use of the full range of available equipment. Data were collected using the following types of equipment: tuned transducer, 3.5 kHz, Sonia, side-scan sonar, Uniboom, sparker and CDP (Table 1). In addition, dart core, vibro-core, and jet core samples and the onshore geology were integrated into this report.

California State University, Northridge (CSUN)/California State University, San Diego (CSUSD) Surveys

Data collected by the writer for this investigation consisted of 3.5 kHz continuous high resolution seismic reflection profiles. An EDO Western Corp. Model 515 system was used for this survey (Table 2). The 3.5 kHz transducer was mounted in an Envicom "fish" and towed at 4 to 4.5 knots. Resolution provided by the system is normally 0.3 m to 0.5 m with an average penetration of 25 m. Seismic surveys were conducted aboard the Southern California Ocean Studies Consortium's R/V Nautilus. Six days were spent at sea by the author in 1978 for this survey.

Additional 3.5 kHz data, obtained from CSUN/CSUSD, were collected between 1973 and 1977 aboard the R/V Nautilus and the Scripps Institute of Oceanography's M/V Gianna. These earlier surveys used a sled-mounted transducer which was towed at 5 to 7 knots. High boat

Table 1

SEISMIC PROFILE DATA SUMMARY*

Source	(Total Line Length) 7.0 kHz	3.5 kHz	Sonia 3.0 kHz	Uniboom	Sparker	CDP	Side-scan Sonar
CSUN/CSUSD (1973-1978)		148 km					
Ertec Inc. (Fugro Inc.) (1978)			37 km				
Nekton (General Oceanographics) (1970)		13 km			44 km (3 kJ)		
Intersea Research Inc. (Marine Advisors) (1979)				13 km	111 km (24 kJ)		
USGS (1970)				61 km	61 km (33 kJ)		
Western Geophysical (1971) (Proprietary)						57 km	
Woodward-Clyde Consultants (1978)	106 km			106 km	106 km (66 kJ)		106 km
Subtotals	106 km	161 km	37 km	180 km	322 km	57 km	106 km

TOTAL - 969 km

*Equipment specifications are listed in Table 2.

Table 2

EQUIPMENT SPECIFICATIONS

CSUN/CSUSD	
3.5 kHz	
Power:	8,000 watts
Frequency:	3.5 kHz
Recorder Sweep:	1/4 second
Ertec Inc. (Fugro Inc.)	
Sonia	
Frequency:	3.0 kHz
Recorder Sweep:	1/4 second
Nekton (General Oceanographics)	
3.5 kHz	
Power:	100-300 joules
Frequency:	3.5 kHz
Recorder Sweep	1/4 second
Sparker	
Power:	3,000 joules
Frequency:	200-500 Hz
Filter:	75-150 Hz
Recorder Sweep:	1 second
Intersea Research (Marine Advisors)	
Sparker	
Power:	2-4 joules
Frequency:	200-500 Hz
Filter:	100-200 Hz
Recorder Sweep:	1 second
USGS CR/V Polaris	
Uniboom	
Power:	1 K joule
Frequency:	1000 Hz
Filter:	170-725 Hz
Sparker	
Power:	33 K joule
Frequency:	100 Hz
Filter:	31-125 Hz
Recorder Sweep:	3 seconds
Western Geophysical	
Aquapulse	
Power:	N/A
Frequency:	20-50 Hz
Recorder sweep:	6 seconds
Woodward-Clyde Consultants	
Tuned transducer	
Frequency:	7 kHz
Side-scan sonar - EG&G Mark 1-B	
Frequency:	105 kHz
Acoustipulse	
Power:	3.0 K joule
Filter:	400-4000 Hz
Recorder Sweep:	1/4 second
Sparker	
Power:	6.6 K joule
Filter:	60-180 Hz
Recorder sweep:	1 second

speeds and equipment instability inherent to this early system resulted in a reduction in data quality. A total of 148 km of CSUN/CSUSD data shown on Plate 1 was used in this study.

Surveys conducted between 1973 and 1976 were positioned by combining triangulation from two or three shore based alidade stations, radar ranges and bearings, and dead reckoning. This technique was compared with mini-ranger positioning during surveys off San Diego County. An accuracy of ±30 meters was recorded when visual contact was maintained with the shore stations (Henry, 1976). For positions beyond visual range, an accuracy of ±300 m to 1 km was reported (Rudat, 1979). Subsequent cruises aboard the R/V Nautilus employed an improved range finding radar system. An accuracy of ±150 m was determined when this system was compared to a Del Norte precision electronic navigation system. All CSUN/CSUSD seismic profile lines were later checked and, if necessary, readjusted to bathymetry and structural features mapped from precisely navigated lines of other surveys.

Southern California Edison Data

A total of 275 km of seismic reflection profile data was obtained from Southern California Edison (Plates 1 and 2). Numerous surveys were conducted as part of the preliminary safety investigation for Units 2 and 3 of the San Onofre Nuclear Generating Station. Data collected included: sparker and 3.5 kHz profiles and dart cores from Nekton Inc. (General Oceanographics), Sonia (3.0 kHz) profiles from Ertec Inc. (Fugro Inc.), Uniboom and sparker profiles from Intersea

Research Corporation (Marine Advisors), and CDP profiles from Western Geophysical Company (Table 1). Specifications for this equipment are listed in Table 2.

Various precision electronic navigation systems provided the positioning for the surveys (Table 3). An accuracy of ±10 m was maintained by all of the systems.

Woodward-Clyde Consultants Survey

A geophysical survey of a portion of the shelf off Camp Pendleton was conducted by Woodward-Clyde Consultants in March 1978 (Table 1) (Plates 1 and 2). Equipment used included: tuned transducer; side-scan sonar; high resolution, "Acoustipulse" subbottom profiling system; and a moderate resolution, deep penetration sparker system (see Table 2 for specifications). Positioning for this survey was accomplished by combining Cubic ARGO and Motorola mini-ranger systems (Table 3). ARGO is a hyperbolic, range-range electronic system with an accuracy of ±3 m and a range of 700 km. The mini-ranger is a line of sight range-range system with an accuracy of ±3 m.

United States Geological Survey (U.S.G.S.) Data (R/V Polaris)

In 1970, the U.S.G.S. conducted a seismic survey between Port Hueneme and Point Loma, California (Moore, 1975). Uniboom and sparker data from this survey (Plate 2) were reviewed for this study (see Table 2 for specifications). Positioning for this survey utilized a Hirex radio-navigation system with an accuracy of ±10 m (Moore, 1972).

Table 3

NAVIGATION SYSTEMS

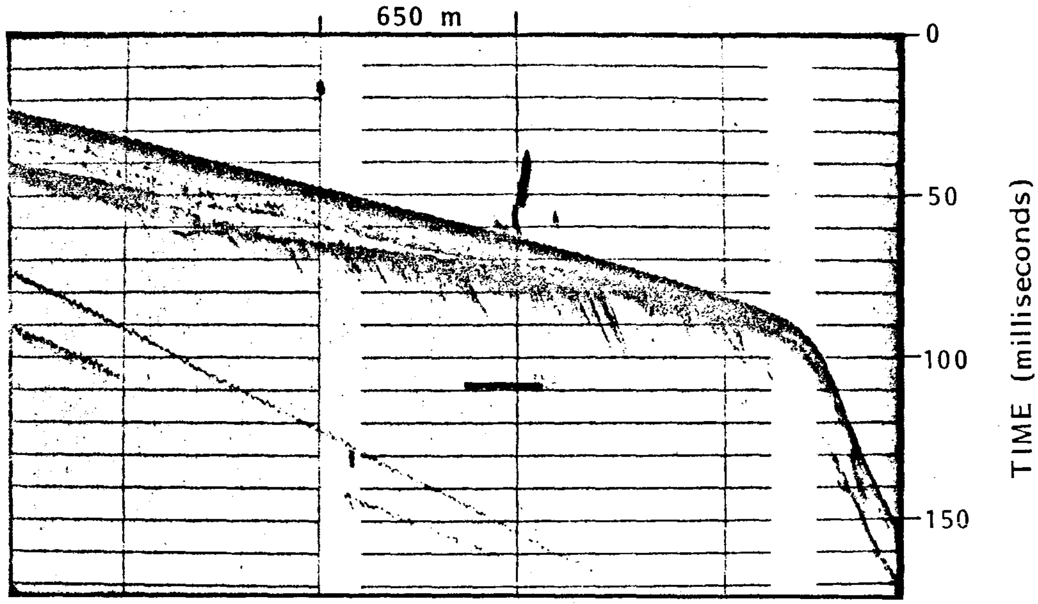
Survey	Type of Equipment	Accuracy
CSUN/CSUSD 1973-1976	Shore-based alidade method Radar	±30 m ±300 m to 1 km
CSUN/CSUSD 1977-1978	Range-finding radar	±150 m
Ertec (Fugro Inc.) (1978)	Del Norte Mini-Ranger	±3 m
Nekton (General Oceanographics) (1970)	Motorola Mini-Ranger	±10 m
Intersea Research (Marine Advisors) (1970)	Cubic autotape precision range positioning system	±15 m
Proprietary Data (1969-1971)	Hirex radio location system	±10 m
USGS (1970)	Hirex radio location system	±10 m
Woodward-Clyde Consultants (1978)	Cubic ARCO and Motorola Mini-Ranger systems	±3 m

Data Reduction and Interpretation

Interpretation procedures for seismic reflection profiles are reviewed by several authors (Moore, 1969; Vedder and others, 1974; Greene and others, 1975; Sieck and Self, 1977). The analog record of the seismic profiles displays density interfaces which reflect the acoustic signal transmitted by the system. These interfaces represent a change in the acoustic impedance of the materials, which is a function of the density and elastic properties (Dobrin, 1976). Typical reflectors include: the sea floor, unconformities, bedding planes, faults, gas zones, and gas bubbles in the water column (Sieck and Self, 1977). High frequency sources reflect only the sea floor and water column anomalies. Lower frequency systems penetrate the sea floor and reflect deeper interfaces.

Seismic reflectors are displayed graphically. Two-way travel time of the acoustic signal to the reflector and back is recorded vertically in milliseconds. Distance along the trackline is displayed horizontally with the scale dependent on the speed of the ship and the recorder paper feed. Typical records are vertically exaggerated 5 to 15 times. Subbottom seismic profiles normally present reflections from the sea floor, one or more deeper reflectors, and multiples of the sea floor. A representative example is presented as Figure 4.

To determine the thickness of sediment or bedrock units, the seismic velocity through the medium and the travel time to the interface must be known. Travel time is measured directly from the seismic profiles. Seismic velocities can be determined by laboratory measurements, refraction surveys, or by comparing a known interval thickness to the same unit on a seismic profile.



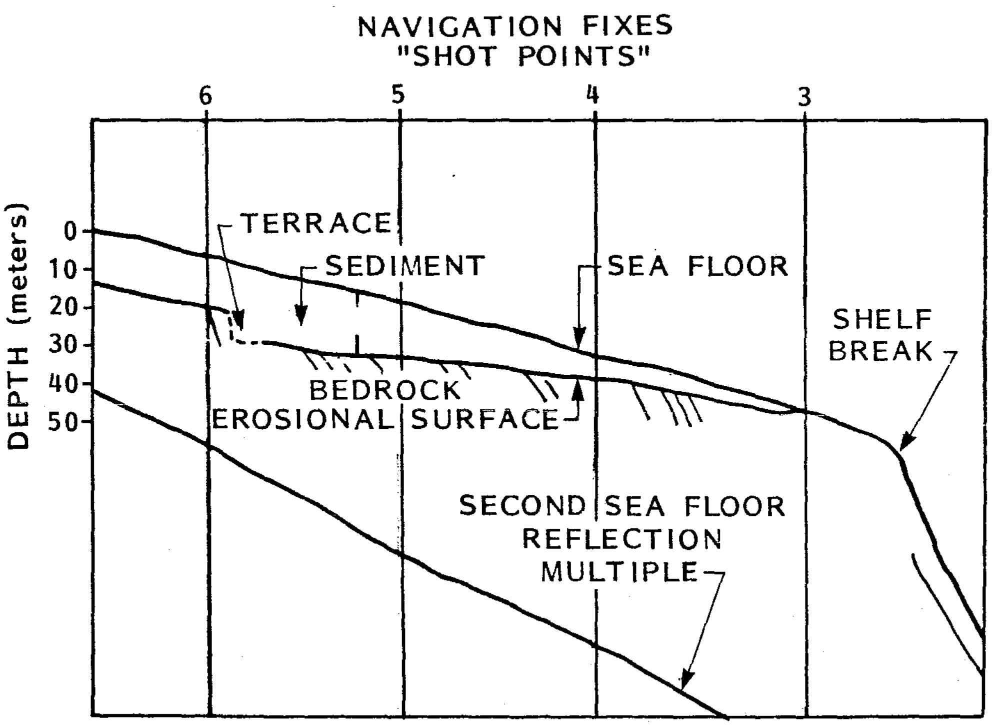


Figure 4. **DIAGRAMATIC SUBBOTTOM PROFILE OF CSUN LINE 35 (3.5 kHz)**

Seismic velocities, related to grain size and other properties of the sediment, have been determined by direct laboratory measurements in previous investigations of the shelf off southern California. Surface sediments of the study area range from coarse silt to very fine sand (Wimberly, 1964; Welday and Williams, 1975). Hamilton (1970) calculated velocities of 1677 m/sec to 1711 m/sec for this type of sediment. Moore and Shumway (1959) measured velocities of 1526 m/sec to 1676 m/sec on the shelf near Pigeon Point for a silt to very fine sand bottom. On the San Pedro shelf, an interval seismic velocity of 1700 m/sec was determined from core hole data for Holocene and latest Pleistocene sediments (Fischer and others, 1977; Rudat, 1979). After reviewing these figures, a seismic velocity of 1700 m/sec was selected for Upper Quaternary sediments of the study area based upon lithologic similarities with the sediments of the San Pedro shelf.

Thickness measurements for upper Pleistocene units were based on a seismic velocity of 1730 m/sec as determined from core hole data on the San Pedro shelf (Fischer and others, 1977). Seismic velocities for the sedimentary rocks off the shelf range from the general value of 2000 m/sec for post-Miocene strata (Vedder and others, 1974), to 2135 m/sec calculated from a refraction study of the Plio-Pleistocene San Mateo Formation underlying the San Onofre Nuclear Generating Station (Weston Geophysical Engineers Inc., 1971). The standard velocity used by the petroleum industry for Neogene bedrock units of the Santa Barbara Channel is 2130 m/sec (Ashley, 1974). The refraction velocity of 2135 m/sec was used for bedrock units in the study area.

Apparent strikes and dips were measured along seismic profile lines. Apparent dips were calculated from the equation:

$$\text{apparent dip} = \tan^{-1} \frac{\Delta V}{D}$$

where ΔV is the depth difference of the reflector and D is the horizontal distance between the two measurements. The profile line direction served as the apparent strike. True strikes and dips were determined at the intersection of two profile lines using the Wulff stereonet.

STRATIGRAPHY

Introduction

Exposed geologic units in the study area range in age from the mid-Miocene San Onofre Breccia to Holocene sediments. Older units are exposed in the Santa Margarita Mountains to the northeast (McNey, 1979) and in the San Joaquin Hills to the northwest (Yerkes and others, 1965) (Figure 5). Mesozoic basement rocks crop out at these sites and also in the Palos Verdes Hills (Yerkes and others, 1965) and on Santa Catalina Island (Woodford, 1924). Because the seismic systems used in the study area could not penetrate beneath the San Onofre Breccia on the shelf, older units were only detectable on the slope and on the basement high off Dana Point. The San Onofre Breccia is considered to be acoustic basement south of the San Joaquin High (Western Geophysical, 1972).

A subcrop geologic map for the study area was constructed from seismic reflection profiles, limited dart cores and vibro-cores, and the extrapolation of onshore geologic data (Plate 3). For the map, the late Pleistocene and Holocene sediments were removed.

Basement

As previously mentioned, the Mesozoic basement rocks are divided into the eastern and the western complexes (Woodford, 1925; Yerkes and others, 1965; Vedder and others, 1974). The Newport-Inglewood zone of deformation may form the boundary between the two basement complexes (Hill, 1971).

The eastern basement complex consists of the Triassic Bedford Canyon Formation, the Jurassic Santiago Peak Volcanics (Larsen, 1948)

Period	Epoch	mybp	San Joaquin Hills (Yerkes, et al., 1965)	Dana Point (Edgington, 1974)	San Onofre (McNey, 1979)	Camp Pendleton (Moyle, 1973)
Quaternary	Holocene		Alluvial & Beach Deposits	Marine & Continental Terrace Deposits	Young Alluvium	Alluvial & Beach & Landslide Deposits
	Pleistocene	.011	Marine Terrace Deposits with Nonmarine Cover San Pedro Fm. 300 m		Terrace Deposits 45 m	Older Alluvium & Terrace Deposits
Tertiary	Pliocene L	1.8	Fernando Fm. 400 m Niguel Fm. 100 m	Niguel Fm. 45 m	Capistrano Fm./ San Mateo Fm. 725 m	San Mateo Fm.
	Pliocene E	3.0	Capistrano Fm. 725 m	Capistrano Fm. 725 m		Capistrano Fm.
	Miocene L	5.0	Monterey Shale 450 m	Monterey Fm. 160 m	Monterey Fm. 250 m	Monterey Fm.
	Miocene M	10.9	San Onofre Breccia 760 m Topanga Fm. 2100 m	San Onofre Breccia >300 m Topanga Fm. 2100 m	San Onofre Breccia 1400 m	San Onofre Breccia
	Miocene E	15.0	Vaqueros Fm. 1150 m	? — ?	Topanga/Vaqueros? Fm.	
	Oligocene	23.5	? — ? Sespe Fm. 750 m			
		38.5				

Figure 5. **STRATIGRAPHIC CORRELATION CHART (MODIFIED FROM ELLIOT, 1975)**

and Cretaceous granitic rocks (McNey, 1979). Slightly metamorphosed slates and argillites are characteristic of the Bedford Canyon Formation of the Santa Ana Mountains (Larsen, 1948). The Santiago Peak Volcanics, consisting of andesite, quartz latite, rhyolites and basalts, unconformably overlie the Bedford Canyon Formation (Larsen, 1948).

Catalina Schist forms the western basement complex (Schoellhamer and Woodford, 1951). Exposures of the unit are found on Santa Catalina Island and in the Palos Verdes Hills (Woodford, 1924, 1960). This unit is believed to form the basement for the major portion of the continental borderland (Vedder and others, 1974). Fine-grained chlorite-quartz schist and blue glaucophane- or crossite-bearing schists are characteristic of the western complex (Yerkes and others, 1965). Correlation of the Catalina Schist with the Franciscan Formation of central California coast has been suggested by Woodford (1924, 1960), Reed (1933), and Platt (1975). Based on foraminiferal limestones and the ammonite Douvilleicera, the Franciscan has been assigned an age of Late Jurassic to Early Cretaceous (Irwin, 1957) and possibly Late Cretaceous (Bailey and others, 1964). Suppe and Armstrong (1972) assigned a K-Ar age of 95-109 m.y. to the Catalina Schist exposed on Santa Catalina Island.

Western Geophysical Company (1972) and Sterling (1982) have mapped an acoustic basement unit, which may be Catalina Schist, northwest of the San Joaquin Hills high. This acoustic basement corresponds to a change of internal velocity from 3660 m/sec within the lower sedimentary units, to 4570 m/sec within the acoustic basement. Local outcrops of this basement unit are found on the San Pedro shelf

(Junger and Wagner, 1977; Rudat, 1980). Junger (1974) used sparker data to map a ridge, composed of Catalina Schist, from a point north of Laguna Beach extending 30 km to the south where it is exposed on the sea floor at the 660 m isobath (Figure 3).

Pre-middle Miocene

Pre-middle Miocene strata are not encountered in the vicinity of the study area. Outcrops of Upper Cretaceous to middle Miocene rocks are present in the Santa Ana Mountains, the San Joaquin Hills and on the shelf near Point Loma. Since deep subsurface data are not available in the study area, the presence of these older units is inferred from exposures in the surrounding areas.

Upper Cretaceous strata unconformably overlie basement rocks in the Santa Ana Mountains (Yerkes and others, 1965). Interbedded marine conglomerates, sandstone and mudstone are characteristic of these units. Other Cretaceous outcrops occur on the walls of La Jolla Canyon in the sea cliffs, and on the shelf south and west of Point Loma (Vedder and others, 1974).

A heterogeneous Paleocene succession of nonmarine sandstone and conglomerate overlain by marine siltstone, sandstone and conglomerate is exposed in the Santa Ana Mountains and San Joaquin Hills (Yerkes and others, 1965). Shallow marine and nonmarine sandstones of Eocene age crop out in the Santa Ana Mountains, in the walls of La Jolla Canyon and on the shelf north and west of Point Loma (Vedder and others, 1974; Crane, 1976; Webb, 1982). Nonmarine Oligocene redbeds may be present beneath the Miocene and Pliocene bedrock on the shelf between San Clemente and Oceanside (Vedder and others, 1974). The middle Miocene (Relizean) Topanga Formation (Woodford, 1925), consisting of marine sandstones and conglomerates, is exposed in the northwest section of the Dana Point quadrangle (Edgington, 1974).

San Onofre Breccia

The oldest unit exposed in the study area is the lower to middle Miocene (Temblor) San Onofre Breccia, first described by Woodford (1925) and more recently by Vedder (1971) and Stuart (1975, 1976). The Western Geophysical Company (1972) correlated this formation with acoustic basement at the San Clemente core hole (Figure 1). Northward, this unit continues as the acoustic basement to the San Joaquin Hills High, where the Catalina Schist becomes the acoustic basement. The irregularly bedded San Onofre Breccia, which contains clasts of Catalina Schist-type metamorphic rocks, was derived from a basement high in the eastern borderland during middle Miocene time (Woodford, 1925; Junger, 1974; Stuart, 1975). A portion of this basement high may be present off Dana Point (Sterling, 1982). Suppe and Armstrong (1972) assigned an age of 95-109 m.y. for the Catalina Schist exposed on Santa Catalina Island based on K-Ar dating of white mica, blue amphibole and hornblende components. A K-Ar age of 102 m.y. is assigned to clasts of the San Onofre Breccia found at Dana Point. These dates support the theory of a western basement or Catalina Schist source for the San Onofre Breccia.

Numerous diffractions and chaotic reflectors identify the San Onofre Breccia on seismic profiles. Where the unit approaches the sea floor, numerous strong multiple reflections are encountered on the profiles. This causes a rapid decrease in data quality.

Outcrops of the San Onofre Breccia are found at Dana Point, north of the Dana Point fault (Edgington, 1974; Stuart, 1975, 1976). These exposures extend offshore to the southeast. They are overlain by a thin veneer of Upper Quaternary sediments as is shown on Plate 3.

Monterey Formation

Along the coast southeast of the Cristianitos fault (Figure 3), the San Onofre Breccia is unconformably overlain by the Monterey Formation (Ehlig, 1977; Berggreen, 1979). Microfossil assemblages date this bathyal marine formation as middle to early late Miocene (Ehlig, 1977). In the Dana Point quadrangle, the Monterey Formation conformably overlies the San Onofre Breccia (Edgington, 1974). Outcrops are present in the coastal area southeast of the Cristianitos fault (Ehlig, 1977) northeast of San Clemente (McNey, 1979) and north of Dana Point (Edgington, 1974). Dart core samples collected by Nekton Inc. (General Oceanographics) within the Newport-Inglewood fault zone were dated as early Mohnian and are considered to be part of the Monterey Formation. This formation also underlies Quaternary sediments shoreward of the offshore extension of the Cristianitos fault.

High cycle rates on seismic profiles give the Monterey Formation the laminated appearance reported by Bramlette (1946). Small scale internal deformation often helps to distinguish this unit from other rhythmic Miocene formations over much of the borderland (Vedder and others, 1974). Deformation of the Miocene and Pliocene units in the study area make the stratigraphic separation of these units tenuous. Additional bedrock samples and core hole data are needed to resolve this problem.

Capistrano Formation

The upper Miocene to lower Pliocene Capistrano Formation (White, 1956) conformably overlies the Monterey Formation within the Capistrano Embayment (Ehlig, 1977). Undulating bedding, characteristic of the Monterey Formation is rarely found in exposures of the Capistrano Formation; however, this difference in bedding is not discernible on most seismic records. Identification of these units offshore is further complicated by a conformable contact.

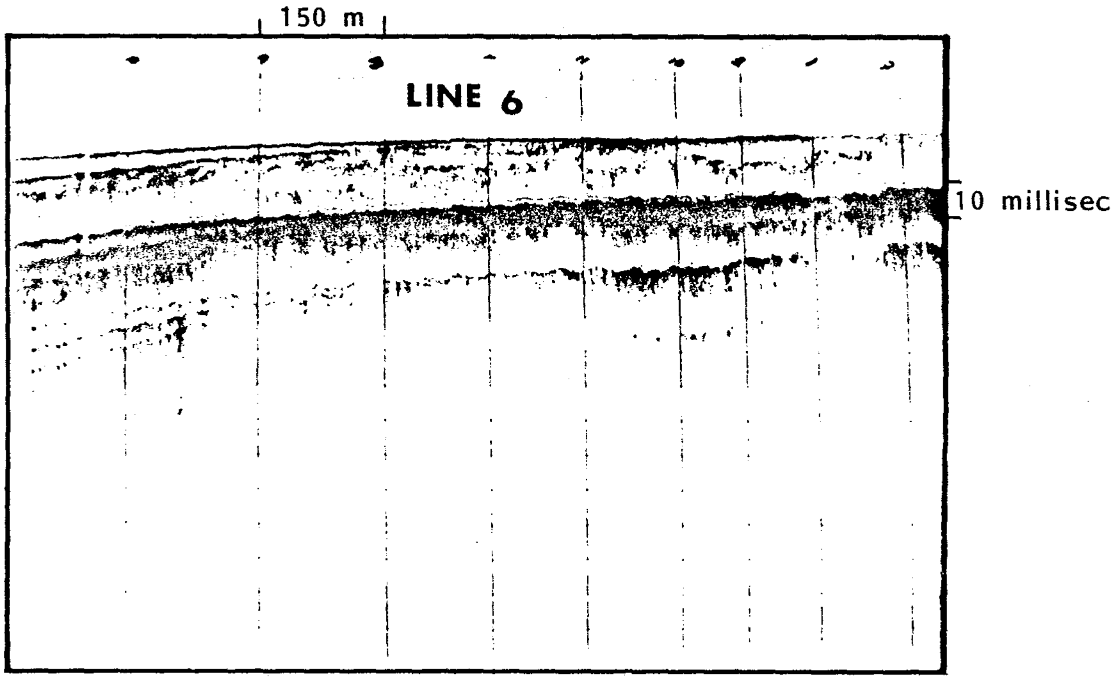
The Capistrano Formation is divided into two units based on lithology and micropaleontology. The lower unit consists of a basal sequence of sand and conglomerate (75 to 100 m thick) which is overlain by a well consolidated, highly fractured, fine siltstone (White, 1971). The Doheny Channel and its associated fan deposits in this lower unit have been interpreted as a deep-sea fan complex at Dana Point (Bartow, 1966; Normark and Piper, 1969, 1971). The 100 m - 125 m thick upper unit consists of loosely consolidated, coarse silt and fine sand (White, 1971). On seismic reflection profiles, the upper unit displays closely spaced rhythmic reflectors. Reflections from the lower unit are distorted and show higher amplitudes, possibly due to a higher degree of consolidation in this unit.

Based on the extrapolation of coastal geology onto the shelf and subtle differences in the seismic characteristics of the Monterey and Capistrano Formations, the upper unit of the Capistrano Formation is mapped beneath the Holocene sediment over most of the study area. The lower unit is exposed along the flanks of the anticline south of Dana Point (Plate 3). Since paleocurrent measurements indicate transport of the fan deposits from the northeast (Bartow, 1966), the lower fan deposits should be present in the area south of Dana Point; however, this facies was not discernible on high resolution subbottom profiles.

San Mateo Formation

Beneath the San Onofre Nuclear Generating Station, a 295 m section of the San Mateo Formation is present (McNey, 1979). Fossils or other datable material have not been recovered from the formation. The stratigraphic position of this unit places it between the upper Miocene and upper Pleistocene (Ehlig, 1977). Exposures of this massive, coarse-grained arkosic sandstone are present along the coast near San Onofre. Vibro-core data from Woodward-McNeil Associates (1974) indicate the presence of the San Mateo Formation below the beach sands and inner shelf sediments adjacent to the San Onofre Nuclear Generating Station (Plate 3). To the north, the San Mateo Formation interfingers with the Capistrano Formation in the cliffs along San Clemente State Beach (Ehlig, 1977).

On seismic profiles, the San Mateo formation closely resembles the upper Pleistocene offshore terrace deposits. Based on the vibro-core data and the coastal exposures, the San Mateo Formation is mapped near shore in the vicinity of San Onofre. Lack of bedding and the chaotic reflections of the San Mateo Formation differentiate it from the underlying, well bedded strata on seismic profiles (Figure 6).



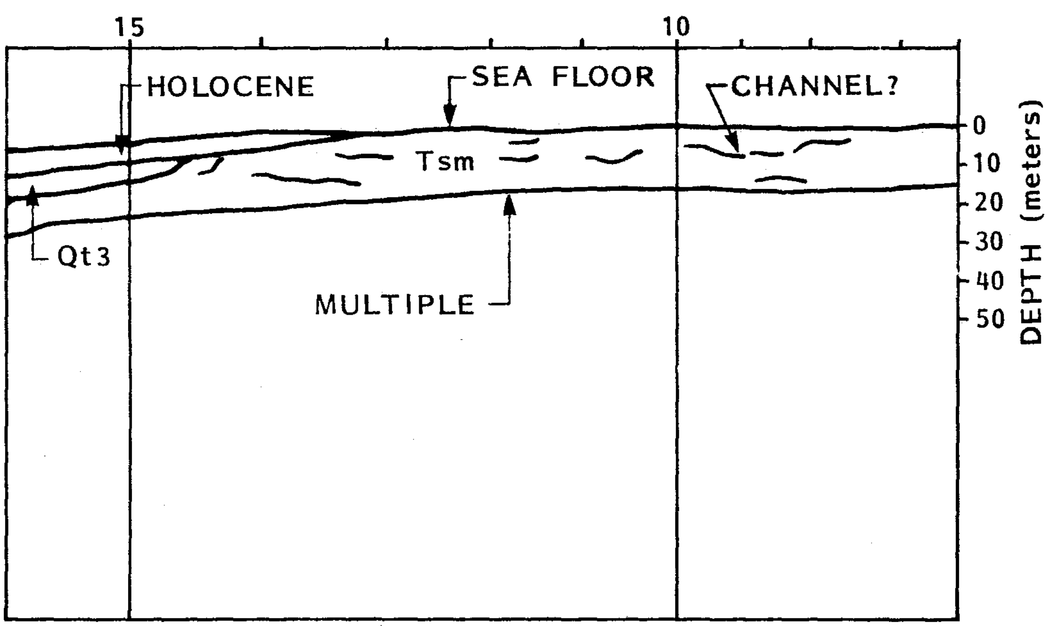


Figure 6. **INTERPRETED SUBBOTTOM PROFILE SHOWING SAN MATEO FM. ALONG ERTEC LINE 6 (3.0 kHz)**

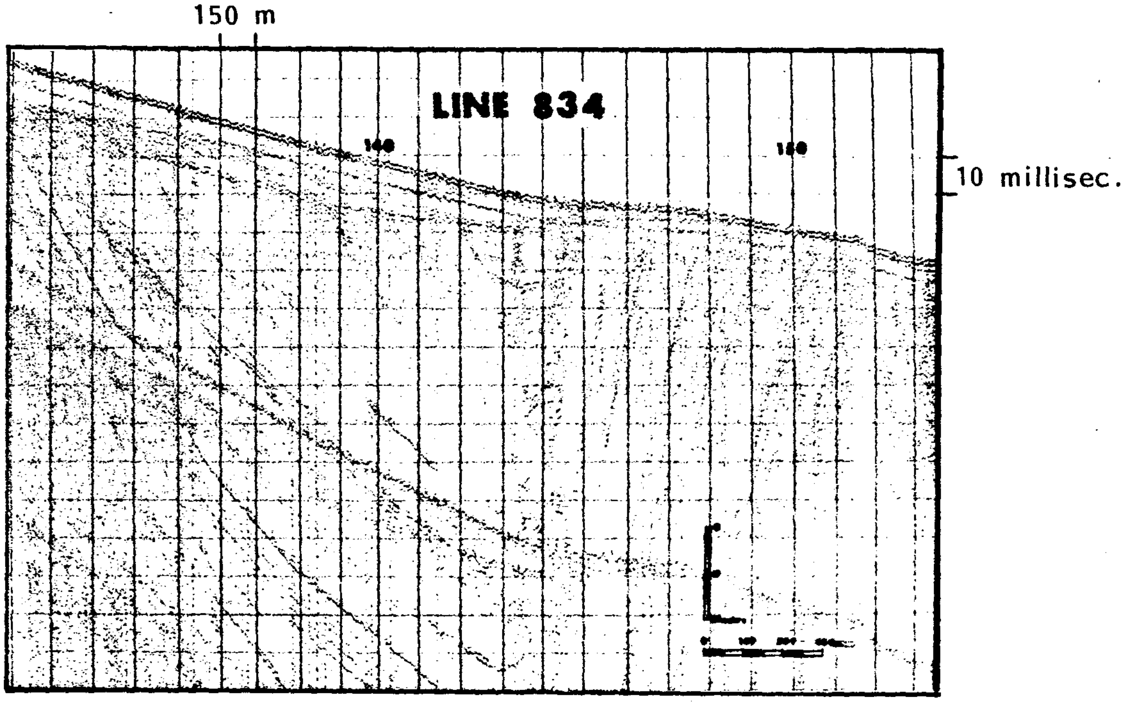
Plio-Pleistocene Trough Deposits (Ptr)

Syncline 1, mapped off San Onofre (Plate 3), forms a northwest-trending depositional trough. Plio-Pleistocene trough deposits unconformably overlie the Capistrano Formation (Figure 7). Strong seismic reflectors, separated by transparent intervals, make up the basal section and indicate a possible unit of interbedded sands and conglomerates. The upper section consists of a thick, transparent unit, possibly a massive sand and/or silt unit. In the axis of the trough, the unit is 125 m thick. Although the trough deposits have not been sampled or dated, their stratigraphic position suggests an age of late Pliocene to middle Pleistocene. This unit may correlate with the upper Pliocene to lower Pleistocene Niguel Formation which unconformably overlies the Capistrano Formation near Dana Point (Edgington, 1974).

Pleistocene Terrace Deposits (Qt1 - Qt3)

Three probable Pleistocene terrace deposits have been mapped on the shelf (Plate 4). Thinly bedded, horizontal reflectors are characteristic of these units. The lowest unit (Qt1) unconformably overlies the late Miocene - early Pliocene bedrock between the Newport-Inglewood fault zone and the shoreward bedrock outcrop (Figure 8). Qt1 crops out between the outer terrace or offshore platform (T1) and the Newport-Inglewood fault zone, south of San Mateo Point (Plate 4).

Subsequent terrace deposits appear conformable and are distinguished by a strong reflector, possibly a basal gravel bed. Qt2



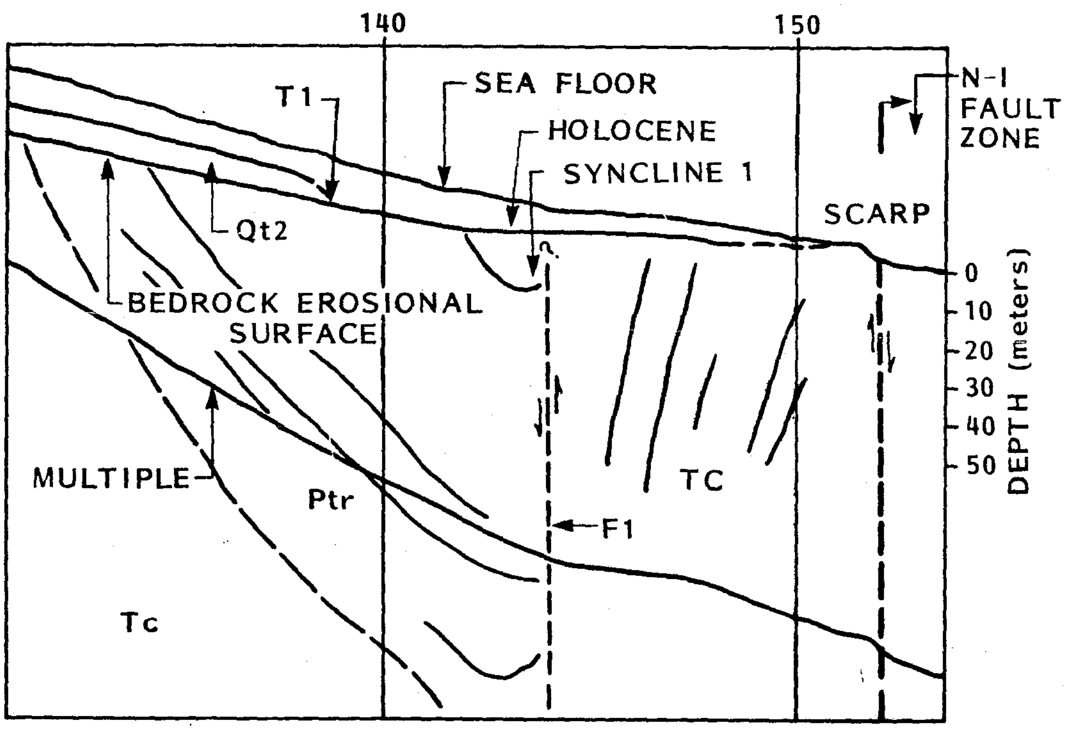
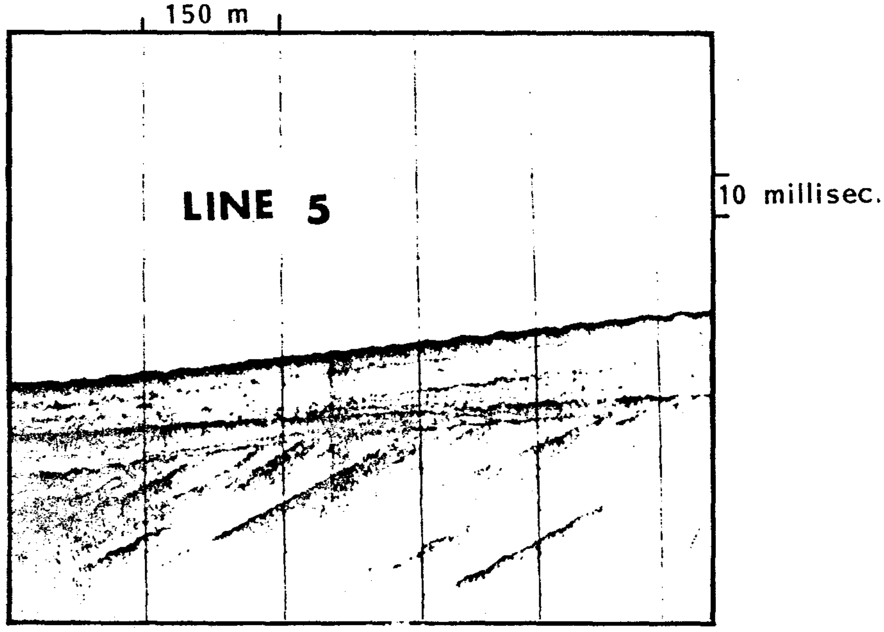


Figure 7. **INTERPRETED SUBBOTTOM PROFILE ALONG LINE W-C 834 (Acoustipulse)**



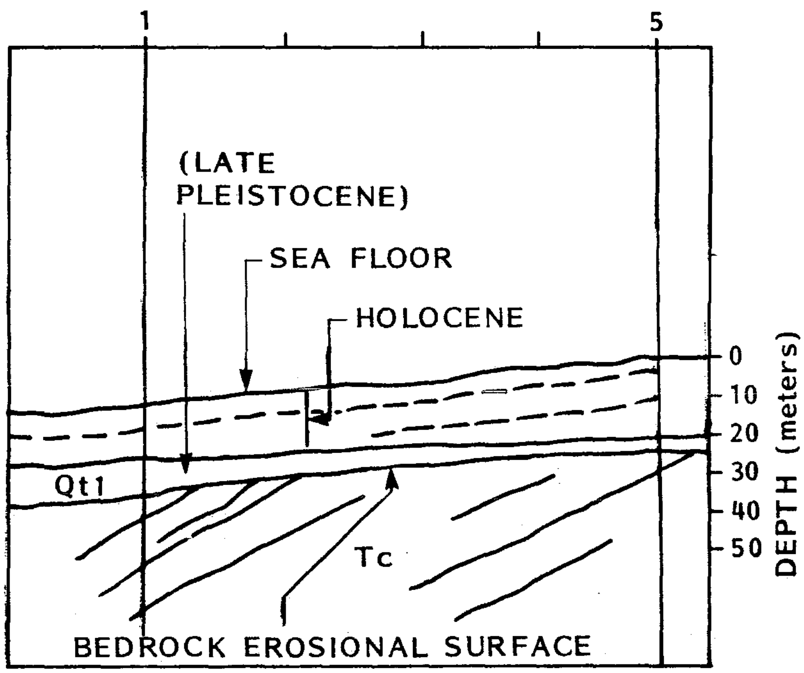


Figure 8. **INTERPRETED SUBBOTTOM PROFILE ALONG ERTEC LINE 5 (3.0 kHz)**

extends from terrace 1 to the shoreward bedrock exposure south of San Mateo Point, cropping out between terraces 1 and 2 (Plate 4).

Qt3, the most extensively exposed Pleistocene unit, crops out between the shoreward bedrock exposure and terrace 2. The unit extends from the southern limit of the area northward to an area between San Clemente and Dana Point (Plate 4). North of this position, the Pleistocene units are not evident on the available seismic data. In this vicinity, the latest Pleistocene/Holocene sediments directly overlie the bedrock erosional surface.

Two ancient fluvial channels are found off San Mateo Point (Plate 4). These channels are apparently seaward extensions of the present San Mateo Creek and San Onofre Canyons. During the late Pleistocene, both channel branches were filled and have been inactive since the beginning of the Holocene transgression (Figure 9).

Terraces (T1 and T2)

Terraces or offshore platforms are believed to be wave-cut features developed in the surf zone (Dietz, 1963; Bradley, 1968). The formation of terraces can occur during pauses in the rise of sea level or at the lowest sea level after regression (Emery, 1958). Two buried terrace levels associated with the Pleistocene terrace deposits are present on the shelf of the southern portion of the study area (Plate 4) (Figure 10). The outer terrace (T1) extends north to the Capistrano Beach area, while the inner terrace (T2) dies out at San Mateo Point. Based on the depth below sea level of the shoreline angle (Figure 11), the terrace north of San Mateo Point was correlated with T1 (Table 4).

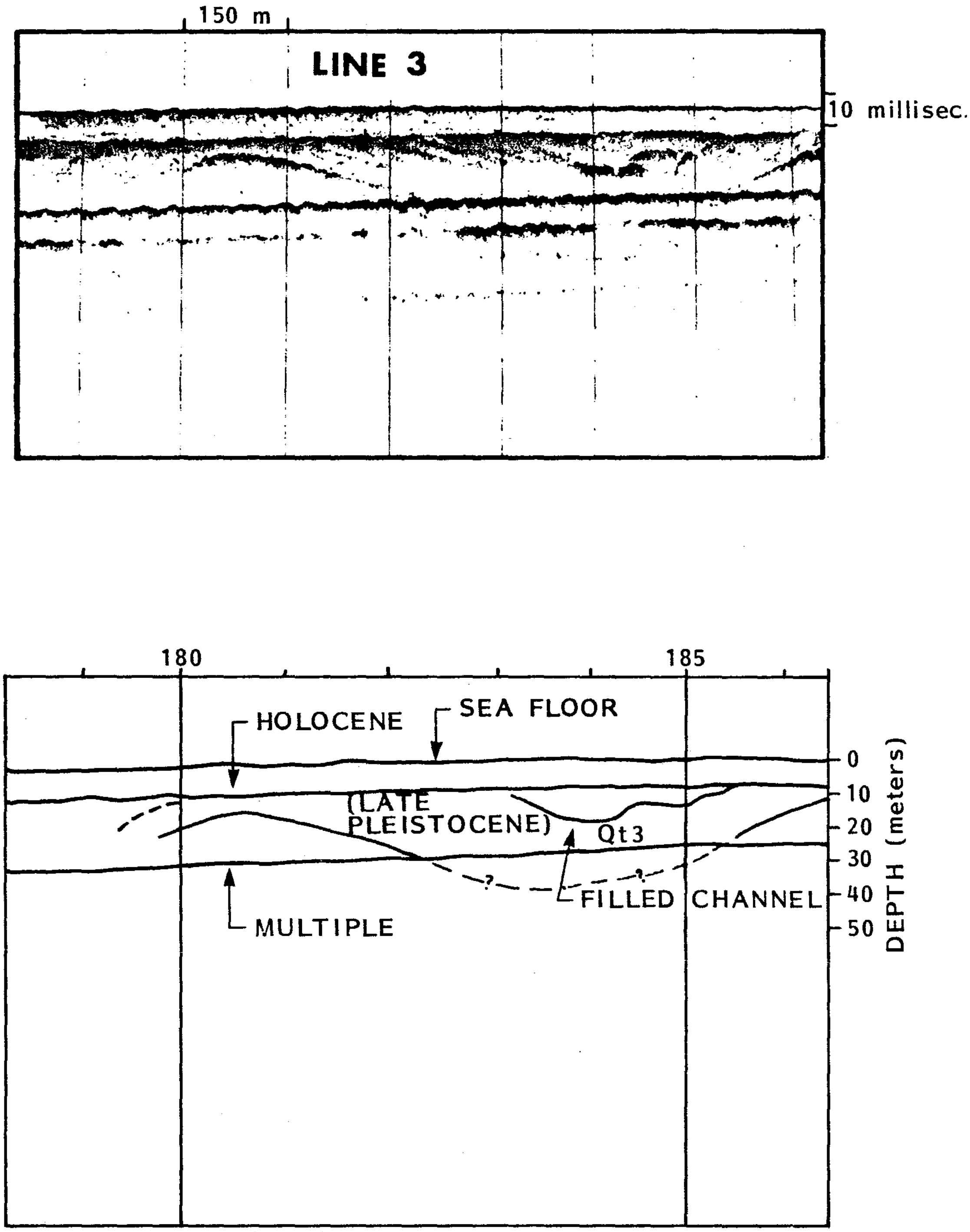
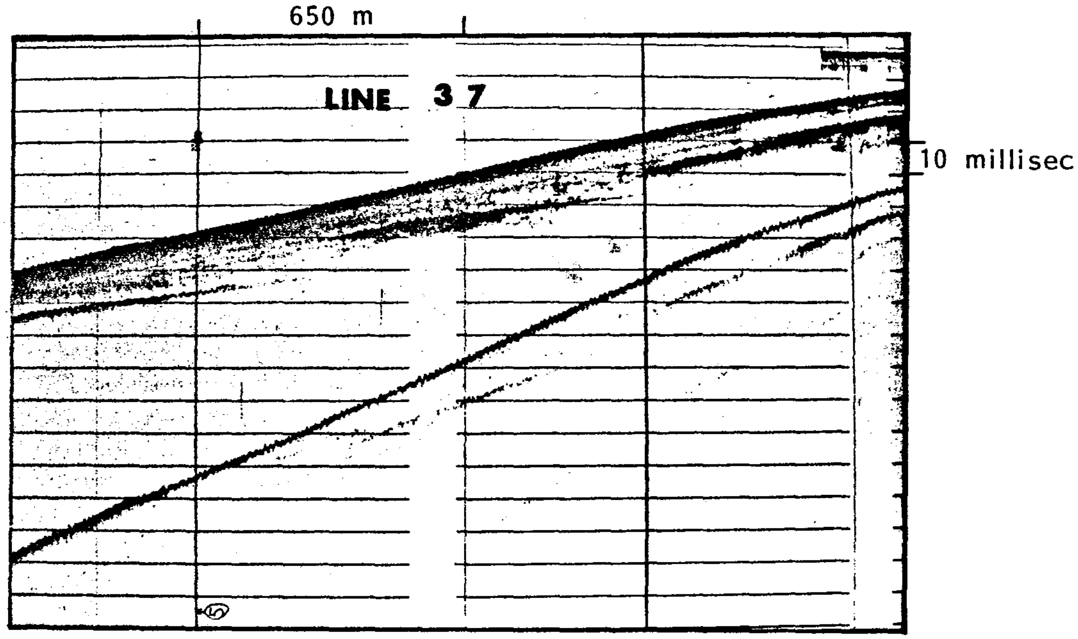


Figure 9. **INTERPRETED SUBBOTTOM PROFILE SHOWING FILLED CHANNEL ALONG ERTEC LINE 3 (3.0 kHz)**



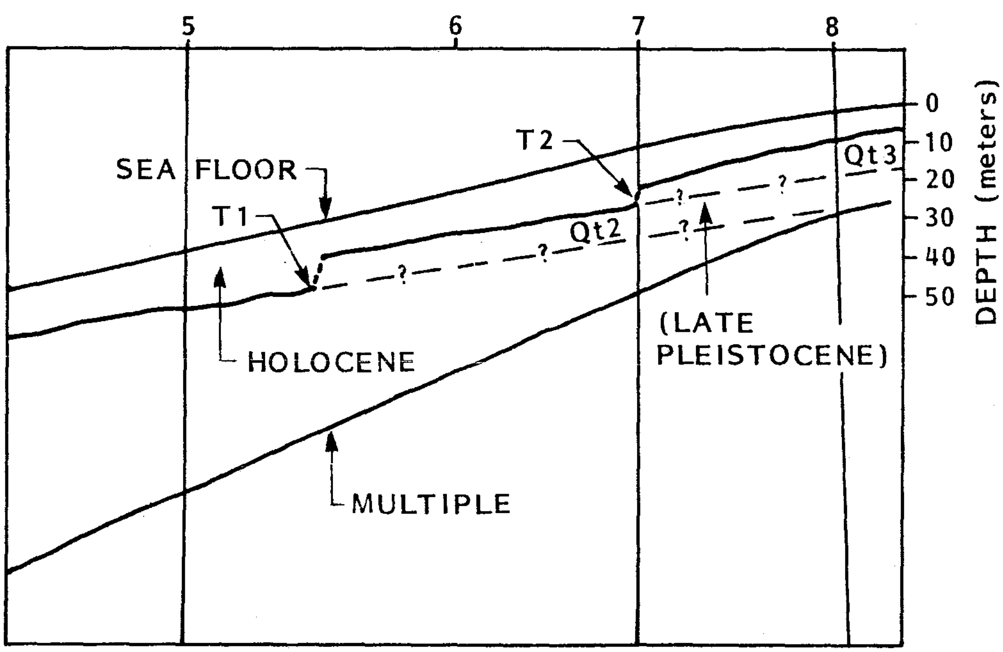


Figure 10. **INTERPRETED SUBBOTTOM PROFILE SHOWING BURIED TERRACE LEVEL ALONG CSUN LINE 37 (3.5 kHz)**

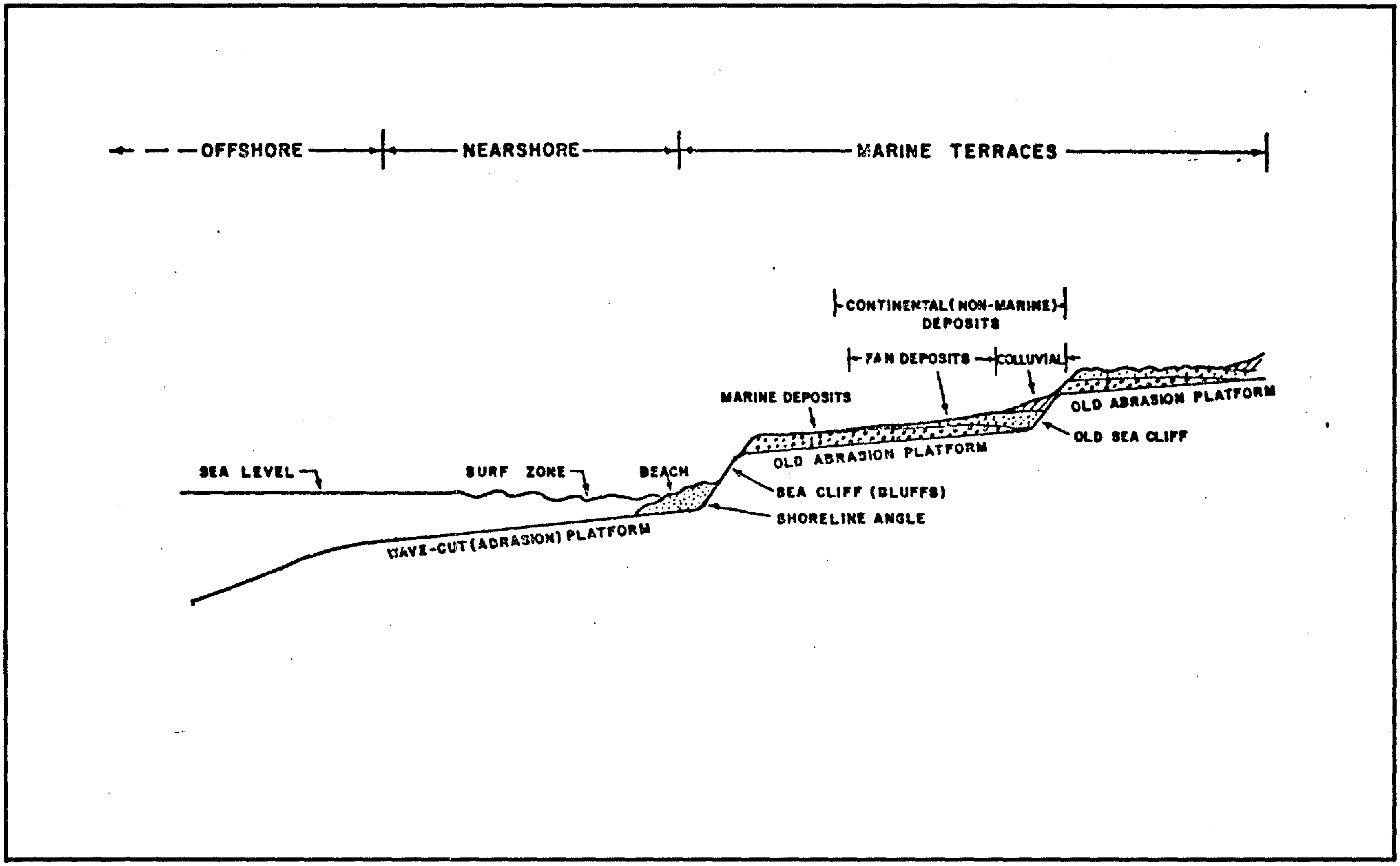


Figure 11. **DIAGRAMMATIC CROSS-SECTION AND GEOMORPHOLOGICAL TERMINOLOGY FOR THE CAMP PENDLETON-SAN ONOFRE STATE BEACH CLIFFED COASTAL AREA. (FROM SHLEMON, 1978)**

Table 4

TERRACE MEASUREMENTS

Line Number	Seaward Dip of Abrasion Platform (°) T1 (outer)	T2 (inner)	Depth Below Sea Level of Shoreline Angle (m) T1 (outer)	T2 (inner)
W-C 825	1.0	1.0	64 (140)*	44 (130)
W-C 830	0.6	0.5	68 (138)	46 (130)
W-C 836	0.7	0.6	68 (139)	46 (130)
W-C 847	0.8	0.4	68 (138)	47 (129)
Ertec 5	0.6	0.5	70 (5)	48 (13)
Ertec 6	0.8	0.8	66 (29)	46 (25)
4823.5	1.4	0.5	67 (3.5)	46 (3)
Ertec 4	-	.9		48 (12)
4829	-	-	62.5 (3.5)	-
4845	1.0	-	62 (3)	-
OC 35	1.0	-	62 (6)	-
OC 34	0.5	-	62.5 (5)	-
OC 33	0.6	-	61 (5.5)	-
4871W	-	-	60.5 (3)	-

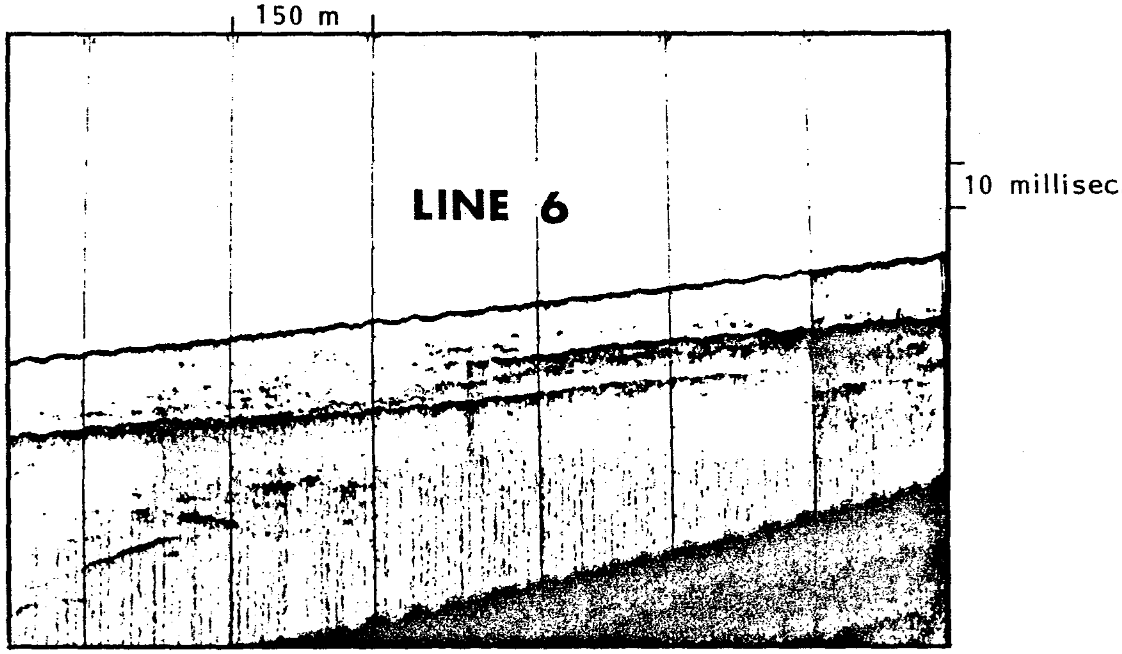
* Numbers in parentheses refer to shot points.

Strong seismic reflectors, possibly representing gravel beds, cap the Pleistocene deposits and the abrasion platform (Figure 12). Abrupt termination of the uppermost strong reflector denotes the paleo-sea cliff (Figure 12). Off San Onofre, these paleo-sea cliffs reach a maximum height of 13 m. Occasional discontinuous reflectors are interpreted to be colluvial deposits found seaward of the shoreface angle on the abrasion platform (Figure 12).

Both offshore terraces were incised in late Pleistocene sediments which would erode rapidly. Only a short stillstand of sea level would be necessary to form these terraces. Later, Holocene sediments buried the terraces and formed the present smooth sea floor shown on the bathymetric map (Plate 5).

Correlation and Age of Terraces

Since samples are not available to date the buried offshore platforms (terraces), an indirect technique was used to estimate their ages. The technique used uplift rates determined by Shlemon (1978b) for the coastal terraces. The first coastal terrace correlates with oxygen isotope substage 5e (125,000 years, Shackleton and Opdyke, 1973). Shlemon (1978b) measured the elevation of the shoreline angle for the first coastal terrace between Camp Pendleton and Laguna Beach. Uplift rates were calculated for original shoreline elevations of both +6 m and +10 m (Table 5). The +6 m shoreline is the generally accepted elevation, while the +10 m elevation represents the conservative case. On the present shelf, the depth below sea level of the shoreface angle of the buried terraces was measured from seismic reflection profiles (Table 4). An error of ±1 m was assumed for the



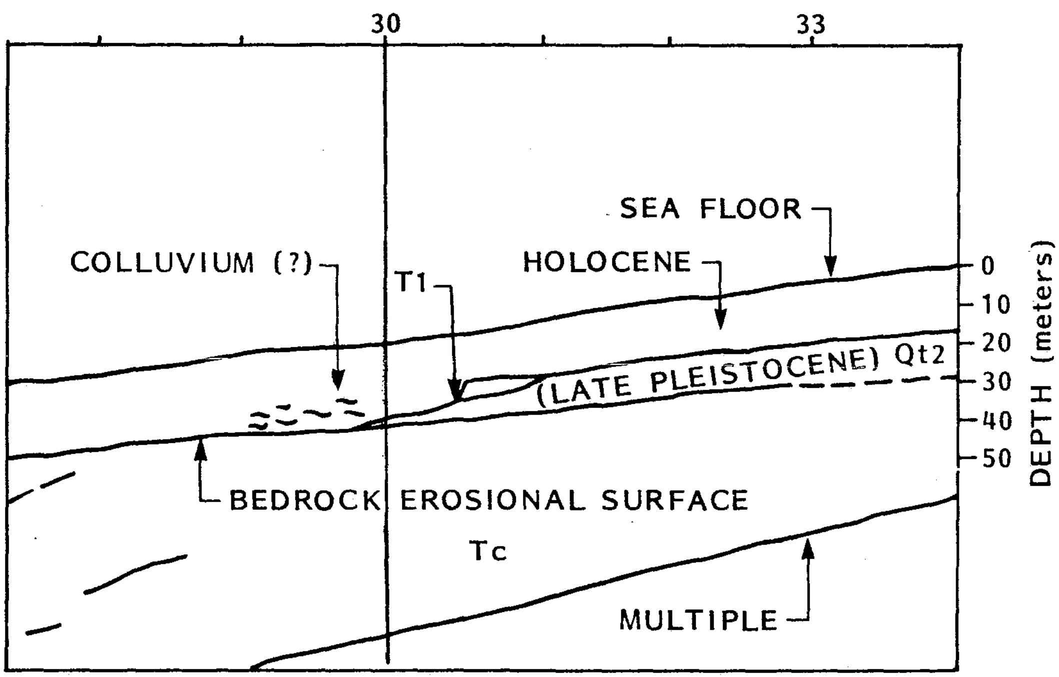


Figure 12. **INTERPRETED SUBBOTTOM PROFILE SHOWING T1 ALONG ERTEC LINE 6 (3.0 kHz)**

Table 5

AVERAGE UPLIFT RATE OF THE FIRST EMERGENT TERRACE
FOR THE LAST 125,000 YEARS (STAGE 5e LEVEL)
BETWEEN LAGUNA BEACH (NORTH) AND TARGET CANYON, CAMP PENDLETON (SOUTH)
(from Shlemon, 1978b)

Locality	Measured or Projected Shoreline Angle Elevation (ft)	(m)	Uplift Rate (cm/1000 years) Orignial Shoreline Elevation +6 m	+10 m
Target Canyon/Camp Pendleton	42	13.0	6	2
San Onofre South	57	17.7	9	6
San Clemente State Beach South	66-68	20.8	12	9
San Clemente State Beach North	68-70	21.4	12	9
San Clemente Pier South	97	30.1	19	16
San Clemente Pier North	83	25.7	16	13
North San Clemente #3	90	27.9	18	14
North San Clemente #2	97	30.1	19	16
North San Clemente #1	116	35.9	24	21
Capistrano Beach	100	31.0	20	17
Dana Point	125-126	39.1	26	23
Niguel Beach State Park	122	37.8	25	22
South Laguna	112-114	35.0	23	20
Aliso Beach	72-74	22.6	13	10
Laguna Beach Recreation Park	30	9.3	3	-1

measurements because of difficulty in precisely locating the shoreline angle. From these measurements, the elevation difference between the north and south ends of the terraces were calculated. The difference in uplift rates of the ends of the terraces were computed from the uplift rates measured by Shlemon (1978b).

The extent of terrace 2 was too short and the difference in depth between the ends was within the margin of error, making it unsuitable for the age estimating technique. Terrace 1, which extends from the southern limit of the study area to Capistrano Beach, was uplifted approximately 7.5 m at the northern end. One slightly shallow value for terrace 1 was found on line 825 (Plate 1). Along this line, the terrace appears to be uplifted from activity along Fault 1 and not by the regional tilt assumed for the age calculations. For this reason, line 825 was not used for age estimation.

From the regional uplift rates (Table 5), a differential uplift rate of 20 cm/1000 years was established between Camp Pendleton and Dana Point. The average elevation difference between the ends of terrace 1 was 6 m. These values yield an age of 30,000 years for terrace 1. Assuming an error of ± 2 m, the range in age is from 10,000 to 50,000 years.

The southern portion of the terrace is along the downthrown side of Fault 1. Activity along this fault or subsidence in the trough associated with synclines 1 and 1A may have caused this portion of the terrace to be anomalously deep. To eliminate the local fault activity, the age of the terrace was calculated using only the portion north of the break at Fault B.

The difference in uplift rates between San Onofre south and Capistrano Beach along the northern portion of terrace 1 is 11 cm/1000 years (Table 5) (Shlemon 1978b). Using the average elevation difference of 1.5 m yields an age of 13,000 years. Assuming an error of ± 2 m gives a range of 0 to 28,000 years. Since the terraces are incised in deposits which overlie the beveled bedrock surface, the terraces must be younger than the low stand which eroded the bedrock. The last major low stand which is believed to have eroded the bedrock surface was 17,000 years - 20,000 years b.p. (Shackleton and Opdyke, 1973).

Radiocarbon dates of 8,500 to 13,000 years b.p. from sediments 5 m to 12 m below the seabed were reported by Woodward-Clyde Consultants in Shlemon (1980). Although the exact location of the samples listed in Table 2B-1 in Shlemon (1980) were not available for this study, these dates are probably associated with the units labeled Holocene and Qt3 in the study (Figure 10). Since the sediments of unit Qt2, which were eroded during the formation of terrace 1, must be older than 13,000 years b.p., the age of 13,000 years for the formation of terrace 1 appears to be a reasonable estimate.

To compare the buried terraces to the first emergent terrace and the present shelf, the seaward dip of the abrasion surface was measured (Table 4). Shlemon (1978b) calculated a seaward dip of about 1° for the first emergent terrace. This is comparable to the modern shelf dip in the study area of 1° or less (Buffington and Moore, 1963; Marine Advisers, 1970; Woodward-Clyde Consultants, 1978). The seaward dip of the buried terraces are also less than 1° (Table 4). If the rate of uplift of the shoreward side of the terrace has been constant and uninterrupted, the offshore terraces are no older than the first emergent terrace.

Latest Pleistocene/Holocene Sediments

Latest Pleistocene/Holocene sediments overlie the Pleistocene terrace deposits, and locally the Miocene/Pliocene bedrock erosional surface. An isopach map of this unit was completed using seismic reflection profile data (Plate 6). These sediments form an elongated prism paralleling the shoreline. Areas of zero sediment extend seaward from an area beyond the surf zone to approximately the 10-20 m isobaths. The inner area of zero sediments generally coincides with the seaward extent of the kelp beds, which use bedrock as a holdfast (Shepard and Emery, 1941; Emery, 1960; Fischer, 1980). Mid-shelf areas of maximum sediment thickness are coincident with the base of buried sea cliffs associated with Pleistocene terraces (Figure 12). Near the shelf break, bedrock is again exposed as the sediment thickness thins to zero. Grain size for surface sediments of the area range from sand in the surf zone, to very fine sand on the inner shelf, to coarse silt on the outer shelf (Wimberly, 1964; Welday and Williams, 1975).

Latest Pleistocene/Holocene sediments were mapped as the unit overlying the uppermost strong seismic reflector (Figure 13). In most areas, this reflector represents a possible gravel bed capping Pleistocene deposits. Locally, this reflector represents the Miocene-Pliocene bedrock erosional surface. This unit has not been cored or dated in the study area. From the stratigraphic position and

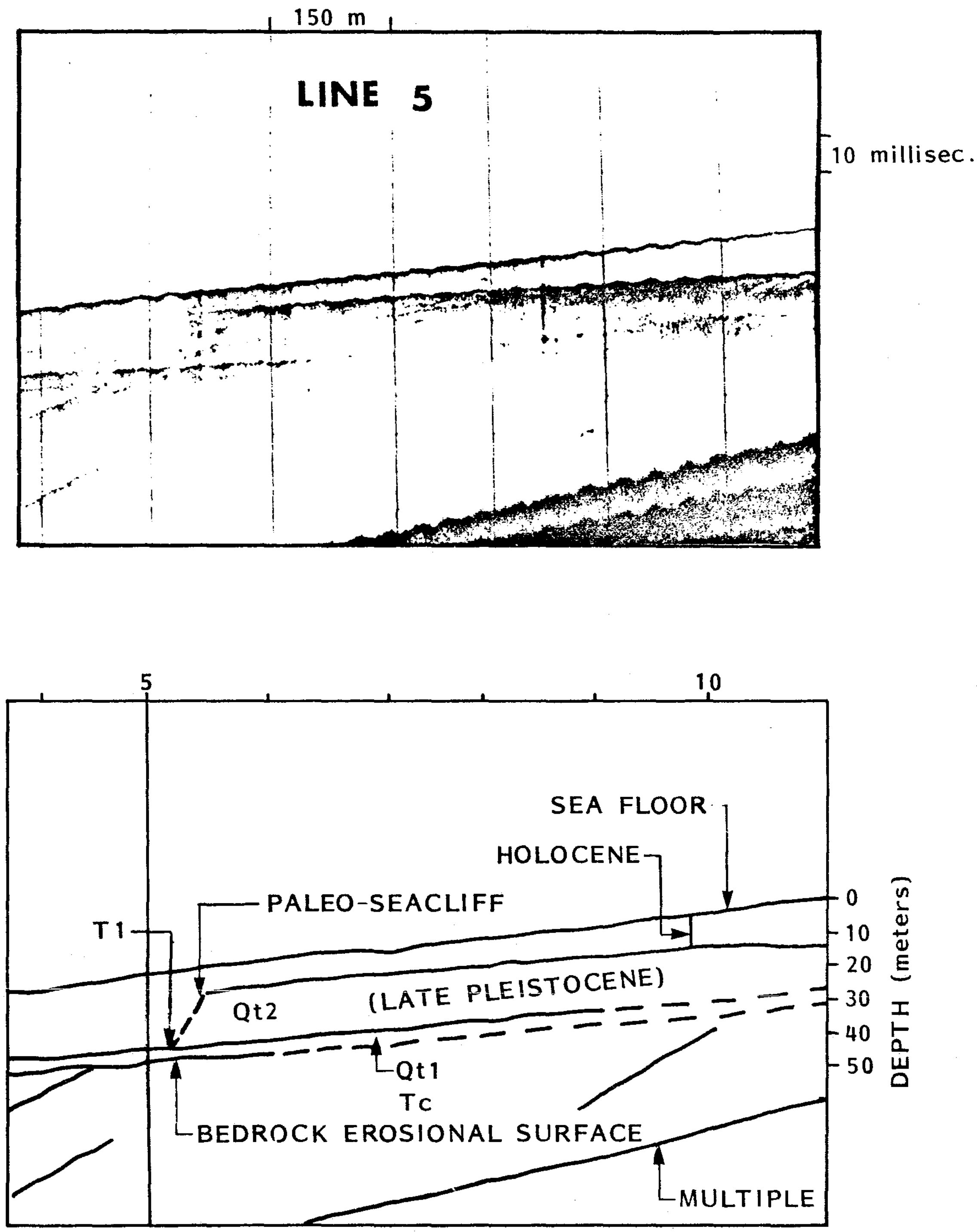


Figure 13. **INTERPRETED SUBBOTTOM PROFILE SHOWING HOLOCENE DEPOSITS ALONG ERTEC LINE 5 (3.0 kHz)**

the lack of strong internal seismic reflectors, the unit is assigned an age of latest Pleistocene/Holocene or oxygen isotope stages 1 and 2 (Shackleton and Opydyke, 1973). The homogeneity of the unit suggests that deposition was continuous during the latest transgression, beginning 17,000 to 20,000 years b.p.

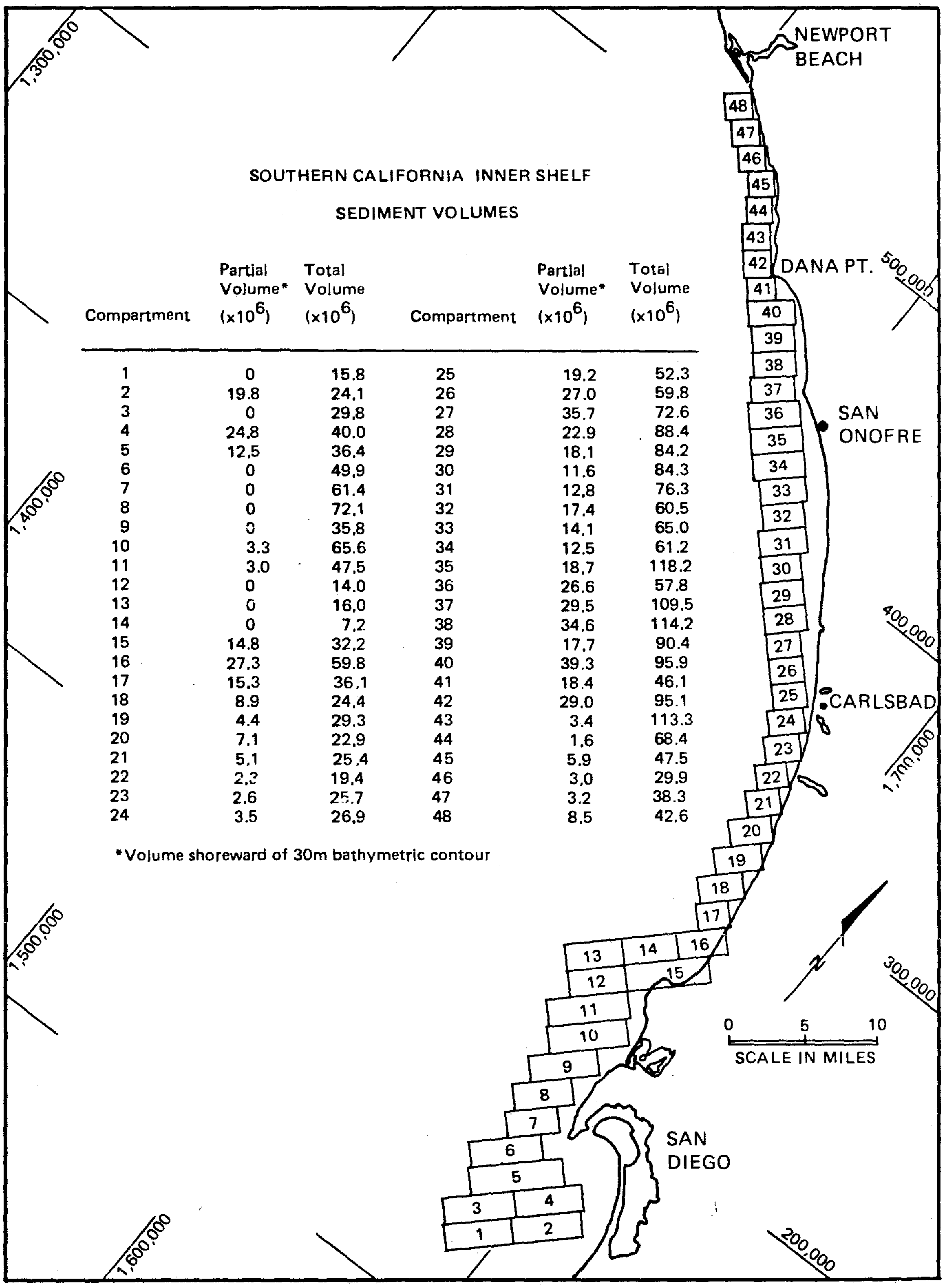
Between Dana Point and San Mateo Point, sediment thickness reaches a maximum between the 30 m and 50 m isobaths (Plate 6). Between these isobaths the maximum thickness is typically 14 m. Two areas of greater thickness are present south of Dana Point and off San Mateo Point. In these areas, the unit is 18 m and 20 m thick, respectively (Plate 6). One buried terrace is present between Dana Point and San Mateo Point, and two are present south of San Mateo Point (Plate 4). Terrace level one (T1), located in 50 m of water, is covered with 18 m of sediment. Terrace level two (T2), at the 35 m isobath, is capped by a 14-m-thick sediment deposit (Plate 6). When bedrock exposures in shallow water are encountered on seismic records, they are between the 10 m and 20 m isobaths. Most seismic surveys did not extend into this zone because of the presence of kelp where bedrock is exposed.

Sediment volumes on the shelf were calculated for 3000-m-wide compartments extending from the shoreward data limit to the shelf break. Since economic and technological limitations presently confine beach replenishment projects to the area inside the 30 m isobath, volumes for this zone were calculated separately. Total volumes range from 46.1×10^6 to 114.2×10^6 m^3. Within the 30 m zone, the volumes range from 17.7×10^6 to 39.3×10^6 m^3 (Figure 13).

Areas of maximum sediment volumes between San Onofre and San Clemente are associated with prominent buried sea cliffs, where elongated thick deposits formed. When compared with sediment volumes for areas of equal size along the coast between Newport and the Mexican border (Fischer and others, 1982), the study area contains anomalously high volumes of sediment (Figure 14). Compartment 38 contains the maximum sediment volume for the area between Newport and the Mexican border with 114.2×10^6 m^3. Volumes within the 30 m zone in the study area are also well above average for the shelf of southern California. The maximum volume of 39.3×10^6 m^3 is found in the study area in compartment 40.

The high volume of sediment in this area of the shelf is related to the prominence of the buried terraces. Although these terraces are traceable to the north and south, the height of the paleo-sea cliffs reaches a maximum of 13 m off San Onofre. These sea cliffs formed temporary barriers to the shoreward transport of sediment by transgressing seas. Higher sea cliffs will trap larger volumes of sediment as the top of the cliff must be breached before shoreward transportation can continue. The presence of a second terrace level off San Onofre further increased the amount of trapped sediment. Subsequent normal shelf deposition erased all topographic expression of these sediment barriers.

San Juan Creek, south of Dana Point, supplies sediments to the northern portion of the study area. San Mateo Creek and San Onofre Creek, which reach the coast at San Mateo Point, are the sediment sources for the southern portion of the study area.



SOUTHERN CALIFORNIA INNER SHELF

SEDIMENT VOLUMES

Compartment	Partial Volume* ($x10^6$)	Total Volume ($x10^6$)	Compartment	Partial Volume* ($x10^6$)	Total Volume ($x10^6$)
1	0	15.8	25	19.2	52.3
2	19.8	24.1	26	27.0	59.8
3	0	29.8	27	35.7	72.6
4	24.8	40.0	28	22.9	88.4
5	12.5	36.4	29	18.1	84.2
6	0	49.9	30	11.6	84.3
7	0	61.4	31	12.8	76.3
8	0	72.1	32	17.4	60.5
9	0	35.8	33	14.1	65.0
10	3.3	65.6	34	12.5	61.2
11	3.0	47.5	35	18.7	118.2
12	0	14.0	36	26.6	57.8
13	0	16.0	37	29.5	109.5
14	0	7.2	38	34.6	114.2
15	14.8	32.2	39	17.7	90.4
16	27.3	59.8	40	39.3	95.9
17	15.3	36.1	41	18.4	46.1
18	8.9	24.4	42	29.0	95.1
19	4.4	29.3	43	3.4	113.3
20	7.1	22.9	44	1.6	68.4
21	5.1	25.4	45	5.9	47.5
22	2.3	19.4	46	3.0	29.9
23	2.6	25.7	47	3.2	38.3
24	3.5	26.9	48	8.5	42.6

*Volume shoreward of 30m bathymetric contour

Figure 14. **DIAGRAMMATIC MAP OF INNER SHELF SEDIMENT VOLUMES (FROM FISCHER, 1982)**

STRUCTURE

Structural features of the study area are characterized by the typical northwest trends of the Peninsular Range Province and the southern California Continental Borderland. Within the study area, faults are the dominant structural elements.

Newport-Inglewood Fault Zone

The major structural feature of the study area is the northwest trending Newport-Inglewood fault zone. Ranging in width from 300 m to 900 m, this zone parallels the shoreline 6 km to 7.5 km offshore (Plate 3).

Previous Work

Intersea Research (Marine Advisors) (1970) located the Newport-Inglewood fault zone on 14 sparker profiles, tracing it north from San Onofre to a point 7 km south of Dana Point. Based on the limited data available, Jahns and others (1971) considered the zone an anticlinorium with tight folds, broken locally by short faults near the axis, with no pronounced sea floor displacement. Western Geophysical Company (1972) used proprietary digitally processed CDP data to estimate maximum offsets along the zone. The maximum vertical displacement was 1700 m on the basement and 60 m on an upper Miocene reflector. A right lateral offset of 2100 m has been postulated on the San Joaquin High by Western Geophysical (1972). Sterling (1982) has estimated a right lateral offset of 4200 m along the zone between Newport Beach and Dana Point. Woodward-Clyde Consultants (1978) mapped disrupted reflectors and local sea floor scarps along the zone between San Onofre and Camp Pendleton using high resolution profiles.

The offshore Newport-Inglewood fault zone has been traced from Newport to San Onofre (Fischer and others, 1979). A connection of this fault with the Rose Canyon fault to form a 200-km-long zone from the Santa Monica Mountains to La Jolla has been suggested (Emery, 1960; Marine Advisers, 1970; Barrows, 1974; Greene and others, 1979; Woodward-Clyde Consultants, 1980). Legg and Kennedy (1979) extend the fault zone even further to the south to connect with the Vallecito and San Miguel faults and report Quaternary and Holocene activity in many places along its length. Others believe the onshore Newport-Inglewood fault zone and the Rose Canyon fault are independent features separated from the offshore Newport-Inglewood fault zone of this study (Jahns and others, 1971).

<u>This Study</u>

Using all available data, including new 3.5 kHz profiles collected for this study, the Newport-Inglewood fault zone was mapped between Dana Point and San Onofre. Subbottom profiles within this study area display convincing evidence and features characteristic of a fault zone, including sea floor scarps (Figure 15), disturbed near surface reflectors (Figure 16), dip changes and offset reflectors (Figure 17). The fault zone was located on all 42 profiles which cross its trace from the northern to the southern boundaries of the area of investigation (Plate 3). A sea floor scarp is present on 16 of these profiles.

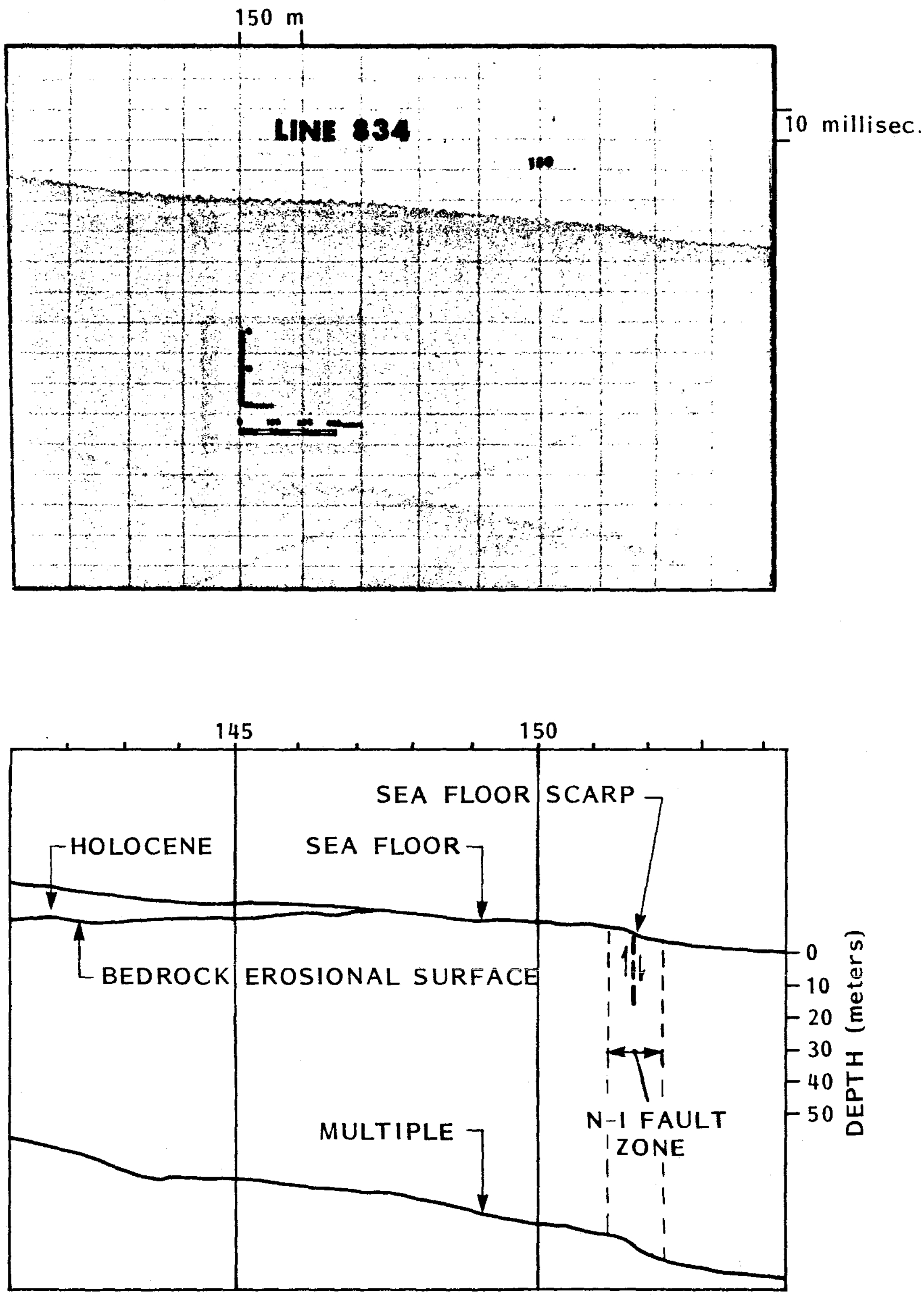
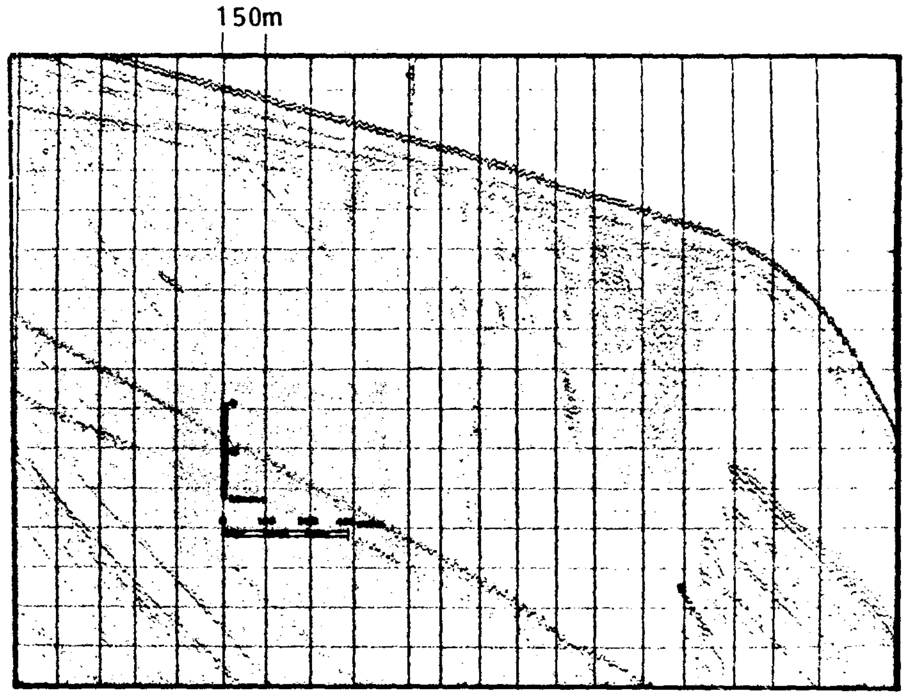


Figure 15. **INTERPRETED SUBBOTTOM PROFILE SHOWING SEA FLOOR SCARP WITHIN N-I FAULT ZONE ALONG W-C LINE 834 (7.0 kHz)**



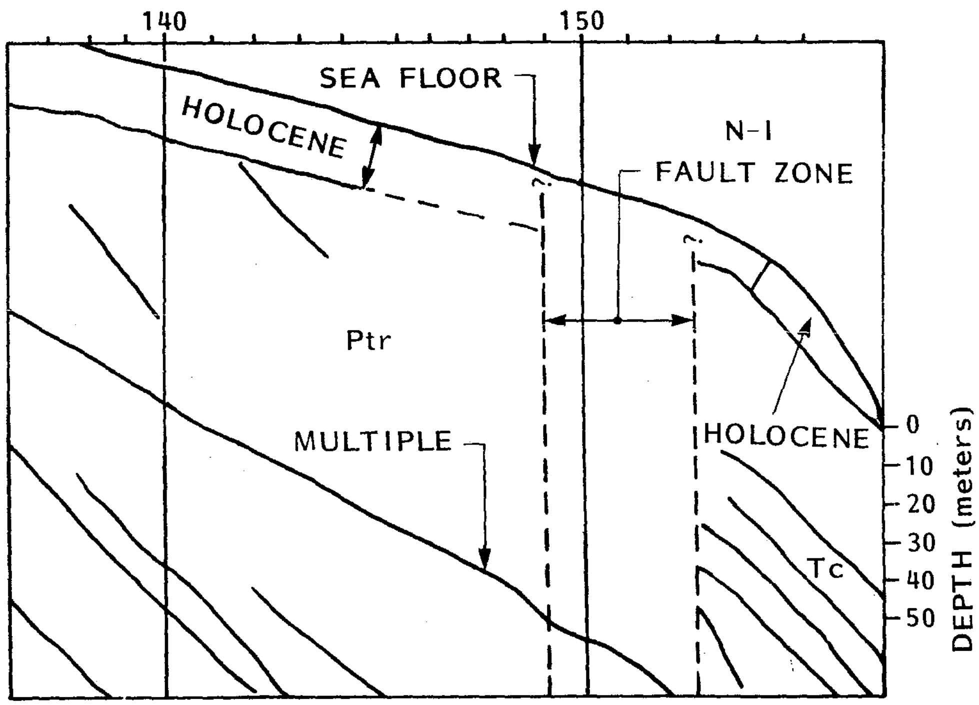


Figure 16. **INTERPRETED SUBBOTTOM PROFILE SHOWING DISTURBED ZONE WITHIN N-I FAULT ZONE ALONG W-C LINE 845 (Acoustipulse)**

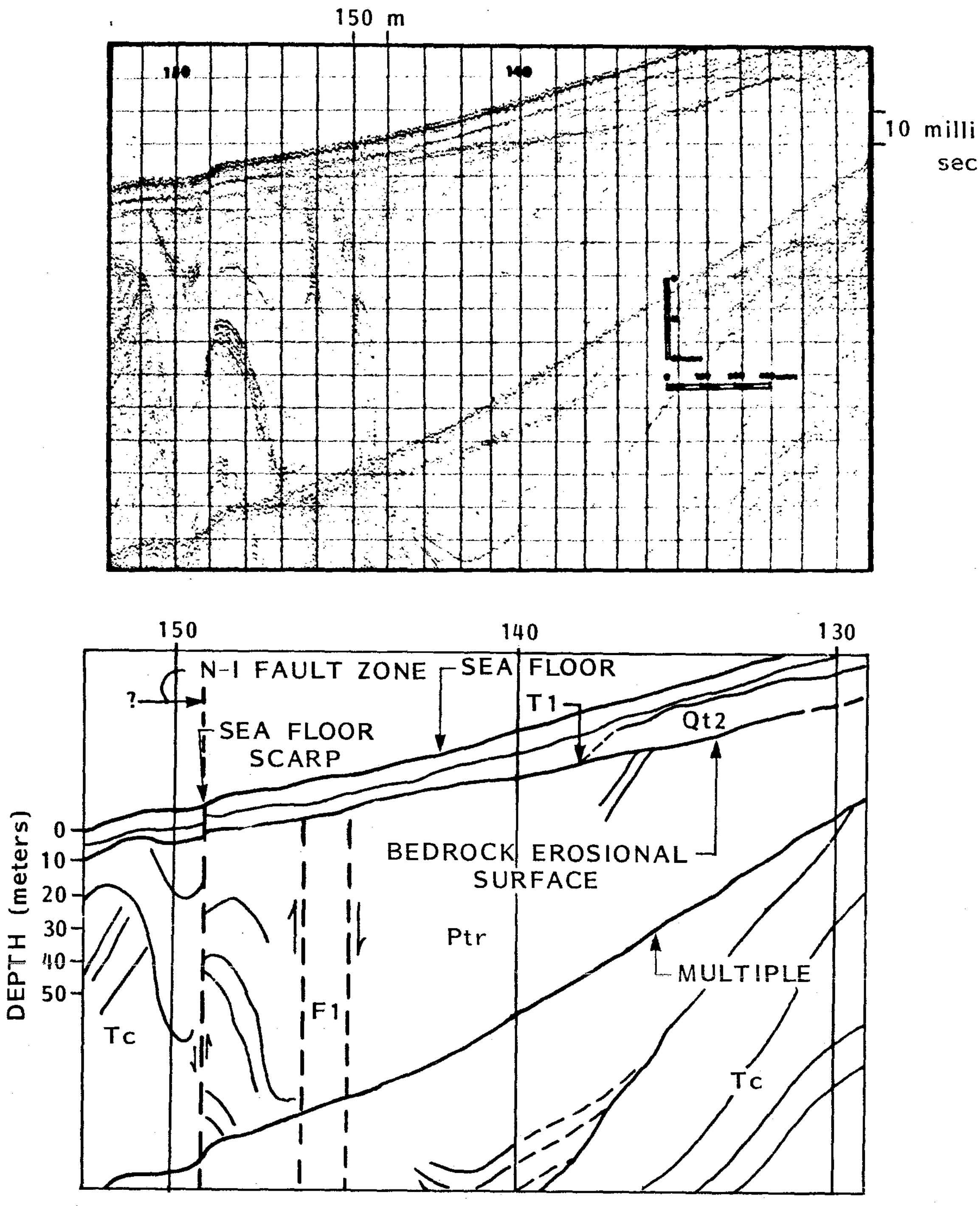


Figure 17. **INTERPRETED SUBBOTTOM PROFILE SHOWING DIP CHANGES AND OFFSET REFLECTORS WITHIN N-I FAULT ZONE ALONG W-C LINE 841 (Acoustipulse)**

The zone displays varying characteristics, possibly associated with the degree and age of activity, along its length within the study area. These apparent changes within the fault zone, however, may be related to variations in the density of available seismic survey coverage. Within the southern portion of the study area, the line density is the greatest with a minimum line spacing of 300 m. Near San Mateo Point the line spacing increases to 2000 m and increases to 3000 m near Dana Point (Plates 1 and 2). In addition, the majority of the high quality Uniboom data was collected along the southern section of the fault zone.

In the southern portion of the study area the Newport-Inglewood fault zone and a possible splay, Fault Zone A, are characterized by disturbed bedding and sea floor exposures of bedrock as shown on cross section A-A' (Plate 7) and Figure 18. Holocene sediments pinch out over Fault Zone A, where the Capistrano (Tc) and possibly the Monterey Formations (Tm) are exposed within the sea floor anomaly (Figure 18). Seaward dipping reflectors are present west of the fault zone.

North of cross section A-A' Holocene sediments are present within the zone. Offset Holocene and deeper reflectors and a sea floor scarp delineate the zone along line W-C 841 (Figure 17). The presence of sea floor anomalies and offset Holocene reflectors indicate Holocene activity along the Newport-Inglewood fault zone within the southern portion of the study area.

Although there is no evidence of Holocene activity north of San Mateo Point, the amount of data is an order of magnitude less than that of the southern portion of the study area. In addition, Fischer

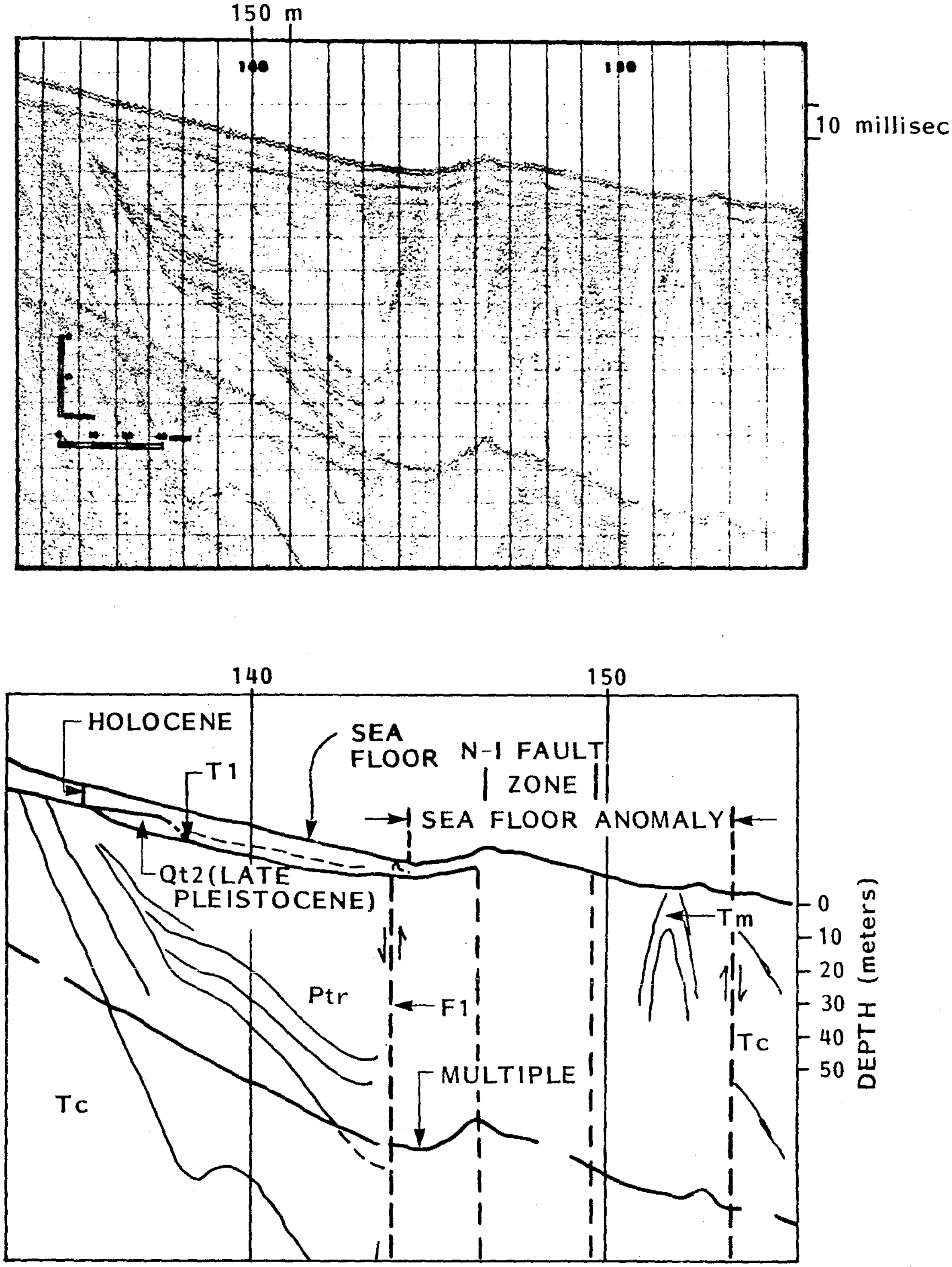


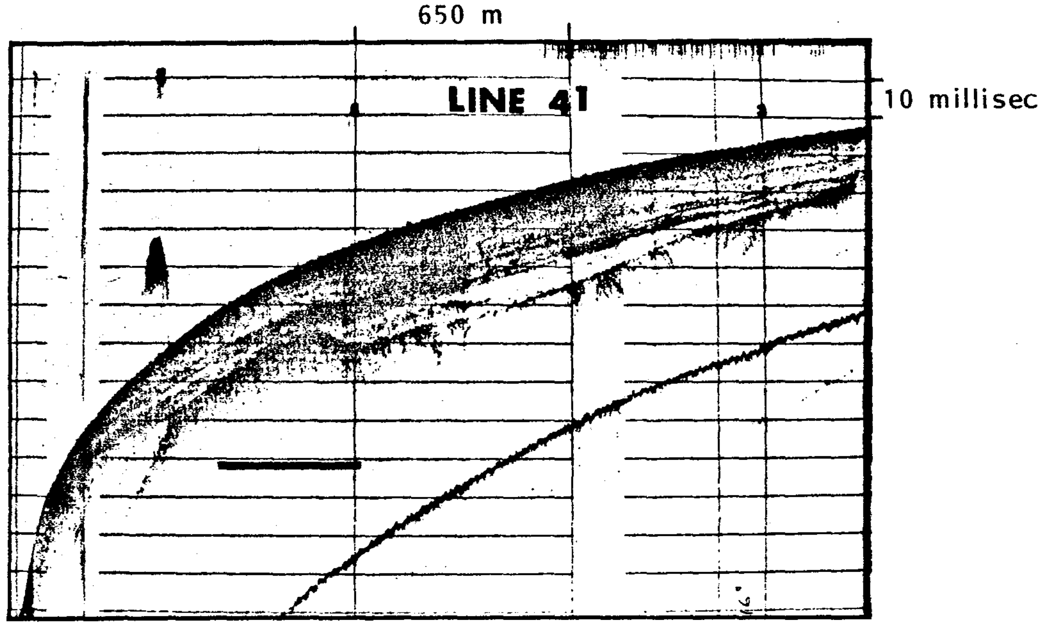
Figure 18. **INTERPRETED SUBBOTTOM PROFILE SHOWING SEA FLOOR BEDROCK EXPOSURE WITHIN N-I FAULT ZONE ALONG W-C LINE 825 (Acoustipulse)**

and others (1979) found Holocene activity north of Dana Point (Figure 19).

Offshore from San Onofre, the fault zone is characterized by offsets and disturbed reflectors as shown on cross section B-B' (Plate 8). Reflectors within the Plio-Pleistocene trough sediments (Ptr) are offset and the uncomformable contact of these sediments with the Capistrano Formation (Tc) is uplifted on the west (Figure 20). Reflectors within the Capistrano Formation are disturbed within the zone. Because the base of the Holocene sediments cannot be identified within the disturbed reflectors of the fault zone, definitive evidence for Holocene activity is not present on Ertec line 6 (Figure 20). CSUN line SD 3A-4823.5W 200 m north of Ertec line 6 shows offset reflectors and also shows an offset of the sea floor within the fault zone (Figure 21). This topographic anomaly and the offset of near surface reflectors are indicative of at least localized Holocene activity off San Onofre.

North of San Mateo Point the sea floor and the underlying bedrock erosional surfaces do not appear to be displaced as shown on cross section C-C' (Plate 9). Disturbed seismic reflectors are evident on sparker profiles (Figure 21) between San Mateo Point and the Dana Point fault. The degree of this disturbance decreases to the northwest along the fault zone. Northwest of the Dana Point fault, recognition of the Newport-Inglewood fault zone is difficult on high resolution data due to the shallow chaotic reflections and diffractions caused by the San Onofre Breccia.

However, as shown by Sterling (1982), the Newport-Inglewood fault zone is the basement fault mapped by Western Geophysical (1972) near



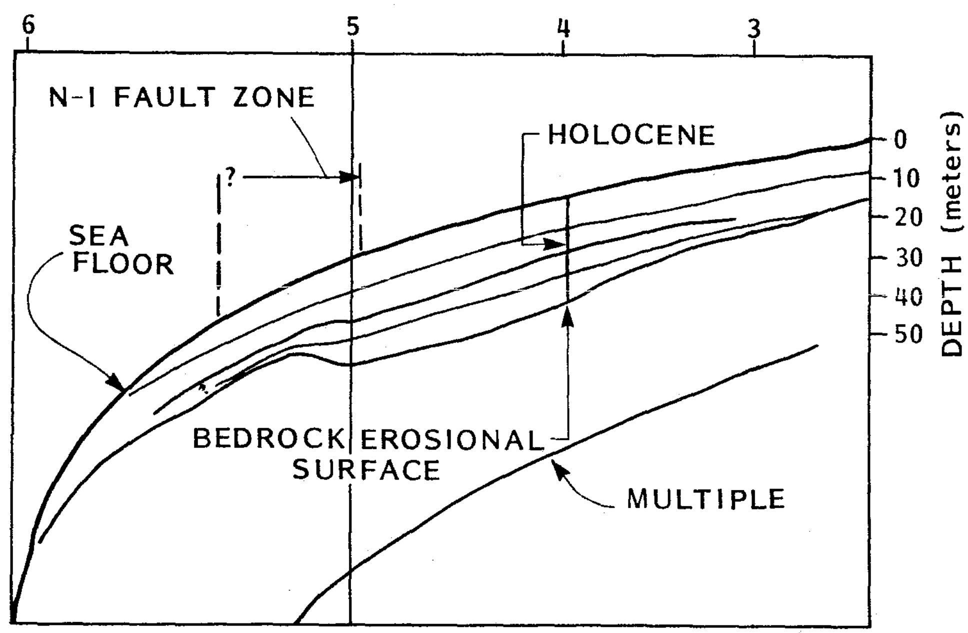
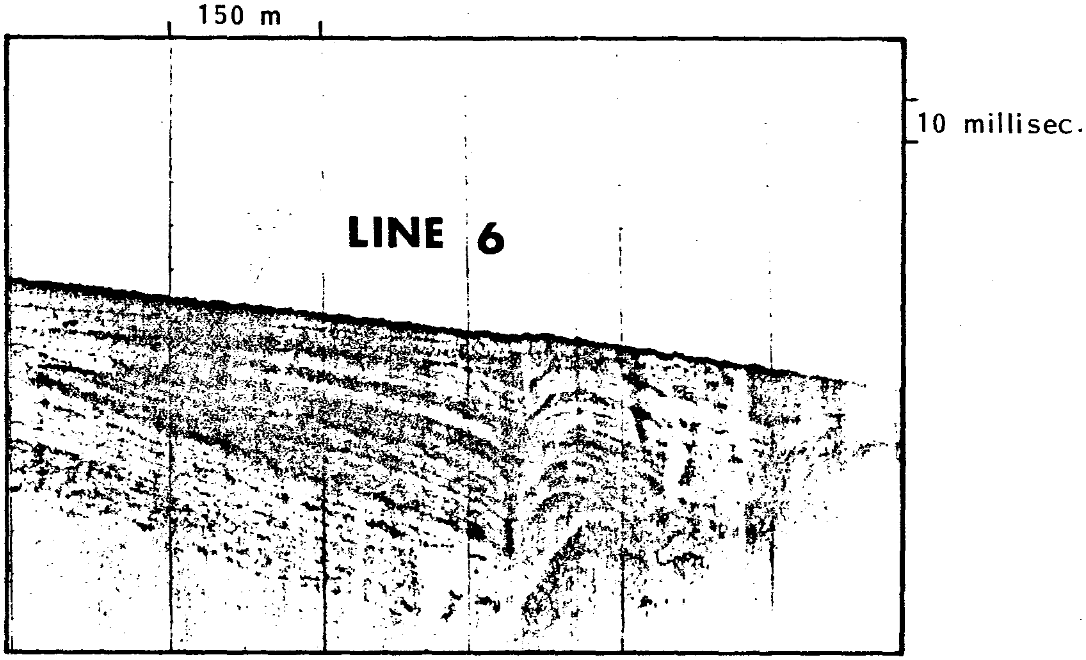


Figure 19. **INTERPRETED SUBBOTTOM PROFILE SHOWING WARPING OF BEDROCK AND SEDIMENTS ALONG CSUN LINE 41 (3.5 kHz) OFF DANA POINT**



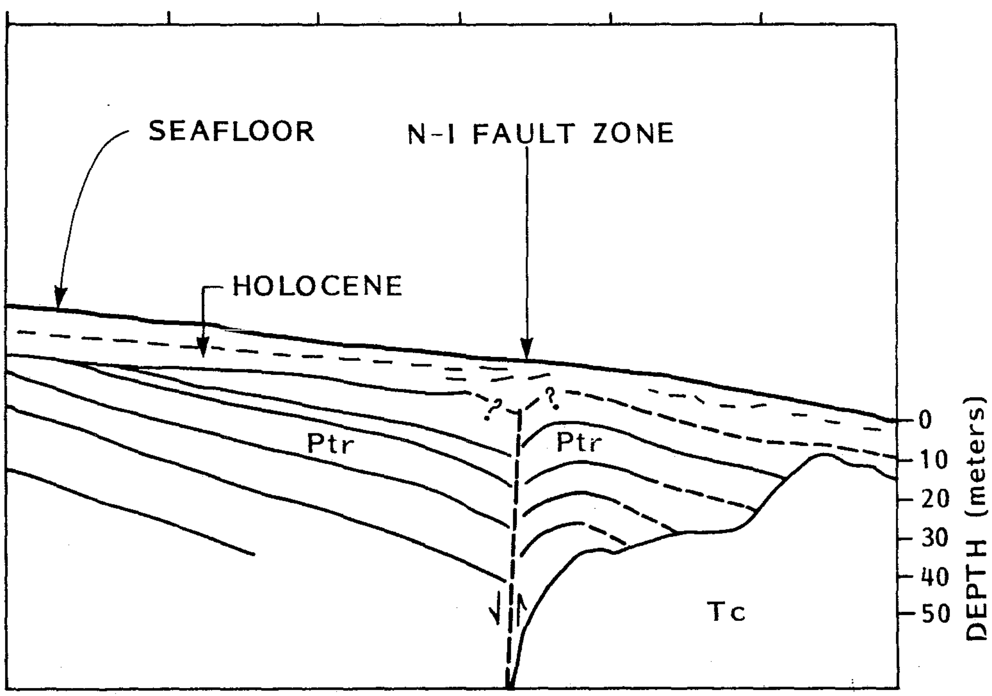
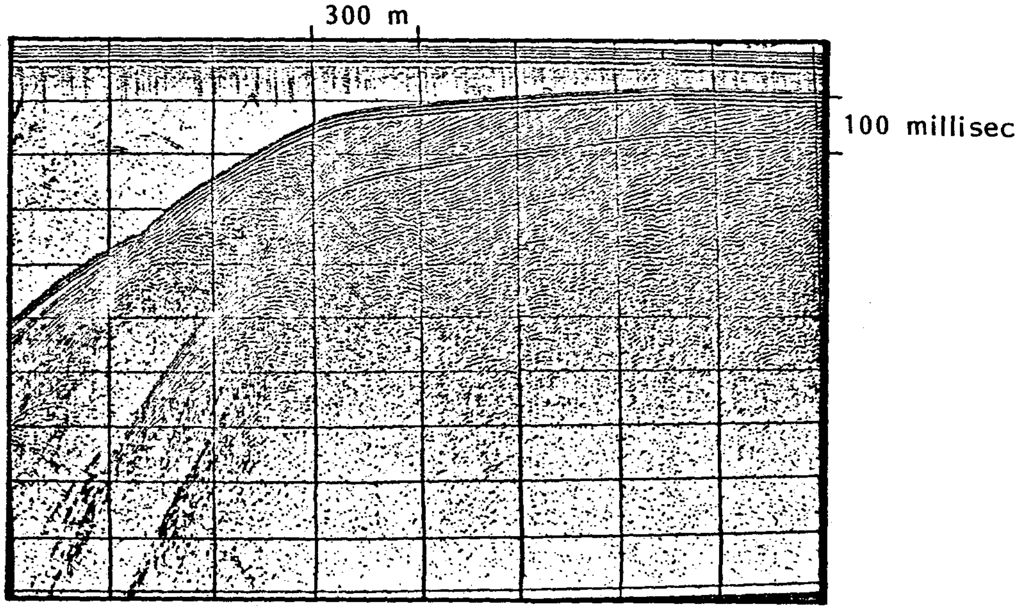


Figure 20. **INTERPRETED SUBBOTTOM PROFILE SHOWING OFFSET REFLECTORS WITHIN N-I FAULT ZONE ALONG ERTEC LINE 6 (3.0 kHz)**



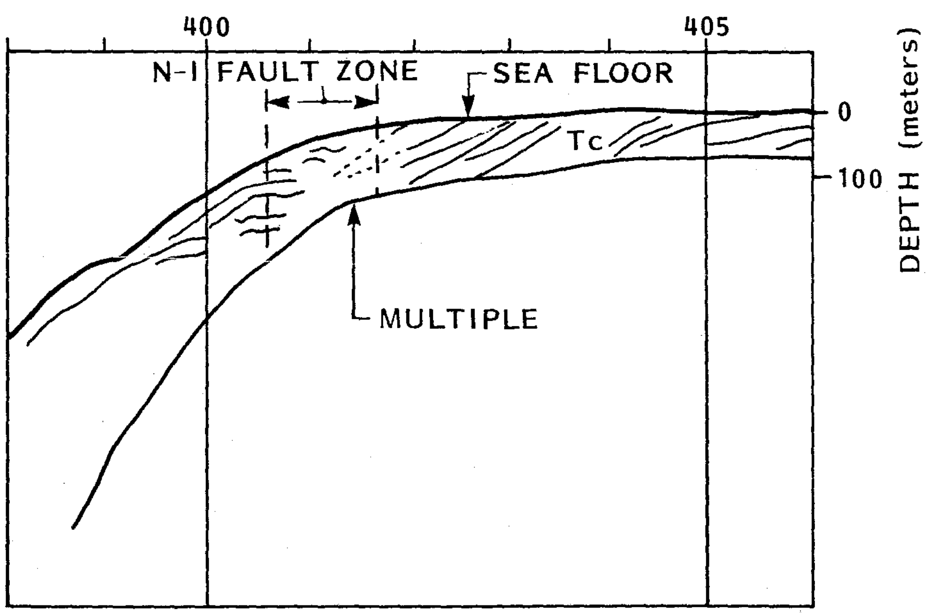


Figure 21. **INTERPRETED SUBBOTTOM PROFILE SHOWING DISTURBED ZONE ALONG INTERSEA LINE 32 (Sparker)**

Dana Point. This basement fault has been traced northwest, across the San Joaquin Hills High to the vicinity of Newport Beach (Fischer, 1979; Sterling, 1982).

Summary

Activity along the Newport-Inglewood fault zone varies within the study area. South of San Mateo Point, displacement of the latest Pleistocene/Holocene sediments and the sea floor along the zone indicate Holocene activity. North of San Mateo Point, no activity was noted during latest Pleistocene-Holocene time (oxygen isotope stages 1 and 2 of Shackelton and Opdyke, 1973). Holocene activity is again displayed on the northern or shelf branch of the zone near Laguna Beach (Fischer and others, 1979; Sterling, 1982).

Within the Late Quaternary units, minor vertical offsets with major disruption of reflectors suggests strike-slip movement along this fault zone. The variation in age of dart core samples taken across the fault zone from lower to upper Mohnian (Plate 3) is evidence of only minor vertical movement (Jahns and others, 1971).

The Newport-Inglewood fault zone has been mapped across the entire study area (Plate 3). This fault zone has been traced by Sterling (1982) to the basement fault mapped as part of the Newport-Inglewood fault zone of deformation to the north and should be considered part of the same system. The Holocene activity documented along the Newport-Inglewood fault zone within the study area is restricted to the section south of San Mateo Point.

Cristianitos Fault

The Cristianitos fault is a normal fault, downthrown on the west, exposed in the sea cliff 0.8 km south of San Onofre (Figure 3) (Hunt and Hawkins, 1975; McNey, 1979). Striking N20°W, the fault extends 32 km inland, juxtaposing the Pliocene San Mateo Formation against the upper Miocene Monterey Formation (Ehlig, 1977; McNey, 1979) or the upper Miocene Capistrano Formation (Hunt and Hawkins, 1975). Late Miocene to early Pliocene activity along the fault was associated with subsidence in the Capistrano Embayment. Based on stratigraphic juxtaposition, maximum displacements of 1050 m to 1220 m are found along the central portion of the fault (Hunt and Hawkins, 1975). In the sea cliff exposure, the Cristianitos fault does not offset terrace deposits dated by Shlemon (1978a; personal communication, 1982) at 125,000 years (Hunt and Hawkins, 1975; Ehlig, 1977; McNey, 1979). The age of faulting is pre-125,000 years. According to McNey (1979), there is no evidence of movement along the Cristianitos fault during the past 5,000,000 years.

Various offshore extensions of the Cristianitos fault offshore have been suggested by previous authors. Western Geophysical Company (1972) used proprietary CDP data to extend the fault seaward to the Newport-Inglewood fault zone but found no evidence of activity during Miocene time. Intersea Research Corporation (Marine Advisors) (1970) proposed that the Cristianitos fault turns south and parallels the coast, as Fault 2 shown on Plate 3. Changes in the character of subbottom reflectors on Intersea's sparker profiles were the basis for this interpretation of the extension of the fault. Jahns and others

(1971) also believe these sparker records show that the Cristianitos may turn south and die out less than 3000 m offshore.

This study found no evidence to extend the Cristianitos fault to the Newport-Inglewood fault zone. Numerous diffractions and an apparent change in seismic character of the bedrock were found along Fault 2. Apparent dips change from near horizontal to 12° at the seaward border of the fault (Plate 3). Although diffractions may arise from features other than faults, the probable change of bedrock character and the apparent dip increase suggest a possible fault, downthrown on the west. Shallow water between Fault 2 and the coastal exposure of the Cristianitos fault precluded the collection of definitive seismic reflection data. Based on the similarity of trend, age and style of faulting, diffractions, bedrock lithologic change and apparent dip change, the Cristianitos fault is tentatively correlated with offshore Fault 2.

Dana Point Fault

Edgington (1974) mapped an unnamed fault across Dana Point which was later referred to as the Dana Point fault (West, 1979). This northwest trending, high angle normal fault is downthrown on the east side. San Onofre Breccia is juxtaposed against the Capistrano Formation at Dana Point. Ziony and others (1974) dated activity along this fault as Late Cenozoic (5-12 million years).

Offshore, a fault with similar characteristics has been mapped as the extension of the Dana Point fault (Plate 3). Closely spaced, parallel seismic reflectors of the Capistrano Formation and the Monterey Formation on the south side of the fault are juxtaposed against chaotic reflectors of the San Onofre Breccia to the north. Increased multiple reverberations, characteristic of the San Onofre Breccia are found on the upthrown side of the fault.

On the outer shelf, the Capistrano Formation is juxtaposed against the Monterey Formation. This may be due to decreasing throw along the fault in the seaward direction. The Dana Point fault appears to terminate at the Newport-Inglewood fault zone near shelf break. Activity along the offshore Dana Point fault is interpreted to be pre-Pleistocene due to the continuous reflectors above the Pliocene Capistrano Formation.

Fault 1 (F-1)

Approximately 1.2 km shoreward of the Newport-Inglewood fault zone in the southern portion of the study area is the high angle Fault 1 (Plate 3). This fault trends northwest, parallel to the trend of the Newport-Inglewood fault zone. The east side is downthrown approximately 900 m (Western Geophysical Company, 1972), forming an asymmetric depositional trough. Typical seismic reflection profiles which cross the fault show apparent dip changes from 4°-6° on the east flank to 25°-35° on the west flank (Figure 22). True dip changes from 8° to 22° across the trace of the fault. These abrupt dip changes were the primary basis for mapping this fault, although minor (5-10 m) bedding offsets were found on Uniboom records.

The fault extends 3350 m north from the southern boundary of the study. On the northern end, the fault diverges from the trough and is traced as disturbed bedding on sparker profiles. Both the fault and the trough appear to terminate in this area.

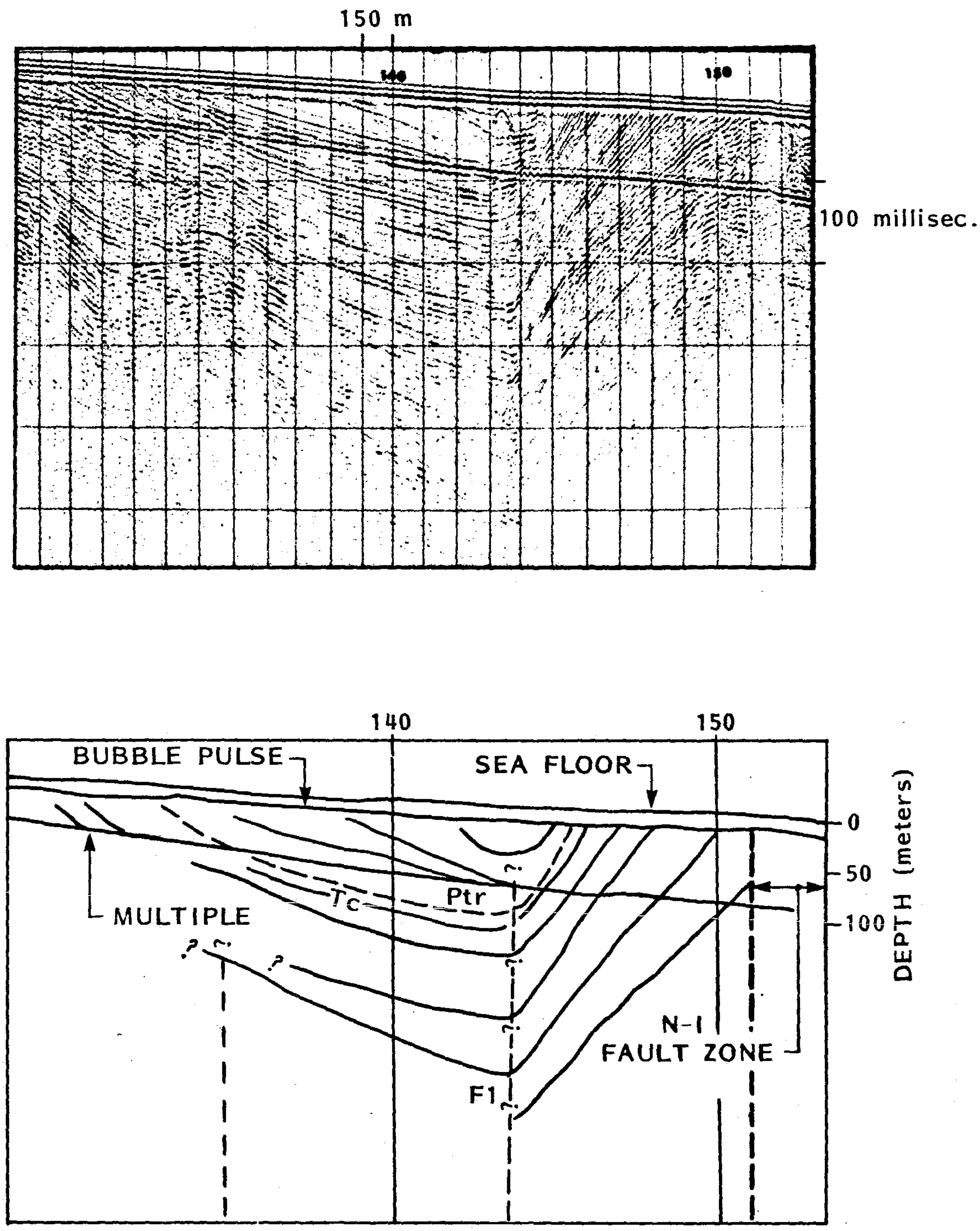


Figure 22. **INTERPRETED SUBBOTTOM PROFILE SHOWING DIP CHANGE AT F-1 ALONG W-C LINE 834 (Sparker)**

Ziony and others (1974) has assigned a Late Cenozoic age to this fault. The bedrock erosional surface appears to be uplifted on the western side of the fault (Figure 18). This may be the result of late Quaternary activity or the presence of more resistant bedrock associated with the structural high. There is no evidence of displacement of the sea floor or the sediments along the fault.

Fault 3

As mapped by Marine Advisers (1970) and this study, Fault 3 strikes north-northwest approximately 1.5 km offshore from San Onofre (Plate 3). Disturbed bedding and diffractions are characteristic of the fault on 21 profiles in the southern portion of the study area. A slight apparent dip change of about 5° is seen across this fault but vertical displacement of the reflectors could not be verified. No evidence of displacement of the bedrock erosional surface or sea floor was found; therefore, the fault is assigned a pre-Pleistocene age.

Other Faults

Other faults on the shelf and slope are apparently short and discontinuous (Plate 3). Most were mapped on the basis of disturbed or offset bedding and do not display evidence of Late Quaternary activity.

Only Faults A and B, short splays of the Newport-Inglewood fault zone show evidence of Late Quaternary activity. Fault A, a fault zone near the southern boundary of the area, displaces the sea floor. Off San Mateo Point, Fault B truncates syncline 1A and displaces the bedrock erosional surface but not the sea floor.

Folds

Fold axes were mapped on the basis of dip reversals seen on seismic reflection profiles (Plate 3). Major folds parallel the northwest trend of the Newport-Inglewood fault zone, while some minor folds on the inner shelf south of San Onofre trend north-northwest. Rocks of the middle Miocene and lower Pliocene formations have been folded and warped, probably during Neogene time according to Ehlig (1977). In the Late Quaternary, minor folding was reactivated during a second stage of deformation perhaps related to movement along the Newport-Inglewood fault zone.

Syncline 1 and 1A

Syncline 1 forms an assymetric trough which plunges to the southeast, 6.7 km offshore. True dips of 8° on the east flank and 22° on the west flank were measured (Plate 3). Bordering the syncline on the west is Fault 1, downthrown on the east (Figure 18). On the northwest end, the syncline becomes symmetric and shallows where it separates from Fault 1. The sediments which fill the trough are probably Plio-Pleistocene in age and onlap the Capistrano Formation. These younger sediments are folded, giving evidence of continuing tectonic activity after their deposition. The late Pleistocene erosional surface is not visibly folded.

Syncline 1A, an asymmetric syncline off San Mateo Point appears similar to syncline 1. Apparent dip changes from 6° on the northeast to 18° on the southwest are shown by line 23. It forms a trough with onlapping sediments and is associated with Fault B. This syncline terminates at Fault B on the southeast and may terminate at the Newport-Inglewood fault zone to the northwest.

Anticline 1

A change in dip direction from northeast along the coast to southwest on the outer shelf suggests the presence of a major anticline between Dana Point and San Clemente (Plate 3). Although the fold axis is not well defined on seismic reflection profiles, changes in dip direction are evident. Minor folding is present along the crest of the fold which may be underlain by the Monterey Formation. This anticline is terminated to the northwest by the Dana Point fault and appears to die out to the south where only seaward dipping strata are present.

Other Folds

The presence of an anticlinal crest within the Newport-Inglewood fault zone is indicated by a change of dip direction across the zone. Although the fold axis is occasionally present on seismic reflection profiles, it appears to be broken and displaced. Minor tight folds and vertical displacement mask evidence of the fold axis. North of San Mateo Point, only seaward dipping beds are present on the outer shelf.

Other minor folds of the study area are short and discontinuous. Trends are generally northwest with a more northerly trend noted on the inner shelf southeast of San Onofre. This trend change may be due to movement on Faults 2 and 3, or these minor folds may have been formed by a more recent episode of diastrophism with a slight directional change of the compressive force.

GEOLOGIC EVOLUTION

Plate Tectonics

Magnetic anomaly patterns provide evidence of plate motion in the eastern Pacific. These patterns and ages also provide evidence for the existence of a Paleozoic trench off the west coast of North America. Anomalies found represent the western side of the typical symmetrical pattern associated with a ridge system. This evidence indicates the presence of a trench which consumed the eastern anomalies and the spreading center, which formed the boundary between the Pacific and Farallon plates (Atwater, 1970). This spreading center was located a few hundred kilometers off the present west coast about 38 m.y. b.p. (Atwater and Molnar, 1973). Because the rate of consumption in the trench (7-10 cm/yr) was greater than the spreading rate (4-5 cm/yr), the Farallon plate was consumed (Atwater, 1970).

By about 20 m.y. b.p., the spreading center was consumed in southern California and plate motion was taken up by strike-slip movement along the ocean-continent boundary (Atwater, 1970). Great Valley and Franciscan-type rocks may have been rifted north from Baja about 18 m.y. b.p. due to the southern migration of the ridge-fault-trench triple junction along the continental margin (Crouch, 1979). The Farallon plate had disappeared along the entire length of the present San Andreas fault by 10 m.y. b.p. (Atwater, 1970).

The relationship of plate tectonics to the origin of the continental borderland remains the subject of debate between proponents of the theories of dominant extension (Yeats and others, 1974), large-scale oblique strike-slip displacement (Howell and others, 1974), and rotation of blocks (Luyendyk and others, 1979). Blake and others (1978) believe that a change in relative plate motion about 10 m.y. b.p. may have produced the necessary extensional component to form the borderland basins. Changes in the orientation or slip rate of the plate boundary between 12 and 3 m.y. b.p. may have caused subsequent convergent dextral shear and en echelon folding (Nardin and Henyey, 1978). The opening of the Gulf of California and the northerly migration of Baja, beginning 5 m.y. b.p., resulted in north-south compression in the borderland (Crouch, 1979).

Recent paleomagnetic studies by Luyendyk and others (1979) suggest a possible 70 to 30 degree rotation of crustal blocks bound by east-west trending left-lateral faults since Miocene time. Their model suggests that deep triangular basins would open during rotation of blocks between right-lateral and left-lateral faults.

Pre-Quaternary Evolution

Right-lateral shear, which began near Santa Cruz Island in late Oligocene to early Miocene time, caused widespread basement deformation and vertical movement along both the Santa Cruz Basin and Newport-Inglewood faults (Stuart, 1975). By the early Miocene, volcanism and tectonism became active within the Los Angeles Basin and in the borderland (Ehlig, 1977).

Uplift in the borderland formed a ridge or island offshore, which subaerially exposed the Catalina Schist by the middle Miocene (Woodford, 1925; Yerkes and others, 1965; Junger, 1974; Stuart, 1975, 1976). This basement ridge may have reached a maximum of 1200 m above sea level in the middle Miocene (Junger, 1974) and extended from Newport to Oceanside (Woodford, 1925). During this time, a shallow embayment was created between the Miocene ridge and the location of the modern coast. The deltaic to shallow marine San Onofre Breccia was deposited in the embayment in the middle Miocene (Stuart, 1975).

After middle Miocene time, the sea withdrew and the area was eroded (Yerkes and others, 1965). The unconformity between the San Onofre Breccia and the Monterey Formation is evidence of this regression. Rapid subsidence began in the late Miocene, reaching 1000 m in the Los Angeles Basin by the end of the Miocene (Yerkes and others, 1965). The thick, upper Miocene Monterey Formation indicates a deep and rapidly subsiding basin with deposition at bathyal depths (Stuart, 1976; Ingle, 1971).

The conformable contact between the upper Miocene Monterey Formation and the upper Miocene to early Pliocene Capistrano Formation is evidence that the study area remained below sea level throughout that time. Late Miocene through early Pliocene dip-slip movement along the Cristianitos fault formed the Capistrano Embayment (Ehlig, 1977, 1979). Continued subsidence in the embayment resulted in the deposition of several hundred meters of upper Miocene to lower Pliocene sediments (McNey, 1979). The Capistrano Formation was deposited at depths ranging from 900 m (White, 1956) to 1800 m-1900 m (Ingle, 1971). The top of the Capistrano Formation probably marks the end of subsidence. This was followed by a period during which the influx of sediment matched the outflow to the open ocean basin (Ehlig, 1979).

Evidence of middle Pliocene events was removed by erosion in the region (Ingle, 1971). An unconformity between the upper Pliocene to lower Pleistocene Niguel Formation (Vedder and others, 1970) and the underlying Capistrano Formation is evidence of this erosional period. Shallow marine conditions prevailed during the deposition of the Niguel Formation (Edgington, 1974).

Regionally, the Pliocene was a time of active subsidence, with the Los Angeles Basin attaining a depth of 2000 m in the early Pliocene (Yerkes and others, 1965). In the study area, subsidence in synclines 1 and 1A associated with movement along Faults 1 and A (Plate 3), may have begun in the Pliocene. Plio-Pleistocene(?) sediments were deposited in the trough formed by the subsidence. Deformation of the upper reflectors (Figure 7) suggest the trough remained active at least until the formation of the bedrock erosional surface in the late Pleistocene.

Quaternary Evolution

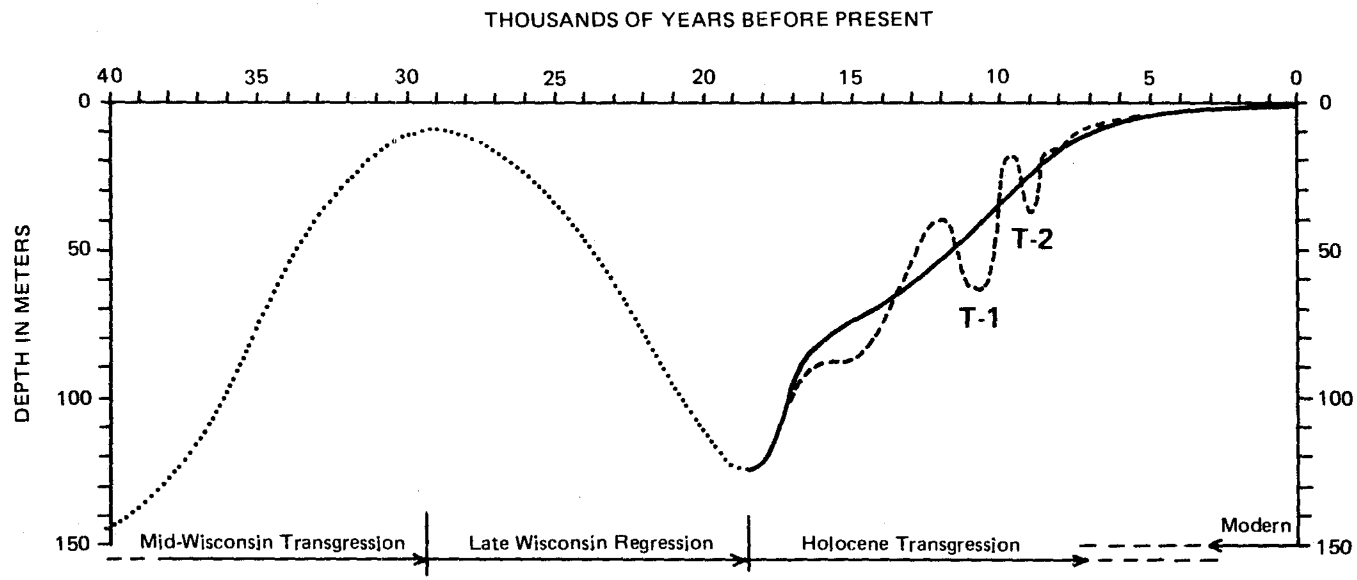
Interaction between tectonism and fluctuations of sea level are responsible for the development of most Quaternary landforms (Shlemon, 1978a). In addition to the nine coastal marine terraces, ranging in age from 125,000 to 780,000 years, mapped by Ehlig (1977), two offshore buried terraces were identified in the Camp Pendleton/San Onofre area.

Broad regional uplift and tilt along the coast are believed to be responsible for the formation of the older coastal marine terraces. Some studies supporting this theory include: the Malibu coast (Birkeland, 1972), the Palos Verdes Hills (Woodring and others, 1946), the San Diego coastal area (Kern, 1977) and the San Onofre area (Shlemon, 1978b). Since sea level was no higher than the high stand 125,000 years b.p. (stage 5e) for all the middle Pleistocene (130,000 - 700,000 b.p.) (Shackleton and Opdyke, 1973), it appears that regional uplift was the dominant force involved in the formation of the coastal terraces. Shlemon (1978b) compared the present elevation of the first emergent coastal terrace to the estimated sea level at the time of formation, to determine uplift rates within the area of the study. These rates range from 26 cm/1000 years at Dana Point to 6 cm/1000 years at Camp Pendleton (Table 5), indicating a regional tilt to the north during the Late Quaternary.

Two major late Pleistocene low stands of sea level have been determined from oxygen isotope data from deep sea cores. At 60,000 years ago (stage 4), sea level was at -80 m (below the present sea level) and at 17,000 - 20,000 years b.p. (stage 2) sea level was at -120 m (Shackleton and Opdyke, 1973). During the transgressions and regressions associated with these low stands; the Monterey, Capistrano and San Mateo Formations were eroded to form the bedrock surface, which underlies the Holocene and late Pleistocene sediments of the present shelf (Figure 12). Both the San Mateo Creek and the Santa Margarita River incised deep channels during the stage 2 low stand. The extension of the San Mateo Creek channel is seen below the Holocene sediments on the present shelf (Plate 4) (Figure 9). Both channels were filled during the subsequent transgression. By projecting the base of the Santa Margartia River channel to a depth of -105 m, Shlemon (1978a) postulates that the shoreline was about 3.2 km west of the present coast during the last low stand.

A rapid rise of sea level followed the stage 2 low stand between about 20,000 and 5,000 years b.p. (Curray, 1961, 1965; Shepard, 1967; Shackleton and Opdyke, 1973). Curray (1961, 1965) suggests fluctuations during this transgression (Figure 23). Two buried terrace levels on the shelf were found at depths of approximately -45 m and -66 m. These depths may correspond to the minor fluctuations of sea level at about 12,000 and 9,000 years b.p. The formation of wave-cut terraces in the easily eroded unconsolidated Pleistocene deposits would require little time.

The Holocene modern shelf sediments have buried most erosional features and has smoothed the sea floor of the shelf. Bedrock exposures are limited to the shoreline and the shelf break (Plate 6). Irregularities of the sea floor are due to resistant bedrock which was not beveled during the late Pleistocene and continuing tectonic activity. The sea floor scarps present on the outer shelf of the southern portion of the study area are the result of movement along the Newport-Inglewood fault zone.



From compilation of published and unpublished radiocarbon dates and other geologic evidence. Dotted curve estimated from minimal data. Solid curve shows approximate mean of dates compiled. Dashed curve slightly modified from Curray (1960, 1961). Probable fluctuations since 5,000 B.P. not shown here.

Figure 23. **LATE-QUATERNARY FLUCTUATIONS OF SEA LEVELS, MODIFIED FROM CURRAY, 1965**

SUMMARY AND CONCLUSIONS

Subbottom profiles provide evidence of late Miocene to Holocene tectonic activity within the study area. The offshore Newport-Inglewood fault zone, the Cristianitos fault, and numerous uplifted coastal marine terraces are expressions of this tectonism.

The offshore Newport-Inglewood fault zone is the major structural element of the study area. It extends from the onshore Newport-Inglewood zone of deformation, which has been traced to Newport Beach, to the Rose Canyon fault (Fischer and others, 1979; Greene and others, 1979). The offshore Newport-Inglewood fault zone can be traced from the southern boundary of the study area to the basement fault mapped as part of the Newport-Inglewood zone of deformation to the north. Over most of this fault zone, the late Pleistocene erosional surface is not displaced, indicating that activity ceased prior to the last low stand of sea level (20,000 years b.p.). Holocene activity is restricted to the section south of San Mateo Point and to the shelf branch of the fault zone between Laguna Beach and Dana Point (Fischer and others, 1979). Sea floor scarps, offset Holocene sediments and warping of the erosional surface indicate Holocene activity in these areas.

The Cristianitos fault, which is exposed in the sea cliff 0.8 km south of San Onofre, is correlated with Fault 1 offshore. Late Miocene to early Pliocene activity along the fault was associated with the subsidence which formed the Capistrano Embayment. Coastal marine terraces dated at 125,000 years by Shlemon (1978a) have not been offset and there is no evidence of movement along the Cristianitos fault during the past 500,000 years (McNey, 1979). Offshore this is confirmed by uncut units above the lower Pliocene Capistrano Formation.

Correlation of subbottom data with the onshore geology indicates that the modern shelf sediments are underlain by units ranging in age from middle Miocene to late Pleistocene. The middle Miocene San Onofre Breccia unconformably overlies the basement rock which is believed to be Catalina Schist. The overlying deep water Monterey and Capistrano Formations were deposited during a major transgression during middle Miocene to early Pliocene time. Subsequent regression resulted in the erosion of the middle to upper Pliocene units.

Erosion from subaerial exposure of the shelf during the last low stand of sea level (17,000 - 20,000 years b.p., Shackleton and Opdyke, 1973) formed the bedrock erosional surface. No record of the Quaternary is present except the Plio-Pleistocene trough deposits and three units (Qt1 - Qt3) of late Pleistocene sediments which unconformably overlie the erosional surface.

Nine coastal marine terraces and at least two buried offshore terraces have been mapped within the study area. Regional uplift with rates ranging from 6 to 24 cm/1000 years along the coast of the study area during periods of sea level fluctuations, resulted in the formation of these marine terraces. The sea cliffs along the modern coast suggest a continuation of this process.

The modern shelf is blanketed with latest Pleistocene/Holocene sediments. A study of the volume of these sediments along the shelf from San Pedro to the Mexican border found anomalously high volumes of sediment present within the study area (Fischer and others, 1980). Terraces cut into the soft Pleistocene units may have acted as dams trapping large volumes of marine sedimments during the last transgression.

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