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SAN ONOFRE
NUCLEAR GENERATING STATION
UNITS 2 AND 3

LATE QUATERNARY EVOLUTION OF THE CAMP PENDLETON-SAN ONOFRE STATE BEACH COASTAL AREA, NORTHWESTERN SAN DIEGO COUNTY, CALIFORNIA

JANUARY 1978

Southern California Edison Company

SAN DIEGO GAS & ELECTRIC COMPANY

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San Onofre

Nuclear Generating Station

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LATE QUATERNARY EVOLUTION OF THE CAMP PENDLETON - SAN ONOFRE STATE BEACH COASTAL AREA, NORTHWESTERN SAN DIEGO COUNTY, CALIFORNIA

for

SOUTHERN CALIFORNIA EDISON COMPANY

&

SAN DIEGO GAS & ELECTRIC COMPANY

by

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CONTENTS

CONTENTS (Continued)

FIGURES

FIGURES (Continued)

FIGURES (Continued)

FIGURES (Continued)

FIGURES (Continued)

TABLES

Table No. Page

INTRODUCTION

Purpose

This study is one of several commissioned by the Southern California Edison Company to analyze various aspects of regional geology within several miles of San Onofre Nuclear Generating Stations (SO), Units 2 and 3 (Southern California Edison Co., 1976). The major purposes of this study are:

(1) To reconstruct broadly the Quaternary evolution of the Camp Pendleton - San Onofre State Beach (CP-SOSB) coastal area;

(2) To identify major coastal landforms (e.g. marine and fluvial terraces, alluvial fans) and formulate the most plausible hypotheses for their origin in light of all evidence presently available;

(3) To date, where possible, all Quaternary geological units, both marine and non-marine, in the area by:

(a) radiometric assay, particularly carbon-14, of non-marine (continental) sediments underlying the San Onofre Bluffs;

(b) amino-acid stereochemistry of molluscan shells from a marine terrace deposit in the sea cliffs near the CP-SOSB boundary;

(c) description and analysis of soil development (pedogenic profiles), and rate of profile development, particularly for buried paleosols in continental sediments underlying the San Onofre Bluffs;

(d) correlation with uranium-series (mainly fossil corals) and amino-acid dated marine terrace deposits near San Diego on the south, and along the southern and central California coast from about Dana Point/Newport Beach to approximately San Francisco on the north;

(e) association of marine terrace deposits, particularly those not directly datable by radiometric-decay methods, with late Quaternary glacio-eustatic changes of sea level deduced from the marine oxygen-isotope record in deep sea cores;

(4) To determine the probable last time of displacement of any fault which might be identified or projected into the San Onofre Site area, based on evidence from this or concurrent geotechnical investigations.

Previous Investigations

The geological setting and most recent syntheses of SO 2&3 area geology are spelled out in the Final Safety Analysis Report (FSAR) for Units 2 and 3 (Southern California Edison Co., 1976). The FSAR documents all previous mapping and interpretations of structural and tectonic relationships. Specific data concerning the location and age of Quaternary faults near SO Units 2&3 are also given in Hunt and Hawkins (1975).

In addition to FSAR data, geologic and geomorphic relationships in the Camp Pendleton - San Onofre State Beach area have been mapped by Moyle (1973). This work, however, has been recently superceded in the coastal area by the large-scale (1:6,000), detailed mapping of Ehlig (1977) which has, with respect to Quaternary geological units, identified several discontinuous but sequentially older marine terrace deposits flanking the San Onofre Mountains.

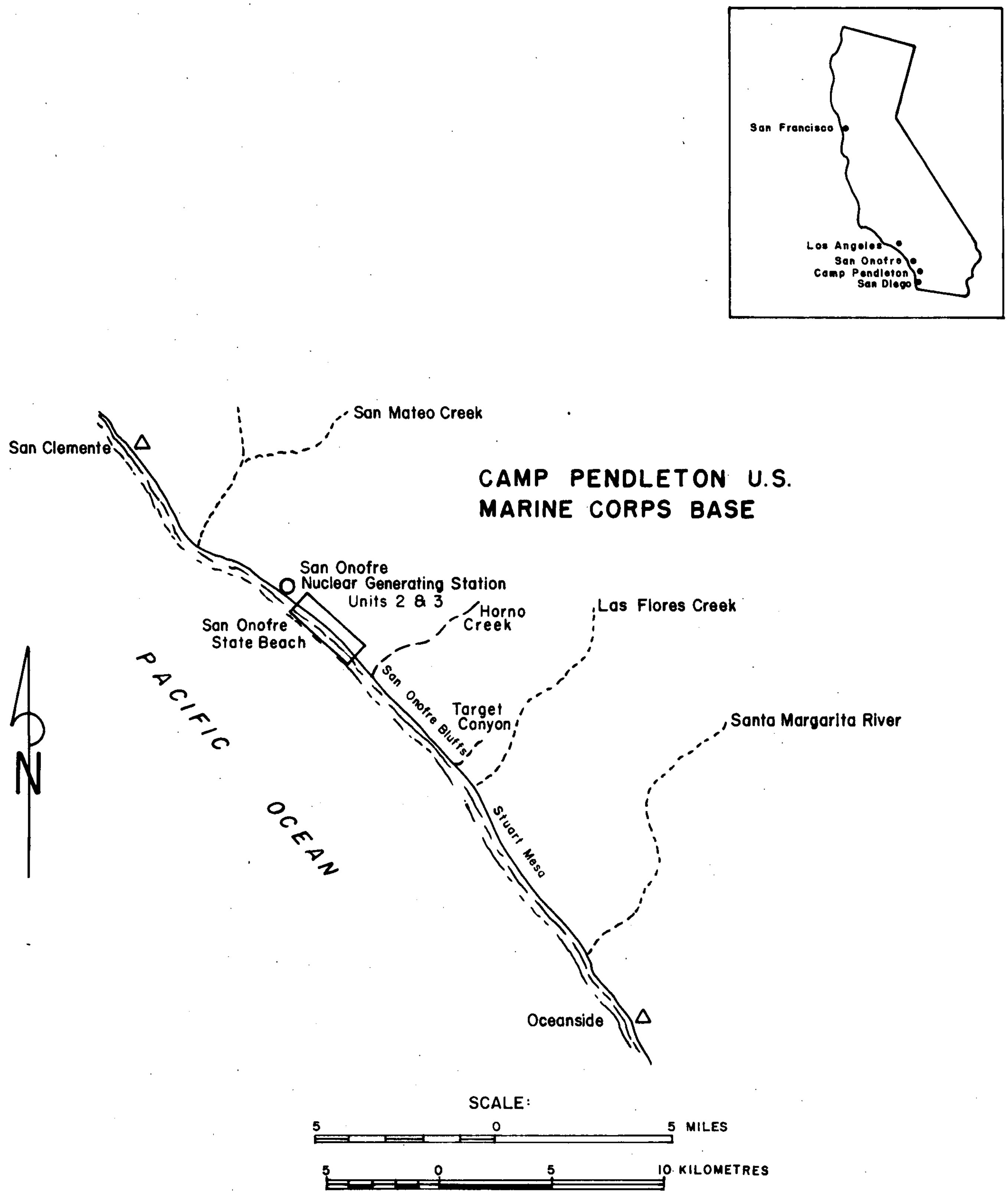


Fig. I Location map, Camp Pendleton and San Onofre State Beach coastal area, northwestern San Diego County, California.

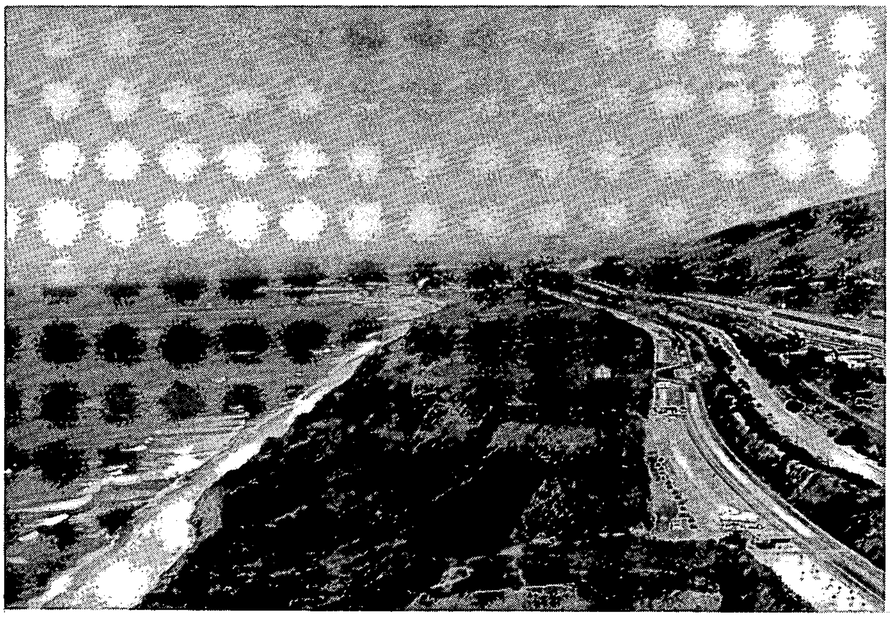


Figure 2. San Onofre State Beach looking north from Weigh Station area. Interstate Highway 5 on right. San Onofre construction Units 2&3, upper center on San Onofre Bluffs.

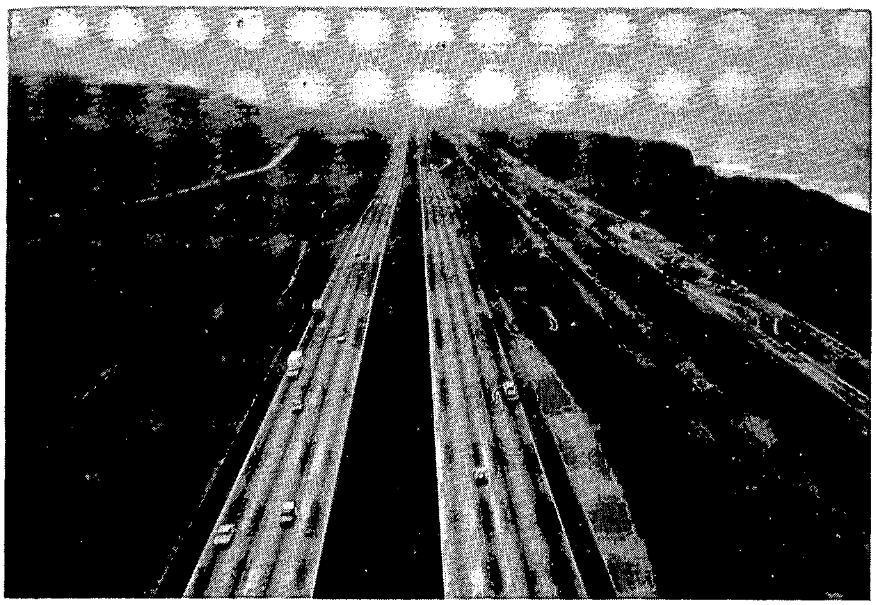


Figure 3. Camp Pendleton Coastal area looking south from Weigh Station on Highway 5. San Onofre Bluffs in fore and middleground; "high-level" marine terrace deposits on San Onofre Breccia and Monterey Formation (San Onofre Coastal Range) on left.

Several short papers concerning mainly bedrock geology and structural relationships in the southern part of Camp Pendleton are contained in a recent guide book (Ross and Dowlan, 1975); and observations regarding the Quaternary section in the central coastal portion have been provided by consultants to the Los Angeles Department of Water and Power (1971) and San Diego Gas and Electric Company (1977).

Soils of the CP-SOSB coastal area have been mapped in a recent survey of San Diego County (Bowman and others, 1973). Soils particularly useful for correlation of local geomorphic surfaces are those on the San Onofre Bluffs and on fluvial terraces, and the floodplain flanking the Santa Margarita River. Except for those identified in this study, there is no pre-existing information regarding the buried and relict paleosols locally exposed on top and within the approximately 50-foot (15 m) thick non-marine sequence underlying the San Onofre Bluffs.

Investigative Procedures and Acknowledgments

The data and concepts in this study derive mainly from two sources:

(1) Assessment of published literature, and unpublished consultants' reports pertaining to mapping and radiometric and relative dating of geomorphic surfaces and geological units, and to reconstructing

and dating sea level fluctuations as they bear upon the late Quaternary evolution of the CP-SOSB coastal area; and

(2) Field observation, description, sampling (where applicable) and interpretation of geomorphic assemblages, soil profiles, water-well logs, and radiometric and amino-acid dating of charcoal and fossil shells.

In addition to literature and field data, the study also devolved from personal communication graciously provided by others working in the immediate area or with techniques directly applicable. In particular, P. L. Ehlig, California State University, Los Angeles, mapped marine terrace deposits on Camp Pendleton and discussed various hypotheses regarding their age and origin; K. R. Lajoie, U. S. Geological Survey, Menlo Park, reviewed various uranium-series dating techniques and collected additional *Protothaca* for amino-acid assay; and G. Kennedy, Los Angeles County Natural History Museum, identified and interpreted the age and environment of an assemblage of invertebrate fauna from first marine terrace deposits near the CP-SOSB boundary.

Logistical support was furnished by the California Edison Company (SCE) Geotechnical Group. J. L. McNey, Senior Engineering Geologist, kindly made arrangements for transportation, aerial photography, and other field support. Additional

field, library and cartographic assistance, was provided by SCE Engineering Geologist P. Hamilton and Technician D. Olson. Greatly appreciated also were the discussions with Mr. Paul Campo and R. Carlson; and the water-well logs, and unpublished maps supplied by the Natural Resources Office, U. S. Marine Corps, Camp Pendleton.

LATE QUATERNARY COASTAL DEVELOPMENT

Late Quaternary marine and non-marine terraces and deposits are some of the most dramatic landforms of coastal California. The origin and development of these "ancient" coasts has been described from many localities, most notably the terrace sequences near Half Moon Bay and Santa Cruz (Alexander, 1953; Bradley, 1957; Bradley and Addicott, 1968; Bradley and Griggs, 1976; Dupre, 1975), the marine-planated surfaces near Cayucos (Veeh and Valentine, 1967); the Malibu coast (Birkeland, 1972); the classic terrace flights of the Palos Verdes Hills (Woodring and others, 1946); and the now radiometrically-dated terraces near San Diego (Ku and Kern, 1974; Kern, 1977; McCrory and Lajoie, 1977; Wehmiller and others, 1977). Quaternary marine terraces and coastal evolution have also been described from offshore islands; for example, San Nicholas and San Miguel Islands (Valentine and Veeh, 1969; Johnson, 1977).

Despite these numerous and well-documented studies of coastal landforms and evolution, the late Quaternary terraces and sediments of the Camp Pendleton - San Onofre State Beach area have remained somewhat enigmatic. To a great degree, this relates to their inaccessibility, located within an area of continual military manuevers. Data from the present study, however, indicate the similarity of the CP-SOSB landforms and deposits to those described elsewhere along the southern and central California coast. It appears, therefore, that the "gap" in knowledge of Quaternary coastal landforms, between San Diego on the south and the Dana Point/Newport Beach area on the north, is now beginning to close.

A wide variety of geomorphic terms have been used to describe similar landforms on the California coast making it difficult to correlate surfaces and deposits. For example, the "first emergent terrace," described from the central California coast (Bradley and Addicott, 1968), has been used by many workers to designate the first bench or geomorphic surface above present-day sea level. However, this marine - planated platform occurs some 50 to 60 feet (15 to 18m) below the first geomorphic surfaces in the San Onofre area. Similarly, marine and non-marine transgressive and regressive deposits have not been clearly defined or even recognized in many studies along the central and southern California coastline. In this study, therefore, the geomorphic terminology used in the CP-SOSB coastal area is defined and applied as illustrated in diagrammatic cross-section (Fig. 4).

This study also reviews the depositional and erosional effects of sea level change on coasts, and those likely induced by tectonic or eustatic changes. Additionally indicated are changes of local base level which have controlled the late Quaternary evolution of many landforms in the Camp Pendleton - San Onofre State Beach area.

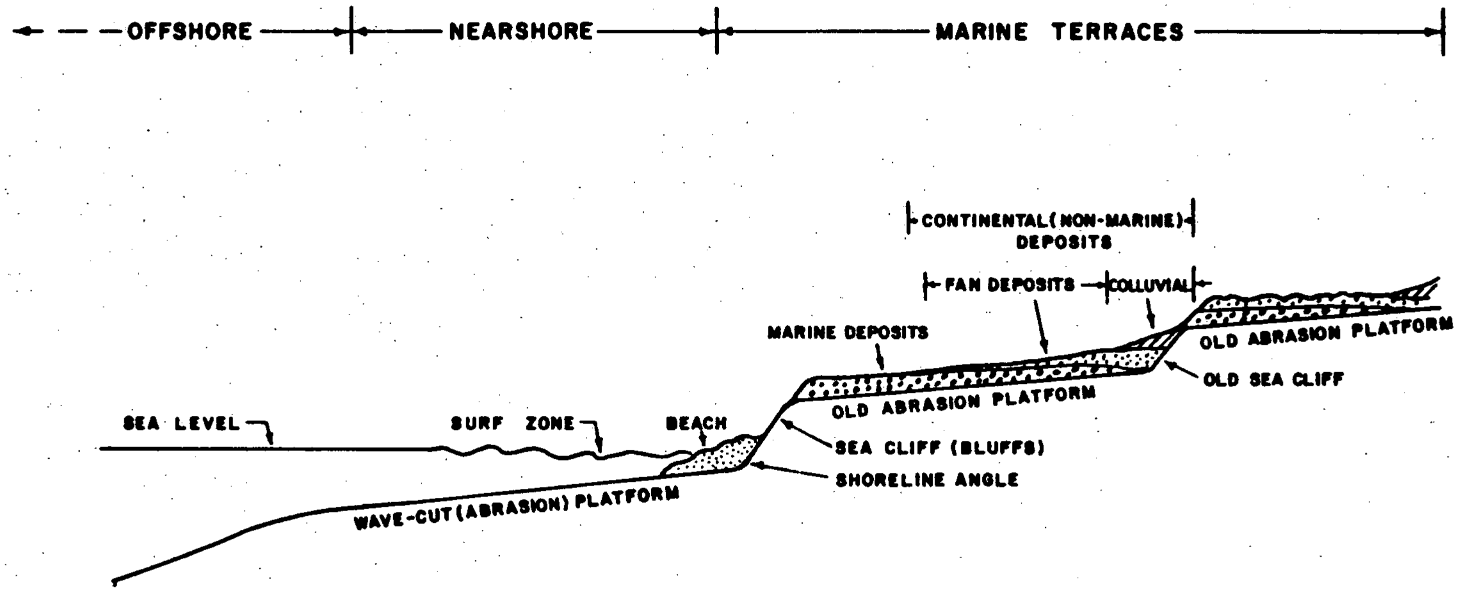


Fig. 4. Diagrammatic cross-section and geomorphological terminology for the Camp Pendleton-San Onofre State Beach cliffed coastal area.

Late Quaternary coastal evolution is also reconstructed by direct dating of some deposits, particularly radiocarbon assay of post-"first emergent terrace", continental sediments, and by amino-acid stereochemistry of marine shells. In addition, sea level change, prior to about 120,000 years ago, can be indirectly deduced by oxygen-isotope analyses of foraminifera from deep-sea cores. All these data are then synthesized into an idealized glacio-eustatic curve for approximately the last million years and applied to the geomorphic surfaces and related deposits in the Camp Pendleton - San Onofre State Beach coastal area in order to determine their most likely origin and age.

Finally pointed out in this section is geomorphic evidence for late Quaternary coastal stability within, at least, the last 100,000 years. This is useful to determine why some marine Quaternary terrace deposits of apparent similar age occur at varying elevations above sea level; and whether these elevation differences reflect late Quaternary tectonism or merely differential coastal erosion.

Coastal Classification and Terminology

Numerous classifications have been proposed for coastal landforms. Some are purely descriptive, others are genetic; and many are completely outdated in view of the now-accepted concepts of plate tectonics and sea floor spreading. Most nomenclature about shoreline development dates back to Johnson's (1919) early classification of emergent versus submergent coasts. This classification, reviewed succinctly by Shepard (1973), though descriptively adequate, fails to assess what is now known as one of the most important factors in coastal evolution, namely, the rapid rise in sea level (Flandrian transgression), about 20,000 to 5,000 years before present (B.P.), associated with melting of the last continental ice sheets. In essence, all coasts are submergent, except those where the rate of tectonic uplift has exceeded the glacio-eustatic rise of sea level.

The CP-SOSB coastal area may be viewed broadly as transitional between a (1) cliffed coast, especially in the northwest near SO Units 2 and 3; and a (2) depositional coast southeastward on Camp Pendleton between about Las Flores Creek and the Santa Margarita River estuary (Fig. 1).

Along cliffed coasts, the offshore wave-cut platform is a zone of bevelling by the present sea (Fig. 4). Most erosion occurs at wave base during major storms. Both low and high tide wave-cut or abrasion platforms are present in the CP-SOSB, but these are usually narrow and often covered by beach dune and berm deposits.

The modern offshore abrasion platform (Fig. 4) may in fact consist of two or possibly more submerged terraces, as deduced by Emery (1954) from boring and offshore geophysical data. The abrasion platform is mantled by gravels and much sand and silt, mostly derived from San Mateo and San Juan Creeks, and from direct coastal erosion of sandy units within the San Onofre, Monterey, Capistrano, and San Mateo Formations (Buffington and Moore, 1963).

The present sea cliff ranges in elevation from about 125 feet (38m) on the north near San Onofre Units 2 and 3 to approximately 40 feet (12m) on the south along Stuart Mesa (Fig. 1). Mass movements, expressed by large landslides and rotated blocks, are dominant mechanisms of coastal retreat in this area (Moyle, 1973; Blanc and Cleveland, 1968; Cleveland, 1975). Elsewhere, rapid coastal erosion is occurring along deeply incised, steep-walled arroyos, graded to sea level, and extending headward into non-resistant late Quaternary continental and Tertiary marine deposits.

Exposed for some 8 miles (13 km) in coastal bluffs southeastward from SO Units 2&3 to approximately Las Flores Creek is an almost table-like buried marine-planated surface (Fig. 5). This old abrasion or wave-cut platform cuts across mainly non-resistant Tertiary formations, though nowhere is its backslope contact with an older sea cliff (shoreline angle) clearly exposed (Fig. 4).

Overlying the abrasion platform are regressive marine deposits, mainly beach facies, and locally 40 to 60 feet (10 to 18m) of prograding, non-marine (continental) sediments. Those post-platform deposits have been dated locally; the marine section by faunal assemblage, and the overlying continental sediments by carbon-14 (see sections on dating techniques).

Because the marine deposits overlying the wave-planated surface are the first above present sea level, they are designated "Terrace 1," though in the CP-SOSB coastal area they are always buried and exposed only in sea cliffs and a few arroyo and road cuts (Fig. 5). The marine terrace deposits, numbered successively, 2 through 9, overlie progressively higher and older geomorphic surfaces. In general, the older marine terrace deposits, east of Highway 5 (Fig. 3), have been mostly stripped of overlying continental deposits.

The non-marine or continental deposits overlying marine sediments on the old wave-cut or abrasion platform (Fig. 2 and 3) give rise to the most extensive geomorphic surface in the study area -- the San Onofre Bluffs. These bluffs range in width from a few tens of feet (ca. 10-30 m) near SO Units 2 and 3 to about two miles (3.2 km) at Stuart Mesa (Fig. 1). This surface is undulating and grades seaward with a 2 to 3 degree slope. It is underlain by coalescing alluvial fan deposits emanating from small drainage basins in the San Onofre coastal mountains. The resulting alluvial piedmont plain is presently undergoing both erosion and deposition. Along the coast, shoreline retreat by mass-wasting and arroyo cutting is the dominant geomorphic process; along the mountain front, aggradation by fan and mudflow deposits continues to build up the surface. Only a few drainages originating in the coastal ranges cut through the San Onofre Bluffs and underlying continental and marine deposits to

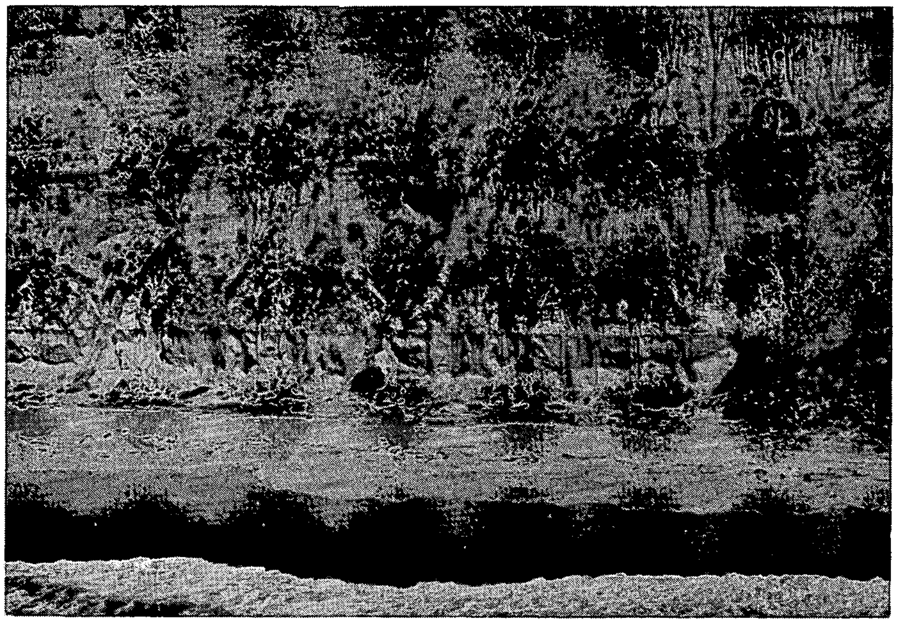


Figure 5. Sea cliff exposures - marine abrasion platform and deposits (Terrace 1) truncating underlying Tertiary formations; overlain by continental sediments.

reach sea level, viz, San Mateo, Horno, and Las Flores Creek (Fig. 1). These few streams thus grade to a sea-level controlled base. Elsewhere, however, local base level for most ephemeral drainage is the surface of the San Onofre Bluffs.

Older marine, wave-cut abrasion platforms are discontinuously exposed in the Camp Pendleton - San Onofre State Beach coastal area. As mapped by Ehlig (1977), the contact between underlying bedrock (usually the Monterey Formation and San Onofre Breccia), and the overlying marine terrace deposits is irregular, with local relief in the order of several feet (2-3 m). Here, only a few exposures reveal the wave-cut platform in contact with an older sea cliff; and therefore the shoreline-angle elevations are determined mainly by projection.

Effect of Base Level Change on Landform Development

Two major interacting processes have affected late Quaternary base level change and landform development in the Camp Pendleton - San Onofre State Beach coastal area: (1) tectonism, the uplift or depression of the land; and (2) eustacy, the fluctuation of sea level. Both processes have been operative in the coastal area throughout late Quaternary time. Determining the relative magnitude and influence of each, however, is a most formidable task and one that typically faces the Quaternary geologist.

Tectonic Change

There is little question that tectonic influences have profoundly affected California coastal landforms. Marine terrace deformation has resulted from epeirogenic movement, or broad-scale elevations or depressions, and isostatic motion, mainly water loading and unloading on the continental shelf. For example, in the San Francisco Bay area tectonic subsidence during the last 100,000 years has ranged between about 20 to 40 cm/1,000 years (Atwater and others, 1977, p. 13). Farther south near Santa Cruz, uplift of marine terraces within the last 125,000 years is an estimated 25 cm/1,000 years (Bradley and Griggs, 1976, p. 444). In southern California, near Malibu, the rate of uplift during the last 110,000 years is about 30 to 45 cm/1,000 years (Birkeland, 1972, p. 441). And the rate of deformation of the approximately 125,000 year old marine terrace in the San Diego area is estimated to be about 16 to 20 cm/1,000 years (Kern, 1977, p. 1563).

Most of this tectonic deformation results from broad epeirogenic or isostatic movement in which coastal landforms have been generally uplifted but not necessarily offset by late Quaternary faults. In general, along the central and southern California coast there is abundant evidence that late Quaternary tectonic uplift is responsible for the present elevations of most marine terraces and underlying sediments greater than about 10 or 12m above sea level.

Superimposed on the rising coastal landmasses are, however, climatically-controlled fluctuations of sea level associated with the major late Quaternary glaciations and deglaciations.

Hydroisostatic movement or changes of base level caused by water loading (Bloom, 1967, 1971; Walcott, 1972) have also probably affected relative base level in the Camp Pendleton - San Onofre State Beach area. However, the magnitude of hydroisostatic-controlled deformation is unknown, though it likely is in the order of a few cm or less, and certainly far less than tens of metres typical of high latitude deglacial ice unloading and isostatic rebound (Bloom, 1971; Mörner, 1978).

Eustatic Changes

Two major eustatic changes, or fluctuations in the absolute volume of ocean water, have affected late Quaternary landform evolution in the Camp Pendleton - San Onofre State Beach area: (1) those related to tectonic controls, primarily the rate of sea floor spreading; and (2) sea level fluctuations owing to the growth and shrinkage of continental ice sheets.

Little is known about early Quaternary eustatic changes in base level stemming from sea floor spreading and increased volume of ocean basins. However, Bloom (1971) has pointed out that during the last 100,000 years, since the last interglacial high sea level, a sea floor spreading rate of approximately 10 cm/yr would create an oceanic basin enlarged by some 2.6 x 10^6 km^3. This increase in ocean basin volume alone would cause present sea level to drop about 8 m from interglacial shorelines of 100,000 years ago (Bloom, 1971, p. 356). This eustatic-tectonic component is vitally important with respect to understanding the present elevations of marine terraces and underlying deposits on the southern California coast, for many landforms higher than several tens of metres may in fact owe their origin to falling sea levels during the Quaternary related to sea floor spreading and increased oceanic volume, rather than to simple tectonic uplift of the coastline.

The best documented glacio-eustatic base level changes are those occurring within about the last 35,000 years. In general, numerous data from deep borings and from radiometric dating of shells, wood, and peat are available to outline broadly the last major fluctuation of sea level (late Wisconsin) related to the growth and shrinkage of continental ice sheets. The resolution of the sea level curve which may be constructed from these data becomes increasingly finer in Holocene time, owing mainly to more abundant radiometric dates of coastal sediments.

The number of curves purporting to show the rate and magnitude in the rise of sea level since the last major lowstand of sea level, approximately 17,000 to 20,000 years B.P., is legion (Bloom, 1977). Some curves are based on the age-depth relations of sediments from, unfortunately, tectonically unstable areas. Others are based on only a few radiometric dates requiring broad interpolations and extrapolations between data points; and still others "fill-in" data based on theoretical calculations of solar flux received by the earth and on permutations in the earth's orbit throughout late Quaternary time (Curray, 1965; Curray and Shepard, 1972; Emery and Garrison, 1967; Donn and others, 1962; Bloom, 1971; Milliman and Emery, 1968; Fairbridge, 1961).

Nevertheless, as pointed out in sections following, the general elevation of sea level in the interval between about 20,000 to 5,000 years ago is sufficiently well known so that now-buried river channels in the CP-SOSB area, graded to the sea, can be relatively dated. Additionally, the rate of coastal retreat during the last 5,000 years may be approximated, based on relative sea level stability during this interval.

Development of Marine Terraces

Despite uncertainties about the precise timing and magnitude of late Quaternary sea level change, whether purely tectonic or glacio-eustatic, the larger effects of these fluctuations are recorded by the development of marine terraces in the CP-SOSB area and elsewhere along the central and southern California coast.

Several studies of the California coast (Bradley, 1957; Bradley and Addicott, 1968; Bradley and Griggs, 1976; Dupre, 1975) show that both a transgressive and regressive cycle of sedimentation are preserved in marine terrace deposits, especially those associated with the last major rise and fall of sea level during "late Sangamon" time, approximately 80,000 to 125,000 years ago.

A glacio-eustatic rise in sea level results in an erosional transgression which abrades and bevels underlying bedrock. If this underlying rock is relatively nonresistant, as the sands and silts of the Tertiary Monterey, Capistrano and San Mateo Formations, the wave-eroded platform may be almost planar, terminating abruptly landward against the sea cliff (Fig. 4). Typically, a thin veneer of transgressive marine sediments may be deposited on the newly abraded surface; however, the high energy of waves on the Pacific Coast, with bases some 30 to 60 feet (10 to 18m) below mean sea level (Bradley, 1958), generally preclude deposition or preservation of many transgressive deposits. Where the transgressing sea has cut across more resistant bedrock, such as the San Onofre Breccia, the resulting wave-cut surface is much more irregular, and local relief may be in the order of several feet (2-3 m). In general, the smoothness of the abraded platform and the landward extent of shoreline erosion resulting from a glacio-eustatic rising sea level relates to resistance of the underlying bedrock and to shoreline configuration.

Lowering sea levels result in deposition of a veneer of neritic, regressive marine and beach sediments on the wave-cut platform, itself eroded mainly during the previous transgression. Many California marine deposits laid down during the regressive epicycle are fossiliferous, and several have been dated by uranium-series and amino acid techniques (Wehmiller and others, 1977). As sea level continues to fall during the regressive epicycle, large streams are incised on the newly exposed continental shelf and extend seaward. In contrast, many small drainages emanating from the adjacent coastal mountains, characterized by ephemeral flow in a Mediterranean climate, fail to reach the coast. Rather, they debouch sediments on top of the now abandoned wave-cut platform and underlying regressive marine deposits. The non-marine (continental) deposits, laid down mainly as piedmont alluvial fans, prograde episodically seaward over the underlying marine sediments, as exemplified by their internal heterogeneity and unconformities, mainly small gravel-filled channels and buried paleosols. Most of the prograding non-marine deposits have long been stripped from high-level marine terrace platforms; but they are still well preserved along the central and southern California coastline, especially where overlying the abraded "Sangamonian" transgressive platform and regressive marine sediments.

The ultimate expression of a marine transgressive and regressive cycle is a coastal terrace; in reality a composite landform underlain by prograded continental deposits, regressive marine and beach sediments, an abraded or wave-cut platform, and finally bedrock, usually pre-Quaternary in age (Fig. 4).

QUATERNARY SEA LEVELS AND COASTAL LANDFORMS

Most marine and fluvial terraces, deposits, and related coastal landforms in the Camp Pendleton - San Onofre State Beach area owe their origin to late Quaternary sea level fluctuation. But the timing of these sea level change and the age of coastal landforms was little known; and until a few years ago, no absolute ages were available from the CP-SOSB area and only a few for other landforms along the central and southern California coast. Thus most coastal landforms were generally deemed as "early," middle," or "late" Pleistocene in age.

Recently, however, refinements in isotope dating techniques and in paleomagnetic stratigraphy, both from terrestrial deposits and deep sea cores, have provided worldwide time markers useful to subdivide the Quaternary Period. The subdivisions now generally accepted are:

<u>Holocene</u>: 10,000 years B.P. to present;

<u>Late Pleistocene</u>: approximately 120,000-130,000 to 10,000 years B.P.; the lower boundary corresponding to a world-wide high stand of sea level expressed geomorphologically as an elevated marine terrace ("Sangamon") or as a time of ocean temperature warming designated "marine oxygen isotope stage 5e" (Broecker and Van Donk, 1970; and Shackleton and Opdyke, 1973);

<u>Middle Pleistocene</u>: about 130,000 to 700,000 years B.P., the lower boundary corresponding to the Brunhes-Matuyama magnetic reversal;

Early Pleistocene: approximately 1,800,000 to 700,000 years B.P., the lower boundary defined as the Olduvai normal event within the Matuyama reversed epoch (Butzer, 1974).

Dating Techniques

More precise dating of Quaternary sea level fluctuations and coastal landforms is now possible based on a combination of direct and indirect dating techniques. The age of Middle and Late Pleistocene marine terrace deposits can now be determined directly by uranium-series and amino-acid assay of fossil corals and molluscs; and an increasing number of radiocarbon dates are available for latest Pleistocene and Holocene alluvial fan and fluvial terrace sediments. The timing of broad sea level fluctuations over the past million years is known from deep-sea oxygen isotope analyses, and can now be applied to date indirectly Middle and possibly even Early Pleistocene marine terrace deposits. Similar indirect dating techniques are applicable to some late Pleistocene and Holocene continental sections where average sedimentation rates can be calculated when "calibrated" by radiocarbon or other absolute dating methods.

Direct Dating

Uranium series:

Several terraces along the central and southern California coast and offshore islands have been dated by uranium-series decay ($Th^{230/234}$ and Pa^{231}/U^{235}) in calcareous fossils, primarily molluscs and corals. Corals have proven to be especially favorable for uranium-series dating (Thurber and others, 1965; Veeh, 1966; Veeh and Valentine, 1967; Valentine and Veeh, 1969; Ku and Kern, 1974). Molluscs, however, appear to be less reliable, owing to probable enrichment by secondary uranium early in the diagenetic history of the fossils (Kaufman and Broecker, 1965; Valentine and Veeh, 1969).

Uranium-series dates for fossil molluscs, interpreted in terms of closed system diagenesis, range in age from approximately 70,000 to 100,000 years for those in the lowest terrace at Newport Beach (Szabo and Vedder, 1971) and at Santa Cruz (Bradley and Addicott, 1968). Coral ages for the "first emergent terrace" are approximately 130,000 to 140,000 ($\pm$30,000) years B.P. from sediments 10 to 20 m above sea level near Cayucos, in San Luis Obispo County (Veeh and Valentine, 1967); 87,000 ($\pm$12,000) and 120,000 ($\pm$20,000) years B.P. for a 30 m high terrace on San Nicholas Island (Valentine and Veeh, 1969); and 120,000 ($\pm$10,000) years B.P. for 15 to 20 m high sediments on the Nestor terrace at Point Loma in San Diego County (Ku and Kern, 1974; Kern, 1977).

Amino-Acid Stereochemistry:

In addition to uranium-series, amino-acid stereochemistry has been increasingly applied to dating terraces along the California coast (Bada and others, 1970; Wehmiller and others, 1974, 1977; Lajoie and others, 1975). Precise dating of marine fauna in terrace deposits by the amino-acid technique is limited by the rate and temperature dependence of the racemization reaction (Wehmiller and others, 1977). Also, the rate of racemization varies widely among foraminifera and mollusc genera; and contamination of samples during diagenesis causes additional age uncertainty. Nevertheless, where amino-acid dates have been obtained from carefully sampled molluscs, the ages correspond closely with those derived from uranium-series assay of fossil corals.

A particularly useful fossil mollusc for amino-acid dating is the genus *Protothaca* (Wehmiller and others, 1977). This particular fossil has proven especially beneficial to correlate widely-separated terraces along the central and southern California coast (Lajoie and others, 1975). *Protothaca* has been found in regressive marine deposits overlying the first wave-cut platform (Terrace 1) near the Camp Pendleton - San Onofre State Beach boundary (SW 1/4 sec. 3, T. 10 S. R. 6 W); and has yielded an amino-acid date of about 125,000 years B.P. (K. R. LaJoie, personal communication, 1978).

Radiocarbon

Few California marine deposits have been dated directly by radiocarbon, for as shown by uranium-series and amino-acid techniques, sediments directly overlying the "first emergent terrace" are about 100,000 to 120,000 years old and thus beyond the range of C-14. Dating charcoal, wood or other material suitable for radiocarbon assay is therefore limited to continental sediments overlying the first wave-cut platform.

The continental deposits in the CP-SOSB area are among the thickest and most extensive on the southern California coast. As noted in sections following, these non-marine deposits were laid down mainly as coalescing alluvial fans which prograded oceanward during times of relative fall or stillstands of the sea.

The continental section ranges in thickness from about 40 to almost 100 ft(10-30m). It contains abundant but widely disseminated charcoal and a few small pieces of wood, especially in now-covered estuarine deposits and in buried soils. Most charcoal fragments occur near the base of the section, and as discussed in later parts of this report, several collected for radiocarbon assay have sufficient organic matter for dating (Table 1).

Though carefully selected in the field and cleaned in the laboratory, the abundance of modern rootlets deep in the continental sediments suggests that there has been some contamination by young carbon. Also, all samples, following laboratory cleaning procedures, are "lean" in organic matter, some containing less than one percent. The dates thus obtained are regarded as minimal; however, most samples still yielded infinite, or dates approaching the limit of carbon-14 (Table 1).

Indirect Dating

Though most marine terraces and underlying deposits on the Camp Pendleton - San Onofre State Beach coastal area are unfossiliferous and therefore not datable directly by

TABLE 1
RADIOCARBON AGE DETERMINATIONS
CAMP PENDLETON - SAN ONOFRE STATE BEACH, CALIFORNIA

SCE SAMPLE NO.	GEOCHRON LAB NO.	WEIGHT OF SAMPLE BEFORE PROCESSING (GRAMS)	CARBON RECOVERED FOR COUNTING	AGE	LOCATION	DESCRIPTION	COMMENTS
—	GX-1899	—	—	>36,000	SW1/4, SE1/4, Section 14, T10S, R6W, Las Pulgas Quadrangle (LPQ)	Charcoal fragments in "sandy soil" (basal non-marine sediments)	Reference: Converse, Davis, and Associates (1971)
1	GX-4953	264 gms	3.1 gms	>37,000	NE1/4, SE1/4, Section 10, T10S, R6WLPQ Head of "Dead Dog Canyon," 0.3 miles SE of Horno Creek; sample 26 feet above Terrace 1 platform.	Charcoal fragments from 2-in. vertical cut in mid-section of 8.5 foot thick silty clay; incipient buried, soil, Sample 3.6 feet below moderately-developed buried argillic horizon.	See photograph, Figure 28.
2	GX-4954	300 gms	0.2 gms	—	SE1/4, SE1/4, Section 14, T10S, R6WLPQ Target Canyon Road Cut	Disseminated charcoal fragments from incipient buried soil; may be slumped area.	Sample too small for count.
3	GX-4955	298 gms	0.08 gms	—	SE1/4, SE1/4, Section 14, T10S, R6WLPQ Target Canyon Road Cut	Disseminated charcoal fragments from 3-inch vertical section in clay (Unit 22, Table 4); 3.5 feet below base of carbonate nodules.	Sample too small for count.
4	GX-4956	175 gms	1.96 gms	1360 $\pm$135	SE1/4, SE1/4, Section 14, T10S, R6WLPQ Haul road in Target Canyon near approximately 1-2 feet above marine bench.	Charcoal fragments from 1 inch vertical cut in clay within reworked beach deposits, base of continental section. Contains shell fragments and rootlets; possible slump area, 30 feet from SCE #2.	Sample suspect: probable contamination by modern carbon, rootlets and shells
5	GX-3957	29 gms	0.05 gms	—	SW1/4, NE1/4, Section 10, T10S, R6WLPQ Sea cliff exposure, 0.1 mi. S. of Horno Creek, almost 2 feet above marine bench.	Very disseminated charcoal fragments from fluvial silty sand; from 3.0-3.5 vertical range. Sample "lean" in carbon.	Sample too small for count.

TABLE 1 (continued)
RADIOCARBON AGE DETERMINATIONS

SCE SAMPLE NO.	GEOCHRON LAB NO.	WEIGHT OF SAMPLE BEFORE PROCESSING (GRAMS)	CARBON RECOVERED FOR COUNTING	AGE	LOCATION	DESCRIPTION	COMMENTS
6	GX-5168	28 gms	0.21 gms	4955 ± 240	NW1/4, NE1/4, Section 4, T10S, R6W San Onofre Bluffs Quadrangle (SOBQ) Sample about 10 feet above Terrace 1 platform, within SOSB Trail 5 comp.	Carbon fragments in a sandy silt soil.	Sample suspect; possible contamination by modern rootlets, also extremely small amount of organic carbon obtainable.
7	GX-5169	8 gms	0.14 gms	—	NW1/4, NE1/4, Section 4, T10S, R6WSOBQ Sample about 40 feet above Terrace 1 platform, near SCE #6.	Carbon fragments in a sandy silt soil.	Sample too small for count.
8	GX-5170	135 gms	0.36 gms	>23,000	NE1/4, SE1/4, Section 4, T10S, R6WSOBQ Coastal canyon near CP-SOSB Boundary, south of SOSB Trail 6. Sample from 25 feet above Terrace 1 platform.	Disseminated carbon fragments from 12-inch vertical and 35" horizontal sections, fluvial silt.	Sample showed no C-14 activity; however age given is maximum owing to small size of sample.
9	GX-5171	180 gms	0.78 gms	>37,000	SW1/4, SW1/4, Section 3, T10S, R6WSOBQ, Sample about 25 feet above Terrace 1 platform, about 300 feet SE of SCE #8.	Carbon fragments in a clayey sand.	-----
10	GX-5172	570 gms	0.43 gms	27,000 +5,700 -3,300	NW1/4, NW1/4, Section 10, T10S, R6WLPQ, Sample from about 10 feet above Terrace 1 platform, 0.4 miles NW of Horno Creek.	Carbon fragments in a sandy clay.	-----
11	GX-5173	140 gms	1.57 gms	>33,000	NE1/4, SE1/4, Section 10, T10S, R6WLPQ "Dead Dog Canyon;" sample 25 feet above Terrace 1 platform; near SCE #1.	Carbon mass from a burn zone with reddish fired clay around the sample.	-----

or amino acid, their approximate age can be determined indirectly by association with Quaternary sea level curves established by oxygen-isotope analyses of foraminifera from deep sea cores and from sedimentation rates.

Oxygen-Isotope Analyses:

The applicability of O^{18}/O^{16} ratios in the shells of planktonic foraminifera to indicate changes in water temperature, ice volume, sea levels and worldwide climatic changes has been documented by Emiliani (1955; 1966), Broecker (1965), Broecker and Van Donk (1970); and Shackleton and Opdyke (1973; 1976).

In addition to recording apparent late Quaternary climatic change, the timing of that change is indicated in several deep sea cores which have been calibrated chronologically by paleomagnetic reversals (see, for example, Shackleton and Opdyke, 1973, 1976). As shown in Figure 6, some 22 stages defining relative climatic change and probable sea level fluctuations are recognized for the late Middle and Late Pleistocene or back to about 700,000 years B.P. Of particular interest is stage 5, which delimits a high stand of sea level between approximately 80,000 and 120,000 years ago. This high stand is probably equivalent to the "late Sangamon" interglaciation of the middlewestern United States. Also, from uranium-series and amino-acid dating of corals and molluscs, this was the time when the "first emergent terrace" (Terrace 1) platform was cut in most central and southern California localities.

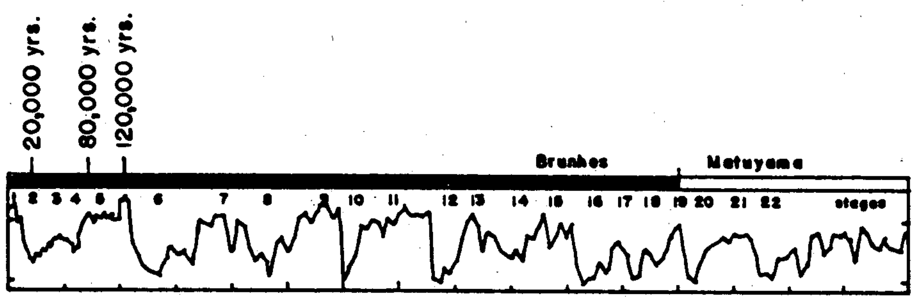


Fig. 6. Relative change in sea level in Middle and Late Pleistocene time, based on oxygen isotope composition of foraminifera in a mid-Pacific core (after Shackleton and Opdyke, 1973, p. 48). Late Pleistocene boundary from oxygen isotope substage 5e (ca. 130,000 years BP) to present, Middle Pleistocene from Brunhes/Matuyama magnetic reversal (ca. 700,000 years BP) to substage 5e.

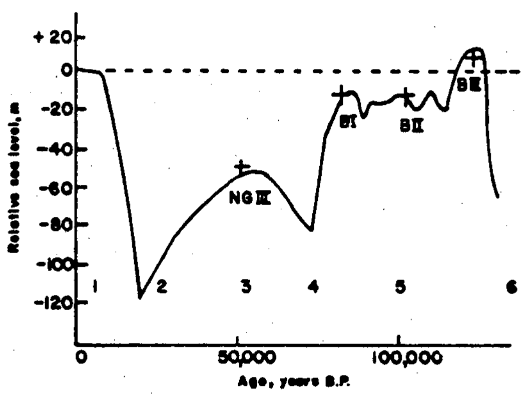


Fig. 7. Glacio-eustatic sea level curve for the past 130,000 years derived from oxygen isotope measurements in mid-Pacific core compared with dated terrace corals from Barbados (BI, BII, BIII, Broecker, and others 1968) and New Guinea (NGIII, Veeh and Chappell, 1970). Curve from Shackleton and Opdyke (1973, p. 45).

Details of stage 5 stratigraphy, derived from a mid-Pacific core (Shackleton and Opdyke, 1973) correspond extremely well to estimated time and elevations of sea level high stands deduced from independent measurements on marine terraces in Barbados (Broecker and others, 1968) and in New Guinea (Veeh and Chappel, 1970; Fig. 7). In addition, short-lived glacial events which lowered sea level to perhaps 70 m below the present (Steinen and others, 1973), are also recognized within stage 5. The five minor high stands have been designated substages 5a through 5e, respectively; the last stage (5e) 10 to 15m higher than the present (Shackleton and Opdyke, 1973, p. 45; Figs. 6 and 7).

The indirect dating of late Quaternary climatic change and sea levels offered by oxygen isotopes has additional interesting implications with respect to the marine terrace sequence in the CP-SOSB area. As pointed out in sections following, some nine distinct marine terrace deposits have been identified in the CP-SOSB coastal area (Moyle, 1973; Ehlig, 1977). The terrace deposits range in elevation from about 30 to 1,250 feet (10-375m). Except for the lowest (Terrace 1), no absolute dates are presently available for the higher terrace abrasion platforms and deposits. Yet these high-level landforms can be indirectly dated: by their apparent association with Quaternary high stands of sea level deduced from oxygen isotope analyses of deep sea cores; and by assumed rate of regional uplift (McCrory and Lajoie, 1977).

Sedimentation Rates:

In addition to oxygen-isotope dating of sea levels and landforms, indirect dating of continental sediments, younger than about 100,000 years, is possible by calculation of approximate sedimentation rates. Sedimentation rates are most accurate when the age of top and bottom units are well known, where deposition is relatively constant, (free of unconformities), and when there has been little post-depositional mixing or disturbance of sediments. Few places in the world offer such ideal conditions though they are approached in the fine-grained deposits of deep sea cores where the stratigraphic boundaries of many are dated radiometrically and paleomagnetically. Terrestrial sequences offer at best only approximate sediment rates, for unconformities abound and deposition is seldom uniform in any one section. Nevertheless, indirect sedimentation rates are useful where no absolute dates are presently available. In the CP-SOSB area, for example, most radiocarbon dates from continental sediments 20 to 25 feet (6 to 8m) above the approximately 125,000 year old Terrace 1 marine deposits yield infinite ages (Table 1). These are in accord with an estimated sedimentation rate of about 1 foot (30cm)/1,000 years deduced from the thickness of the continental deposits and the age of the underlying marine sediments (Shlemon, 1977, p. 8).

Latest Pleistocene - Holocene Sea Level Change

Except for the radiocarbon dates from continental sediments (Table 1), no radiometric ages are available for near-shore marine deposits in the CP-SOSB area less than about 100,000 years old, or equivalent to oxygen-isotope stages 1 to 5. This is a result of (a) no marine fossils of this age suitable for radiometric dating have yet been found; and (b) the probability that fluctuations of sea level during this time did not rise above the present. Nevertheless, coastal landforms and deposits in the CP-SOSB area of post-stage 5 age can be dated relatively, mainly by correlation to glacio-eustatic changes of sea level, particularly the "Wisconsinan," low stands (isotope stages 2 and 4) of about 20,000 and 70,000 years B.P., and the "mid-Wisconsinan high stand" (stage 3), approximately 35,000 to 50,000 years ago (Figs. 6 and 7).

Wisconsinan Low Stands

It has long been recognized that sea level fell 250 to possibly 400 feet (75 to 120m) below the present at least twice during the last 70,000 years (Curray, 1965; Flint, 1971; Donn and others, 1962; Milliman and Emery, 1968). These sea level fluctuations were mostly glacio-eustatically controlled, generally associated with major advances of continental ice deemed the "Wisconsinan glaciations" in the midwestern United States. Many estimates have been made of the depth and time of the Wisconsinan low stands, some based on depths of offshore terraces, submarine canyons, and bedrock notches; others on theoretical calculations of ice volume, changes in solar flux, and deformation of the earth's crust.

On the California coast, the depth of offshore channels cut by major streams, has been used frequently as an indicator of sea level lowering in Wisconsin time. For example, tributaries of the ancestral Sacramento River periodically incised channels 80 to 100 feet (25-30 m) in the Sacramento - San Joaquin Delta, grading to glacio-eustatic lowered sea levels (Shlemon, 1971; Shlemon and Begg, 1975). During the last major low stand, some 17,000 to 20,000 years ago, the Sacramento River probably cut a bedrock notch at the Golden Gate, 380 feet (116 m) below sea level (Louderback, 1951; Atwater and others, 1977).

On the southern California coast, Ellis and Lee (1919) early pointed out that the coastal valleys in San Diego County were filled with alluvium, the base of which extended considerably below sea level as deduced from interpretation of water well logs. Similarly, in the Los Angeles Basin coastal plain, Poland and others (1956; 1959) identified ancestral gravel-filled channels of the Los Angeles, San Gabriel and Santa Ana river trenching well below present sea level. And, Upson (1949) located buried channels of the Santa Maria and Santa Ynez rivers some 300 feet (90m) below the surface, equating them chronologically to a "late Wisconsin" low stand of sea level. In the Camp Pendleton coastal area, as well, water well logs depict a buried channel of the Santa Margarita River, the top of which can be traced to about -120 feet (-36m) at the present coast.

Glacio-eustatic fluctuations of sea level in the last 70,000 to 100,000 years are also recorded by distinct changes of carbonate and organic carbon in sediments on the continental borderland off the southern California coast. Carbonate-rich sediments were laid down in relatively warm water during interglacial times. Conversely, during glacio-eustatic low stands, offshore sediments were low in carbonate but high in turbidites and terrigenous detritus derived from coastal highlands and the exposed continental shelf (Emery, 1952; Emergy and Bray, 1962; Gorsline and Pao, 1976; Gorsline and Prensky, 1975; Gorsline and others, 1968).

Despite the abundant data from these nearshore studies, there are still problems concerning the exact time and depth of Wisconsinan low stands of sea level. Better "resolution" appears to be forthcoming from oxygen-isotope analysis of deep sea cores. For example, recent interpretation of a central Pacific core (Shackleton and Opdyke, 1973, p. 45) suggests that sea level during stage 4, approximately 70,000 years ago, was about 80m below the present; but fell to almost 120m during stage 2, approximately 17,000 to 20,000 years B.P. (Fig. 7). These depths and approximate times are quite comparable to those deduced from geomorphic evidence in many coastal areas, and from radiocarbon dating of middle-latitude continental glacial sections.

Mid-Wisconsinan High Stand

As controversial as the depth and precise ages of post-Stage 5 (Wisconsin) low stands is the time and relative elevation of the "mid-Wisconsinan" interstadial sea level. Based on limited radiometrically-dated shallow water shells and nearshore peat, the "mid-Wisconsinan" sea level (marine oxygen isotope stage 3; Fig. 7) has been construed as ranging from over 100 feet (30m) below sea level to at least several feet (2 m) above the present (Curray, 1961, 1965; Milliman and Emery, 1968; Mörner, 1971a).

Identifying and dating the mid-Wisconsinan high stand is usually beset by several problems: (1) radiocarbon ages for the period are few, compared with those for the post-Wisconsinan (Flandrian) transgression, and most are from shells rather than wood; (2) some dates are derived from active tectonic areas (Hopkins, 1967; Milliman and Emery, 1968); and (3) contamination by younger carbon, as low as 1 percent, typically yields finite dates in the range of 30,000 to 40,000 years B.P. (Mörner, 1971a; Olsson, 1968).

On the cliffed coasts of California a mid-Wisconsinan sea level above the present would likely be recorded by nips or minor planated platforms, but none have thus far been recognized. However, a stage 3 high stand of only a few feet (2 m) above the present may not be preserved owing to (1) a short time (few thousand years) available for cutting; (2) possible superposition, and thus not recognizable, on the more extensive stage 5 marine platforms; or, (3) obliteration by contemporary high-energy wave systems and coastal retreat.

Despite these complexities there are increasing data from the California coast to suggest that the mid-Wisconsinan sea, some 30,000 to 40,000 years ago, did not rise to the present level. This is indicated by the absence of mid-Wisconsinan estuarine deposits in San Francisco Bay (Atwater and others, 1977), the dearth of marine deposits which may have been laid down during this interval along the Malibu coast (Birkeland, 1972), and the lack of wave-cut notches, or any marine deposits younger than stage 5 beach sediments capping the first terrace in the Camp Pendlton-San Onofre Beach area (this report). However, a relative high stand of sea level (stage 3), 30,000 to 40,000 years ago, though not reaching the present level, may likely be recorded in continental sediments overlying first marine terrace deposits (stage 5) at the San Onofre Bluffs. This evidence is primarily in the form of carbonate-rich buried soils, usually indicative of climates warmer or less pluvial than middle latitude glacial epochs, and of periods of non-deposition and relative landscape stability.

Post-Wisconsinan (Flandrian) Sea Levels

Following the late Wisconsinan glacio-eustatic low stand (oxygen-isotope stage 2), there was a rapid rise in sea level about 20,000 to 5,000 years ago (Figs. 8 and 9). Coastal sediments laid down during this post-glacial rise have been deemed "Flandrian" from the well-documented sections in Belgium and the Netherlands (Flint, 1971). Because of the association with rapid retreat of continental

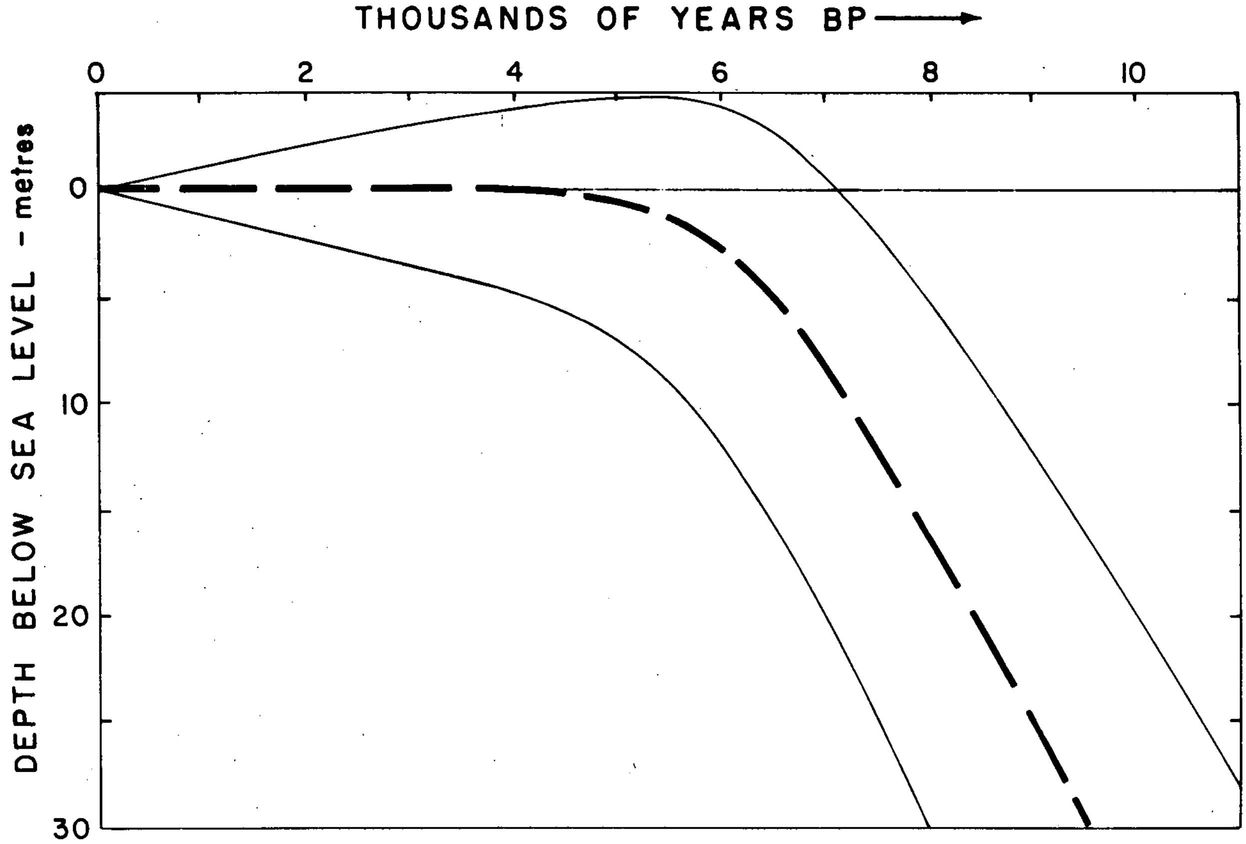


Fig. 8 Enclosing envelope and mean of 15 published curves purporting to show the glacio-eustatic rise of sea level in Holocene time (Flandrian transgression) Modified after Curray and Shepard (1972).

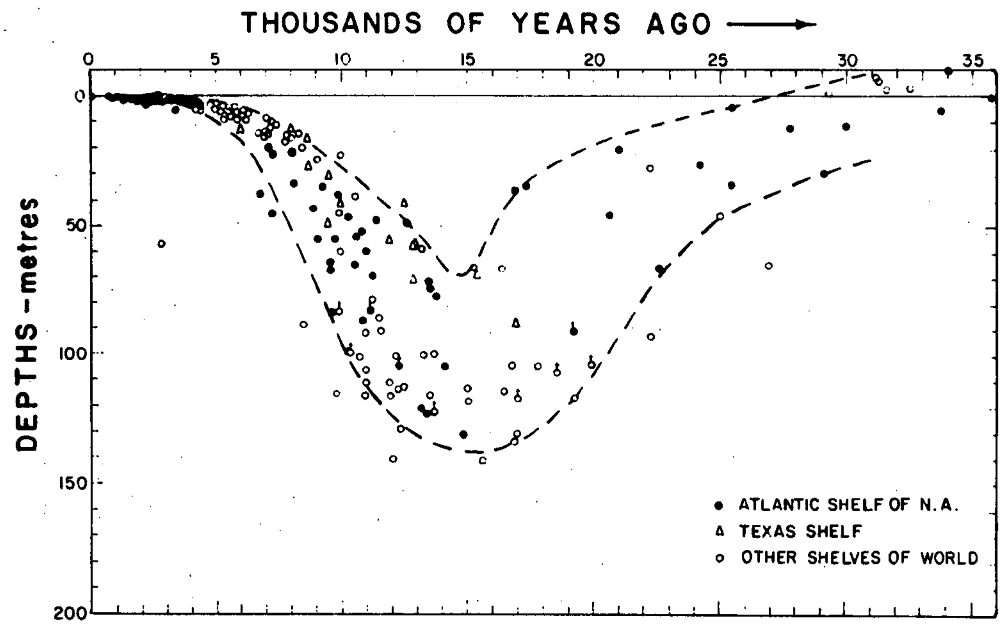


Fig. 9 Envelope defining change of sea level since "mid-Wisconsin" time (marine isotope stage boundary 2-3. of Shackleton and Opdyke, 1973, p. 49). Age and depths from radiometrically dated shallow-water shells, salt-marsh peat, wood and coral. Data from Milliman and Emery (1968) and Emery and others (1971, p. 383).

ice in North America, this sea level rise is also called "post-Wisconsinan" or "post-glacial hemicycle," though the oxygen isotope stage 1-2 boundary is a less provincial designation and one likely to be used more frequently in future coastal studies.

The abundance of radiometrically-datable materials, mainly shells, wood and peat, have made the post-Wisconsinan sea level change the best documented of the Quaternary. Yet here, too, there are conflicting interpretations about the rate and timing of sea level fluctuations, and the impact on coastal erosion -- all bearing on the late Quaternary evolution of the CP-SOSB area.

Rate of Rise:

A "convergence" of data points indicates that the post-Wisconsinan sea rose to the present level about 5,000 years ago (Figs. 8 and 9). There are, however, questions about minor fluctuations since that time. From many coasts of the world, for example, there is evidence suggesting that sea level was 5 or 6 feet (1.5 or 1.8m) higher than the present some 4,000 to 5,000 years ago (Hopley, 1969; Fujii, 1969; Fairbridge, 1961). Alternatively, however, there are increasing data to show that many presumed "two-metre" shoreline notches and terraces have resulted from man's activity or are merely the result of contemporary high wave energy or of coastal tectonic movement (Bloom, 1977; Curray and Veeh, 1970; Mörner, 1971b, 1971c; and Newell and Bloom, 1970).

The effect of sea level rise on coastal development in California during Holocene time has been recognized and described in many studies. For example, the rise of sea level during the last 10,000 years has essentially caused thalassostatic sedimentation and formation of the modern Sacramento-San Joaquin Delta in central California (Shlemon, 1971; Shlemon and Begg, 1975). In San Francisco Bay, deep borings for engineering investigations of proposed bridges have yielded radiometrically-datable sediments indicating that sea level rose about 2 cm/yr some 9,500 to about 8,000 years B.P.; declining to 0.1-0.2 cm/yr from approximately 6,000 years B.P. to the present (Atwater and others, 1977, p. 11). Offshore southern California dating of inorganic carbonates suggests that marine sediments laid down about 6,000 to 7,000 years ago may correlate with the "hypsithermal interval" usually regarded as a short-lived epoch of warming during the Holocene.

The post-Wisconsinan transgression is also recorded in coastal sediments of the Camp Pendleton-San Onofre State Beach area. Although not radiometrically dated, about 120 feet (36m) of "reduced sediments" are recorded in numerous water-well logs and bridge borings which penetrate the lower floodplain of the Santa Margarita River immediately south of Stuart Mesa (Fig. 1). Similar post-Wisconsinan sediments occur in estuaries elsewhere along the California coast as silty and clayey organic-rich deposits overlying gravel and coarse-grained sands of ancient river deposits which graded to the "late-Wisconsinan" sea (stage 2).

<u>Coastline Erosion</u>:

Since sea level reached its approximate present position about 5,000 years ago, the Camp Pendleton-San Onofre State Beach coastline has been retreating. The rate of erosion generally depends on two distinct yet often interacting causes: tectonic deformation of coastal landforms, and "normal" differential erosion induced by wave action, and coastal mass movements.

Erosion owing to Holocene tectonism has been documented at several localities along the central and southern California coast. Lajoie and others (1972), for example, have pointed out that historical seismicity, deformation of post-100,000 year old marine terrace deposits, and Holocene faulting have given rise to cliffed coasts in the Half Moon Bay area now undergoing active undercutting and collapsing as large landslides. Similar topography is well known from the Palos Verdes Hills of southern California (Woodring and others, 1946) where spectacular landslides and active cliff recession occur along zones of weakness and perched groundwater where rocks of varying lithology are juxtaposed by faults.

Yet active cliff retreat is still occurring in southern California coastal areas known to be seismically quiescent during the Holocene: here differential coastal erosion

erosion is caused mainly by concentrated high energy wave systems in the beach and swash zone, often "amplified" by local topographic configuration. The rate of sea cliff retreat varies greatly depending on the relative resistance of exposed country rock. Chert and other siliceous rocks, for example, often form headlands which, according to historical observation, have remained essentially intact for at least the last 50 years (Minard, 1971). Where coastal bluffs are underlain by relatively nonresistant marine or continental sands and shales (e.g. Monterey, San Mateo and Capistrano formations), active coastal undercutting has given rise to spectacular landslides. This is especially evident in the CP-SOSB area where rotated blocks, some 100 feet (30m) high and over 8,000 feet (2,400m) long (Fig. 10) have slumped and are being undercut in the present wave regime (Blanc and Cleveland, 1968; Cleveland, 1975). Detailed mapping (Fugro, 1977a, 1977b) shows that these coastal landslides are not related to late Quaternary faulting.

The relative stability of the Camp Pendleton-San Onofre State Beach coast is also indicated by the magnitude and rate of shoreline erosion that has occurred within, approximately, the last 5,000 years. Post-stage 5 continental deposits overlying the marine platform in the Target Canyon area (Fig. 1) range in thickness from about 30 to 100 feet (9 to 30m) depending on proximity to source. A reconstructed surface gradient on these sediments, projected offshore,

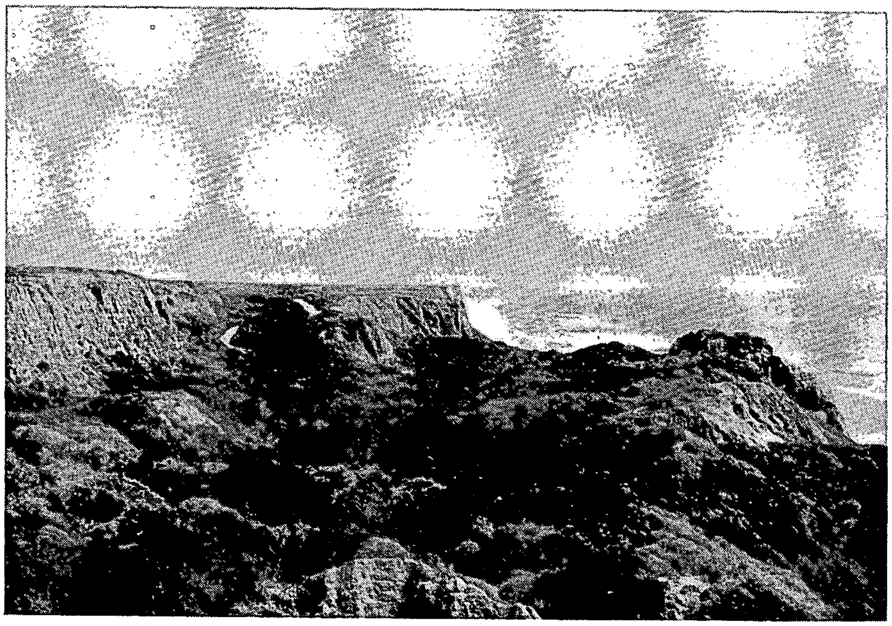


Figure 10. Coastal retreat by landslides, slumps and rotated blocks.

intersects the estimated 5,000 year old sea level approximately 35,000 feet (10,500m) seaward of the present cliffs. Assuming no glacio-eustatic fluctuations of sea level significantly above or below the present, shoreline retreat in the Camp Pendleton-San Onofre State Beach area would thus have averaged about 0.7 ft/yr over the last 5,000 years (0.2m/yr). This rate is a first approximation only, for there was likely much faster erosion in landslide areas. Nevertheless this approximate erosion rate compares quite well with short term measurements elsewhere based on topographic and bathymetric changes depicted on old maps and photographs. For example, Shepard (1976, p. 63) calculated sea cliff retreat in the San Diego area as averaging 0.3m/yr between about 1918 and 1947. Pipkin (1974, p. 44), from a 40-year photographic record, estimated cliff erosion in the Palos Verdes Hills to range from about 0.2 to 0.3m/yr. Tinsley (1972, p. 58) calculated retreat of the San Mateo County coast as an average 0.3m/yr, in some cases, based on accounts of Spanish explorers starting almost 200 years ago. And Cooper (1967, p. 68), from a short term record, observed that coastal retreat near the mouth of the Salinas River in Monterey County presently averages about 0.5m/yr.

Coastal erosion in the CP-SOSB area is also occurring as numerous small landslides heading in steep-walled arroyos in the San Onofre Bluffs. These mass-movements, apparently ubiquitous on the southern California coast (Blanc and Cleveland, 1968; Cleveland, 1975), are but minor landforms superimposed on larger, rotated coastal blocks.

In summation, there is active coastal erosion in the CP-SOSB area, but the rate, when extrapolated over the last 5,000 years, is comparable to or less than modern cliff retreat at many other localities in central and southern California. In essence, shoreline configuration and estimated rates of coastal erosion suggest that the Camp Pendleton-San Onofre State Beach coast has been relatively stable throughout at least Holocene time, with cliff retreat resulting from normal shore processes.

LATE QUATERNARY TERRACES, TERRACE FILL AND CHANNEL DEPOSITS

The term "terrace" is perhaps one of the most confused and misused in geomorphological parlance. It has been indiscriminantly employed to describe a surface as well as underlying deposits. Also, frequently no discrimination is made between fluvial and marine terraces; nor between coastal terraces related genetically to late Quaternary changes of sea level, and those whose origin was controlled dominantly by changes in climate and related alternations of vegetation and of sediment supply.

Terraces are the dominant landforms in the CP-SOSB coastal area; and the age of many, both fluvial and marine, is documented in this section. The term "terrace" as used in this report, is defined as a geomorphic surface. Some terraces, whether marine or fluvial, may be underlain by sediments (Fig. 4). The genesis of some remains enigmatic, perhaps determinable only in the future when the complex interactions of late Quaternary climatic, tectonic, and sea level change are better understood.

Fluvial Terraces

Though often not directly traceable to coastal landforms, fluvial terraces and deposits are still excellent indicators of late Quaternary climatic change and possible tectonism. In the CP-SOSB area the most extensive fluvial terraces flank San Mateo Creek and the lower Santa Margarita River

(Fig. 1). The approximate age of these landforms, in particular those along the Santa Margarita River, can be deduced from their gradient, weathering characteristics (mainly soil profile development), and inferred association with late Quaternary sea levels. Both cut and fill fluvial terraces also occur as discontinuous remnants along Las Flores and Horno creeks, but these landforms are too poorly preserved for reconstructing a real geomorphic evolution.

San Mateo Creek

Fluvial terraces along San Mateo Creek have been identified in reconnaissance by Moyle (1973), Blanc and Cleveland (1968), and described briefly by Southern California Edison Company (1976). These terraces, in general, are poorly preserved, of limited extent, and often veneered by landslide or colluvial deposits derived from adjacent highlands. From reconnaissance, terrace remnants near the coast appear covered by reworked marine beach sands and sandy sediments derived from the Tertiary Capistrano or Monterey formations. Consequently, soil development on the terrace deposits does not reflect landform age, but rather epochs of younger erosion or colluviation. A typical soil is the Marina loamy coarse sand, characterized by a weakly-developed B (argillic) horizon (Bowman and others, 1973). Coarse-grained soils with this relative degree of profile development (Alfic Xeropsamments) are generally believed pre-Holocene in age, but younger than Sangamonian (stage 5), based on limited radiometric "calibration" along the California coast (Helley and others, 1972; Borst and others, 1975; Dupre, 1975).

Santa Margarita River

More extensive and useful for reconstructing the late Quaternary history of the CP-SOSB area are the discontinuous paired terraces flanking the lower Santa Margarita River on Camp Pendleton. There terraces can be traced to within two miles (3.2km) of the coast where the Santa Margarita River crosses old beach ridges and marine terraces (sec. 10, T. 11 S., R. 5 W.).

Pre-Wisconsinan Terrace Deposits

Two fill-terraces are well preserved immediately north of the Camp Pendleton Air Base (sec. 13, T. 10 S, R. 5 W.) on the north side of the Santa Margarita River. Surface elevations are approximately 60 and 160 feet (18 and 48m), respectively, above the floodplain. Terrace extent is insufficient, however, to project gradients downstream for comparison with the present profile or with buried ancient channels identified in water-well logs.

The absolute age of these terraces and their underlying deposits is presently unknown. However, the fluvial sediments underlying the lowest terrace are primarily granitic and give rise to the Ramona soil (Typic Haploxeralf). This soil is characterized by a 40-inch (1m) thick argillic horizon with moderate prismatic to blocky structure and many clay films. This degree of profile development on medium-grained granitic sediments is characteristic of soils dated geomorphically and radiometrically elsewhere as at least 100,000 years old

(Arkley, 1962; Janda and Croft, 1967; Shlemon, 1967, 1972; Hansen and Begg, 1970; Marchand and Harden, 1976).

The lower terrace sediments contain at least one moderately-developed buried soil which, from reconnaissance, appears to have developed on the overbank and backswamp deposits in an ancestral Santa Margarita River floodplain. The ultimate extent and paleoclimatic significance of the buried soil, is unknown; however, its presence underlying a surface at least 100,000 years old is indicative of the complex and extensive fluvial stratigraphic and geomorphic assemblage preserved in the lower Santa Margarita River valley within a few miles of the coast.

Buried Channel Deposits

The lower Santa Margarita River preserves yet another distinctive stratigraphic marker bearing upon the late Quaternary evolution of the coastal area. This, as noted previously, is a buried channel gravel of probable "late Wisconsinan" age traceable in the subsurface by means of water-well logs and bridge borings from about 25 feet (8m) in elevation 10 miles (16 km) inland to approximately 120 feet (36m) below present sea level (Interstate Highway 5) one mile (1.6 km) from the coast (Fig. 11).

Some 15 water-well logs, representative of subsurface data available for the lower Santa Margarita River, show the typical gravels and boulders of the buried channel (Fig. 11).

ANCESTRAL "LATE-WISCONSINAN" BURIED CHANNEL OF THE SANTA MARGARITA RIVER, SAN DIEGO COUNTY, CALIFORNIA (1)

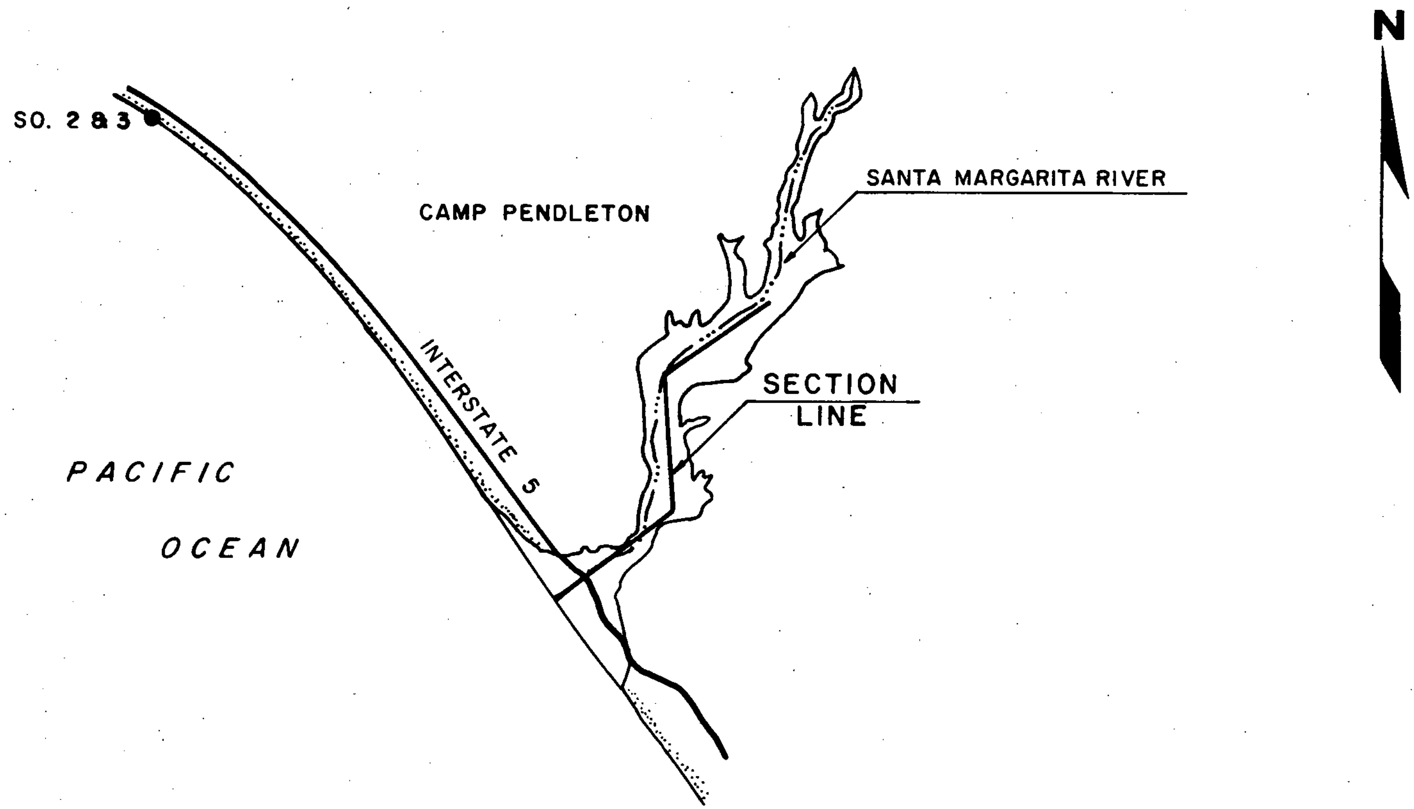
(1) Identification and interpretation from water well logs provided by Natural Resources Office, Camp Pendleton. Location of selected borings indicated by township, range, and 40-acre segment within section (e.g. 10 S - 5 W, 2K1); distance (in feet) and direction from longitudinal profile down present river valley indicated under well identifier (e.g., 100' W).

(2) Lithologic description generalized from drillers' logs.

(3) Gradient of modern river, and top and bottom of buried channel given in Table 2

(4) Channel age approximately 17,000 - 20,000 years BP graded to "Late-Wisconsinan" glacio-eustatic sea level ca. 350-400 feet below present (see text for discussion).

FIGURE 11



LOCATION MAP FOR SECTION BURIED
CHANNEL SANTA MARGARITA RIVER

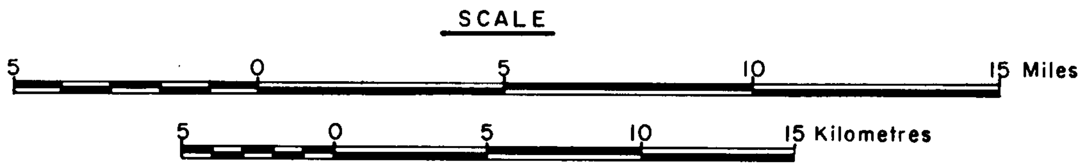


FIGURE 11a

To the east, the ancient channel gravels merge with modern Santa Margarita River sediments; to the west the deposits are traceable to -150 feet (-45m) where they thicken to 75 feet (23m) about 5 miles (8km) from the coast. The basal contact can be projected to at least 210 feet (63m) below sea level at well log 11S-5W-10B (Fig. 11).

The approximate gradients of the top and base of the old channel are 19 and 29 ft/mi (3.6 and 5.4m/km) respectively (Table 2). Compared with the modern Santa Margarita River, the base of the ancestral channel is more than twice as steep. Projecting this basal gradient offshore to a sea level lowstand of -350 feet (-105m) suggests that the late Wisconsinan shoreline was about 2 miles (3.2km) west of the present coast.

The absolute age of the ancestral Santa Margarita River channel is unknown. However, the preponderance of the "boulders" and gravels, as described in drillers' logs, distinguish braided stream deposits probably graded to the last glacio-eustatic lowstand of sea level about 17,000 to 20,000 years ago, equivalent to marine oxygen-isotope stage 2 (Figs. 7 and 9). Buried channels of this age and at comparable depths have been reported from many localities along the California coast (Upson, 1949; Shlemon, 1971, 1972; Dupre, 1975; Atwater and others, 1977). In essence, the ancestral channel of the Santa Margarita River is a strati-graphic marker useful to assess any post-late Wisconsinan

Table 2

Gradients of the Lower Santa Margarita River,

Modern and Buried Channel[1]

	Gradient		Gradient Control Points and Distance		
				Distance	
	ft/mi	m/km	Location	Miles	Km
Surface profile	12.2	2.3	Well 10S-4W,7A1 to Shoreline	9.7	15.5
Buried Channel					
Channel top	19.3	3.6	Well 10S-4W, 7H1 to Shoreline	9.3	14.9
Channel base	28.7	5.4	Well 10S-4W, 7R2 to Well 11S-SW, 10B	6.5	10.4

[1] Computed from topographic (Las Pulgas, Oceanside, and Morro Hill quadranges) and well log control (Fig. 11).

deformation. As shown in Figure 11, within resolution of water-well log lithologic description and elevation accuracy, no such deformation is observable.

With the rapid deglacial rise of sea level starting about 17,000 years ago, thalassostatic sedimentation began along the lower Santa Margarita River. As gradient was reduced, possibly because of a climatically-controlled change in hydraulic regimen, the Santa Margarita River laid down fine-grained deposits, initially oxidized, and later reduced clays and muds. Since sea level stillstand approximately 5,000 years ago, few boulders or gravels reach the present coast. Rather, an estuary has formed with local coastal progradation giving rise to bay spits and barriers.

The latest Pleistocene-Holocene stratigraphy (Flandrian) underlying the lower Santa Margarita River is a "mega-fining-upward" depositional cycle of gravels overlain progressively by sands, silts and clays. Several mechanisms may account for the origin of this sequence. The deglacial rise of sea level is a likely cause, reducing stream gradient and resulting in loss of competence and carrying capacity. This mechanism has been invoked primarily in the lower Mississippi River Valley (Fisk, 1944; Bernard and others, 1962), and to a lesser degree in the San Francisco Bay area (Atwater and others, 1977). But the "mega-fining-upward" sequence has also been reported from interior regions; for example, in the Great Plains (Schumm, 1965), and in the Central Valley of California (Shlemon, 1967, 1972) where rising base levels would have had little if any effect on stream competence. It appears, therefore, that climatically-controlled changes in sediment load, perhaps associated with decreasing glacial outwash or fluctuations in temperature, precipitation, and vegetation may have been controlling factors. Whatever its ultimate origin, the "mega-fining-upward" sequence of the Santa Margarita River is a record of cyclic deposition and a time marker useful to reconstruct the late Quaternary geomorphic evolution of the southern part of the CP-SOSB coastal area.

Marine Terraces

The marine terraces and underlying deposits of Camp Pendleton are some of the most dramatic, yet least known in southern California. To some degree this unawareness stemmed from access difficulty to portions of the base subject to military maneuvers. Therefore, the data and interpretations indicated in this report to a great extent are based on the recent, detailed mapping of marine terrace deposits (Ehlig, 1977), and the detailed logging of post-stage 5 deposits underlying the San Onofre Bluffs, afforded by excellent exposures in coastal badland topography and in new road cuts.

Pre-Stage 5 Deposits

As synthesized by Palmer (1964) the marine terraces of Camp Pendleton were identified mainly by topographic expression, usually a "break in slope" taken to be a high-level marine abrasion platform or beach deposits overlying it. A recent map by Moyle (1973) has identified several subparallel terrace remnants of increasing elevation, well developed in the central coastal area of Camp Pendleton near Las Flores Creek (Fig. 1). But these terrace deposits are not distinguished from younger, continental (nonmarine) piedmont fans built out over marine sands and gravels of the first emergent terrace underlying the San Onofre Bluffs. The detailed mapping of Ehlig (1977) and geomorphic reconnaissance of seaward-facing drainage divides indicates that many breaks in slope thought to be marine erosion in origin are, in fact, no more than remnants of old, now highly dissected, alluvial fans laid down on probable late Pleistocene equivalents of the present San Onofre Bluffs. However, there are at least 9 distinct marine terrace deposits, 8 of which are unburied and lie at successively higher elevations above the first terrace. As shown in composite section (Fig. 12), the pre-stage 5 marine terrace deposits range in elevation from about 250 feet to 1250 feet (75 to 375m). Only a range, rather than a specific value, can be given for the elevation of each terrace, for (with few exceptions) the shoreline angles are not clearly exposed. The lowermost terrace deposits, designated 2 through 5, are best preserved; higher deposits occur mainly as gravel veneers a few feet (1 m) thick (Fig. 12).

That the terrace gravels are marine is indicated by the presence of beach bars and well-rounded pebbles and cobbles.

MARINE TERRACE DEPOSITS
COMPOSITE SECTION, REPRESENTATIVE ELEVATIONS AND APPROXIMATE AGES
SAN ONOFRE STATE BEACH AND CAMP PENDLETON, CALIFORNIA

[Terrace deposits designated sequentially by number in circle; inferred age (years B P) shown in brackets]

NOTES

1. Section line bearing N 40° E; coastal intersection approximately 4 miles SE of San Onofre Unit 1.
2. Terrace deposits, mainly beach gravels, after Ehlig (1977); contour interval 25 feet; supplementary contours 5 feet.
3. Terrace elevation and gravel thickness composite, projected from outcrops between Station 19,000 and 22,000 of Ehlig (1977, Fig. 7). Distance (in feet) and direction of outcrop from section line shown above terrace number.
4. Terrace topography generalized; surface of San Onofre Bluffs from SCE base map, scale 1: 6,000.
5. Thickness of Terrace 1 deposits extrapolated from measured section in "Haul Road Canyon" (Station 35,500 of Ehlig, 1977); see text for discussion.
6. Age of Terrace 1 deposits interpretated from amino-acid dating (Lajoie and others, 1975); older deposits from inferred association with late Quaternary high stands of sea level, deduced from oxygen isotope and paleomagnetic stratigraphy of deep sea cores (Shackleton and Opdyke, 1972; 1976); see text for discussion.

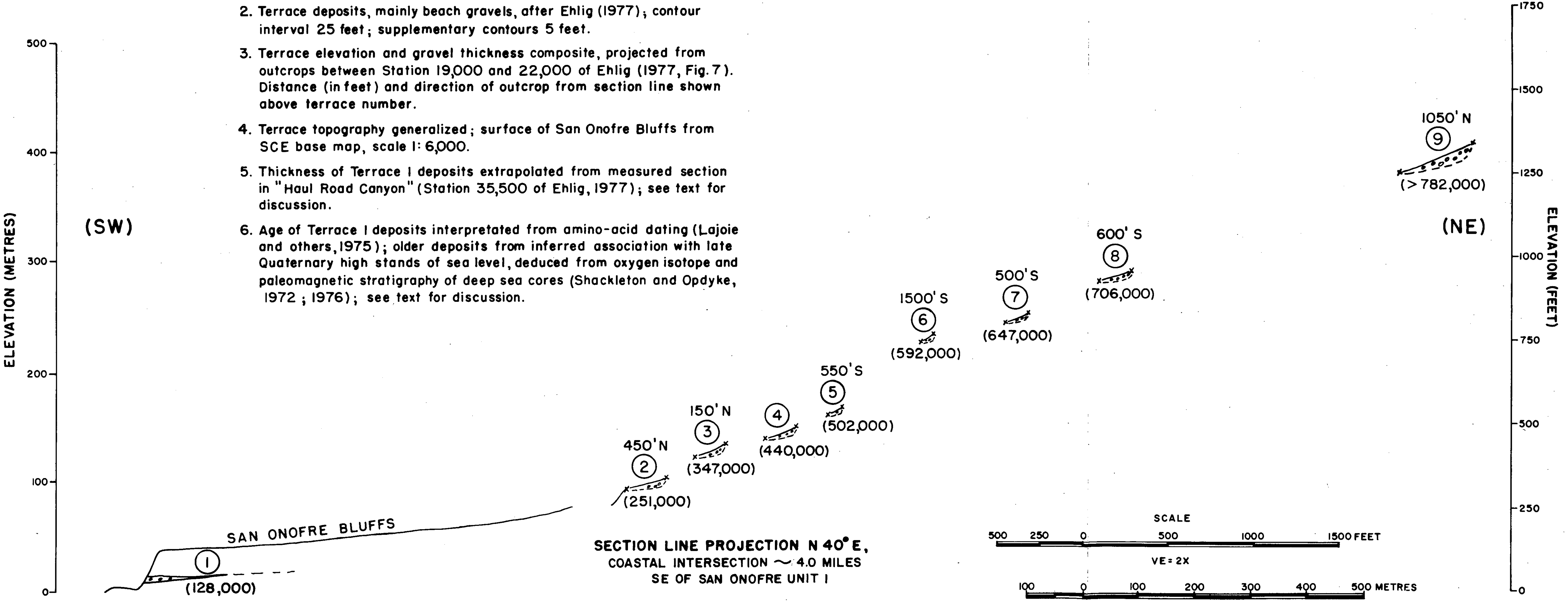


FIGURE 12

In addition, most gravels are volcanic, derived from the Jurassic Santiago Peak Formation in the Santa Margarita Mountains and transported to the coast by San Mateo and nearby creeks (Ehlig, 1977, p. 24).

Age

The age of the pre-stage 5 marine terrace deposits is based mainly by association with climatic and sea level changes deduced from oxygen isotope ratios in deep sea cores (Table 3). Terrace 1 deposits are about 125,000 years old (stage 5e) based on uranium-series and amino-acid dating (Ku and Kern, 1974; Kern, 1977; Wehmiller and others, 1977) and on faunal assemblage (G. L. Kennedy and J. R. Lajoie, personal communications, 1978). Terrace deposits topographically higher are interpreted to be progressively older. Terrace 2 at 325-345 feet (97 to 104m) is about 250,000 years old; terrace 3 at 375-410 feet (112 to 123m) is some 347,000 years old, etc., correlative to the stage oxygen-isotope boundaries and estimated ages of Shackleton and Opdyke (1973; Table 3).

Inspection of Figure 12 shows that there is a "break" in steps of elevation between terraces 1 and 2, and between 8 and 9. For example, whereas typically 50 to 150 feet (15 to 45m) vertically separate most terraces, there is almost 300 feet (90m) between the projected shoreline angle elevations of terraces 1 and 2. Conceivably, therefore, one or more intermediate-level terrace deposits may exist in this interval, but are as yet completely buried by the younger continental fan and colluvial sediments forming the San

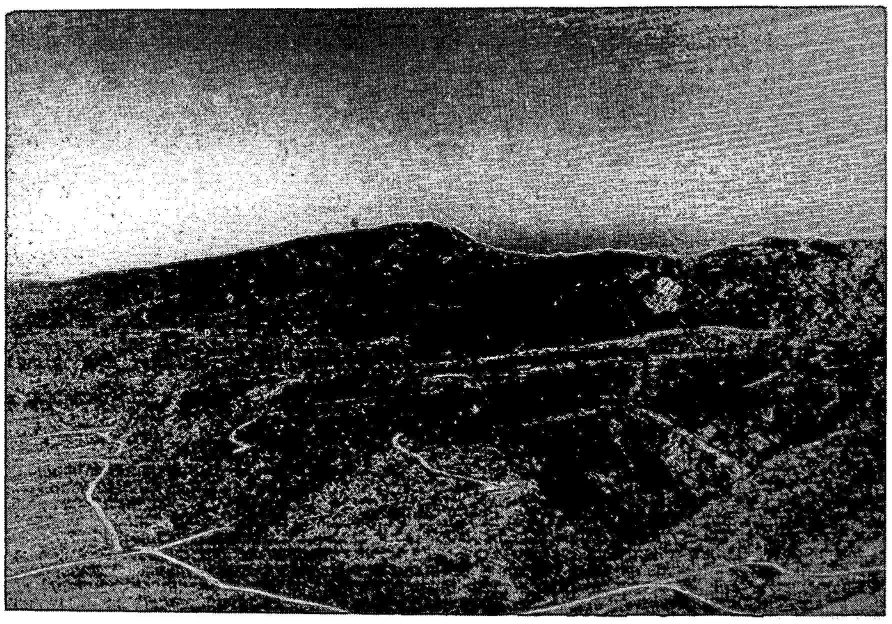


Figure 13. Marine terrace deposits 2 and 3, elevation approximately 340-400 feet (Table 3), Camp Pendleton.

TABLE 3

Designation and Approximate Age, Marine Terrace Deposits, Camp Pendleton - San Onofre State Beach, California

Terrace(1) No.	Terrace Elevation(2) (feet)	Age(3)	Marine Oxygen Isotope(4) Stage Boundary
1	55	128,000	5 - 6
2	325 - 345	251,000	7 - 8
3	375 - 410	347,000	9 - 10
4	445 - 480	440,000	11 - 12
5	500 - 530	502,000	13 - 14
6	725 - 750	592,000	15 - 16
7	805 - 820	647,000	17 - 18
8	925 - 950	706,000	19 - 20
9	1250 - 1310	782,000	21 - 22

(1) Regressive gravel bars and beach deposits; numbers 2-9 mapped by Ehlig (1977). Terrace 1 ("First Emergent") platform and beach deposits buried by post-stage 5 continental underlying San Onofre Bluffs. See also Fig. 12.

(2) Composite section projected N. 40°E. between stations 19,000-22,000 of Ehlig (1977, Fig. 7) from coastal intersection approximately four miles (7 km) SE of SO Units 2&3. Inferred shoreline angle indicated by upper elevation of terraces 2 through 9. Terrace 1 elevation projected from exposures in sea cliffs and in Target Canyon (see Fig. 16).

(3) Ages after Shackleton and Opdyke (1973, p. 49) based on post-Brunhes/Matuyama boundary (ca. 700,000 years B.P.) uniform sedimentation rate in deep-sea cores.

(4) Terrace 1 equivalent to Substage 5e; boundary designation from Shackleton and Opdyke (1973, p. 45 and 49) and Shackleton and Opdyke (1976, p. 455).

Onofre Bluffs. It is thus possible that the approximate ages given for terrace 2 and older deposits (Table 3) may be too young by a factor of at least "one terrace interval" as depicted in Figure 12.

Similarly, Terrace 9, the highest (Fig. 12), is a remnant only, preserved on the San Onofre Mountains at about 1,250 feet (375m) elevation. As such, it is almost 300 feet (90m) higher than Terrace 8, a topographic difference exceeding at least twofold the vertical elevations between successively lower terraces. It is possible, therefore, that intermediate terrace deposits may have been laid down but have since been eroded.

The general association of marine terraces and glacio-eustatic high stands of sea level suggests that late Quaternary deposits at least 780,000 years old are preserved in the Camp Pendleton area (Table 3). There may be topographically higher and presumably older terraces not yet identifed owing to either nondeposition or to subsequent erosion. In any event the flight of terraces at Camp Pendleton rivals in number and elevation the "classic" southern California sequence on the Palos Verdes Peninsula (Woodring and others, 1946).

Origin

The origin and elevation of all marine terraces older than about 100,000 years has been and still is equivocal. Hypotheses range from local tectonic uplift, sea floor spreading and expansion of ocean basins causing base level lowering, to climatically-controlled, glacio-eustatic fluctuations of the sea. In part, all hypotheses may be applicable to the Camp Pendleton area.

Ehlig (1977) has suggested that the entire marine terrace sequence at Camp Pendleton owes its origin to a gradual recession of sea level since lower Pliocene time, based on no evidence for overlapping terrace deposits, and on relative continuity of terraces laterally along the coast (p. 25-26). To some degree this line of reasoning is supported by calculations of Cenozoic sea floor spreading and the resulting continual lowering of sea level (Atwater and Molnar, 1973).

Other studies, however, indicate that the entire Pacific coast has been undergoing general uplift as well as local deformation along specific fault zones. For example, the elevations of most marine terrace deposits along the southern California coast above about 100 feet (30m) have been attributed to broad regional uplift, tilting, and warping; namely, the Malibu coast (Birkeland, 1972), and the Palos Verdes Hills (Woodring and others, 1946; Warhaftig and Birman, 1965), and the San Diego coastal area (Kennedy, 1975; Kern, 1977). In addition, preliminary correlation of terraces near San Diego with those in the CP-SOSB area suggests that at San Onofre terraces slope progressively more steeply toward the coast with increasing elevation, presumably indicative of continuing tilting to the southeast accompanying uplift in middle and late Pleistocene time (McCrory and Lajoie, 1977). This interpretation may also have some support from historic levelling data suggestive of up-to-the-northwest tilt along the coast from La Jolla to about 20 miles (32km) north of San Onofre (Wood and Elliott, 1977).

The amount of apparent uplift and tilt may be more an artifact of terrace preservation rather than true deformation. This is illustrated in Figure 14, where regressive deposits on a gently-sloping abrasion platform are shown immediately following deposition (time A) and after later coastal erosion (time B). As today, cliff retreat in "high terrace time" was probably not uniform along the entire CP-SOSB coast, but rather, locally increased at headlands. For example, because of differential cliff retreat, deposits originally laid down from about 0 to 30 feet (0 to 9m) at time A would be exposed at many intermediate elevations by time B. Those regressive deposits preserved only near the shoreline angle (terrace back edge) would thus appear to have been uplifted and tilted (Fig. 14).

Despite these apparent contradictions for origin of "high level" marine terrace deposits there is perhaps truth in both hypotheses. First, Pleistocene glacio-eustatic changes of sea level have long been documented and cannot be denied; only controversial is the exact timing and magnitude of these fluctuations. In this regard, oxygen isotope analyses of deep sea cores identify another factor of

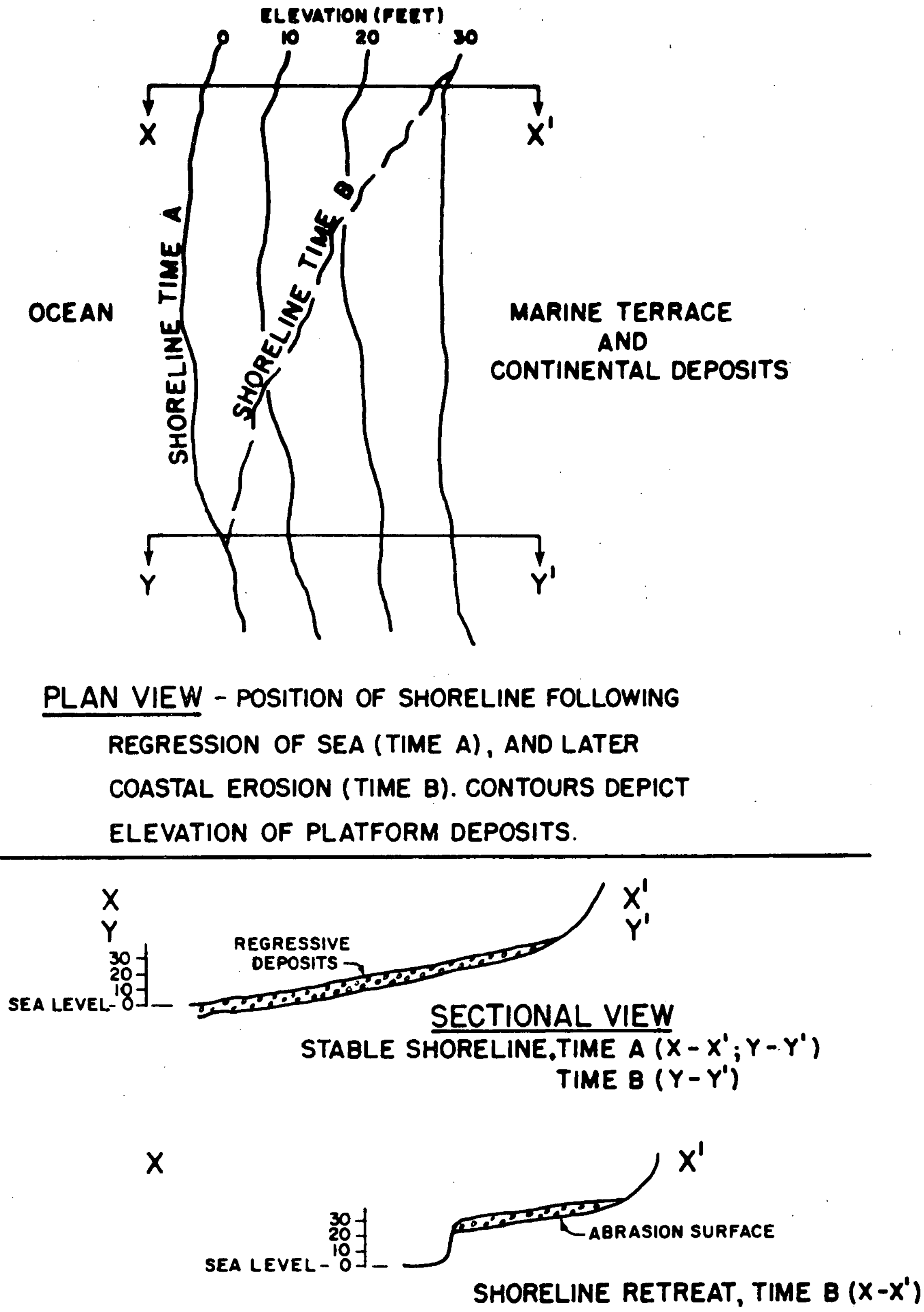


FIG. 14. Irregular coastal erosion (shoreline retreat) causing marine terrace deposits to appear differentially tilted and uplifted. Compare elevation of terrace deposits and abrasion platform along section X - X' following shoreline retreat between time A and B; see text for discussion.

significance; namely, that except for an interglacial high stand about 125,000 years ago (Stage 5e) sea level for probably all of middle Pleistocene time (approximately 130,000 to 700,000 B.P.) has not been higher than the present (Figs. 6 and 7; Shackleton and Opdyke, 1973, p. 50). Thus, it is highly probable that the marine terrace deposits at Camp Pendleton were laid down during high stands not exceeding the present, and therefore the contemporary high elevations are consistent with interpretations of continuing slow uplift upon which has been superimposed glacio-eustatic fluctuations of the sea.

The second hypothesis for origin of high level marine terraces also postulates glacio-eustatic fluctuations, but superimposed on gradually falling sea levels rather than on an uplifting coast. Few data are thus far available to determine the absolute rate and amount of sea level decline owing to plate movement and sea floor spreading, although preliminary estimates have been made (Bullard, 1969; Bloom, 1971). Additionally, the impact of water loading on coastlines is only imperfectly known (Bloom, 1967; Walcott, 1972), and the magnitude of such hydroisostatic deformation is tenuous at best.

In summation, the marine terrace deposits topographically higher than the San Onofre Bluffs at Camp Pendleton seem to span most of Middle Pleistocene time. Continuity of terraces, especially the lower ones indirectly dated as between about 250,000 to 500,000 years old, suggest no post-terrace fault displacement, at least within the resolution afforded by mapping and elevation data obtained thus far. Terrace elevations appear related both to slow uplift as well as to falling sea levels in middle and late Pleistocene time upon which were superimposed several glacio-eustatic fluctuations. Terrace uplift and tilt, suggested by increasing elevations from the San Diego to the CP-SOSB area, may be more apparent than real. Analogous to the younger, better preserved stage 5 deposits, the higher level marine terraces near San Onofre are preserved only near original shoreline angles. Southward, however, terrace deposits are more extensive and preserved more fully and at a wider range of elevations. Thus at least a substantial component of apparent terrace uplift in Middle and Late Pleistocene time (McCrory and Lajoie, 1977) must be viewed in light of differential coastal erosion and selective preservation of terrace deposits.

Terrace 1 Deposits (First Emergent Terrace)

The most extensive marine terrace in the CP-SOSB area is the first above sea level exposed clearly in sea cliffs and coastal arroyos for over eight miles (12km) from SO Units 2&3 on the north to Las Flores Creek on the south (Fig. 15).

One of the most striking features of Terrace 1 is its almost straightedge appearance in sea cliffs where it truncates underlying Tertiary sandstone and siltstones of the Monterey and San Mateo formations. There bedrock units

Figure 15. Planar contact of Terrace 1 in sea cliffs between SO Units 2&3 and Las Flores Creek.

have provided abundant coarse sand which acts as a surf zone abrasive. With few exceptions, the Tertiary bedrock itself is relatively nonresistant to surf abrasion, thus giving rise to a planar contact readily traceable almost a mile (1.6km) inland in canyons and roadcuts (Fig. 16). It is highly probable that the Terrace 1 deposits in the CP-SOSB area, as those well-documented from the central California coast (Bradley, 1957, 1958), were laid down as a regressive sequence when the sea retreated from its stage 5 glacio-eustatic highstand. Near the shoreline angle (terrace back edge), fine-grained beach sands are mixed with sediments derived from adjacent cliffs. Seaward, these sediments grade into coarse-grained marine sands, transported by long-shore drift, and finally into boulders and cobbles mixed and moved in the surf zone primarily during time of high-energy storms (Bradley, 1958). And this entire regressive sequence is clearly exposed in the CP-SOSB coastal area.

Basal marine gravels on the Terrace 1 abrasion platform range in thickness from approximately 2 to 6 feet (0.6 to 2m) and grade upward into coarse-grained sands and shell fragments. The cobbles and boulders are well-rounded indicative of reworking in a high-energy surf zone. Inland, as exposed in steep-walled arroyos and in roadcuts, the marine gravels thin to a feather edge and are replaced by beach sands or terrestrial sediments immediately overlying the platform. Beach sands, derived from local drainages and reworked from Tertiary sediments cropping out in adjacent

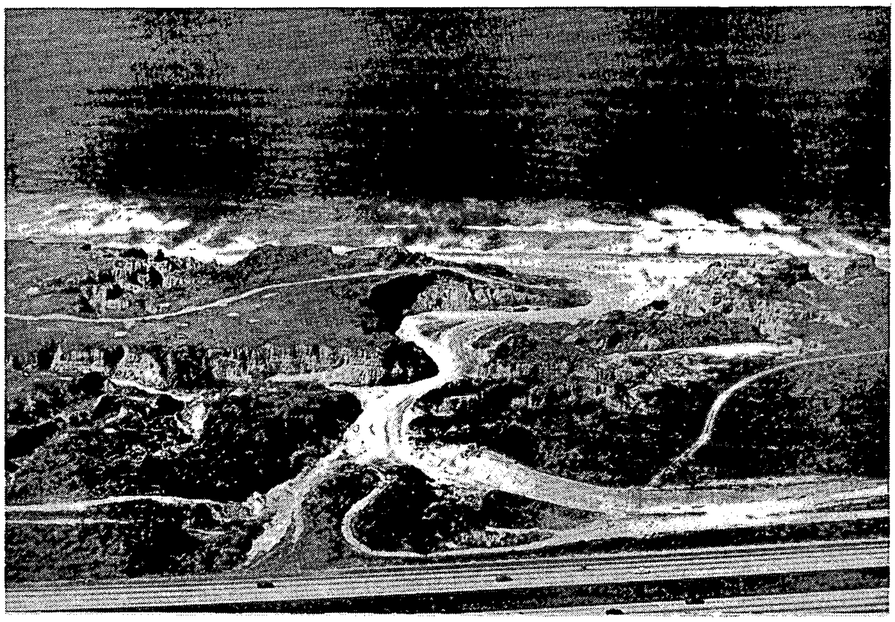


Figure 16. Target Canyon and "haul road" exposures of Terrace 1 platform and deposits, and overlying continental sediments.

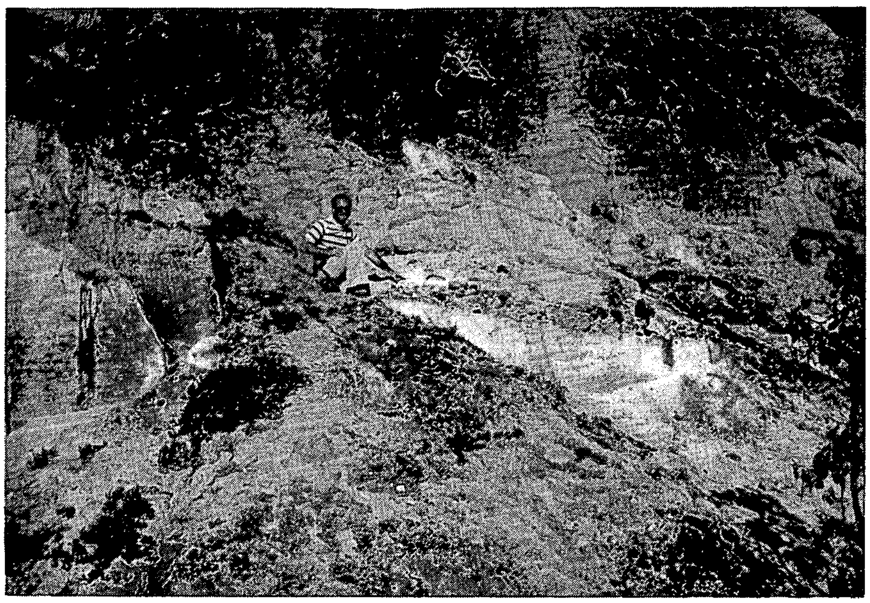


Figure 17. Terrace 1 marine deposits with fossil assemblage containing the mollusc <u>Protothaca</u> collected for amino-acid dating; sea cliff exposure, Camp Pendleton-San Onofre State Beach boundary.

sea cliffs, were laid down in a neritic environment as indicated by relative stratigraphic position and the frequent occurrence of mollusc borings. Fossils associated with these sands are common only locally, the best known site being sea cliff exposures at the boundary between Camp Pendleton and San Onofre State Beach (Fig. 17). Here, the faunal assemblage contains the mollusc Protothaca, useful for amino acid dating (Wehmiller and others, 1977).

The absolute age of the marine deposits overlying the Terrace 1 abrasion platform has only been recently determined by amino-acid assay. Even before, however, there was abundant evidence from radiometrically-dated fossils elsewhere on the southern and central California coast, and from reconstruction of worldwide sea levels, to indicate an age of about 120,000 years B.P. The underlying marine abrasion platform upon which the fossils rest is approximately 125,000 to 130,000 years old, associated with marine oxygen isotope substage 5e, an interglacial highstand of sea level recognized along almost every coast of the world. This is based on faunal assemblage and on correlation to radiometrically dated terrace deposits elsewhere in southern California (Ku and Kern, 1974; Kern, 1977; Lajoie and others, 1975; Wehmiller, 1977).

Invertebrate fossils recently collected from Terrace 1 deposits near the CP-SOSB boundary yield a rich assemblage of over 60 molluscan species useful for relative dating (Table 4). According to paleoecological interpretations of G. L. Kennedy, Los Angeles County Museum of Natural History (personal communication, 14 February, 1978):

> Almost all of the species are ones which would occur in the Californian Province today. Because of the general lack of cool water forms, and the fact that southern extralimital forms are not found in outer coast fossil exposures . . . ., I think the fauna would be representative of the warm water Substage 5e of the isotopic record . . . ., i.e., would be 120-125 ka old.

In addition, newly reported amino-acid dating of <u>Protothaca</u> derived from the Terrace 1 collection indicates an age of about 125,000 years (K. R. Lajoie, personal communication, April 1978), supporting a stage 5e age for the marine deposits.

TABLE 4

Preliminary list of species from LACMNH loc. 5074, sea cliff along northwest corner of Camp Pendleton, San Diego County, California

MOLLUSCA: BIVALVIA

Chama arcana
Clinocardium sp. indet.
Corbula luteola
Cryptomya californica
Donax gouldii
Entodesma saxicola
Gari californica
Kellia laperousii
Leporimetis obesa
Leptopecten latiauratus
Macoma nasuta
Nettastomella rostrata
Ostrea lurida
Penitella penita
P. sp.
Petricola carditoides
Platyodon cancellatus
Protothaca staminea
Saxidomus nuttalli
Semele decisa
Tivela stultorum
Trachycardium quadragenarium
Transennella tantilla
Tresus nuttallii
Zirfaea pilsbryi

MOLLUSCA: GASTROPODA

Acanthina spirata
Acmaea mitra
Amphissa versicolor
Bittium? or Cerithiopsis? sp.
Borsonella sp.
Bursa californica
Calliostoma canaliculatum
C. gemmulatum
C. ligatum
C. tricolor
Conus californicus
Crepidula adunca
C. norrisiarum
C. onyx
Crepipatella lingulata
Crucibulum spinosum
Diodora aspera
"Fusinus" sp. or spp.
Megasurcula carpenteriana
Mitrella carinata
Nassarius delosi
N. fossatus
N. mendicus s.s. or N. m. cf. indisputabilis
M. m. cooperi
N. perpinguis
Neverita reclusiana
Ocenebra spp. (2)
Olivella biplicata
O. pycna
Ophiodermella ophiodermella
Polinices lewisii
Pteropurpura festiva
Serpulorbis squamigerus
Tegula aureotincta
T. eiseni
T. funebralis
T. montereyensis
Terebra sp.

MOLLUSCA: POLYPLACOPHORA

Chiton valves, 2 species

MOLLUSCA: SCAPHOPODA

Dentalium neohexagonum

ANNELIDA: POLYCHAETA

Polydora sp., ? P. commensalis
Spionidae, indet.

Faunal assemblage from Terrace 1 deposits, Camp Pendleton, California (SW 1/4, sec. 3, T. 10 S., R. 6 W., San Onofre Bluffs Quadrangle).

Identification by G. L. Kennedy; Los Angeles County Museum of Natural History, Invertebrate Paleontology, 14 February 1978

CONTINENTAL SEDIMENTS

In addition to the fluvial terrace and channel deposits of San Mateo Creek and the Santa Margarita River, other continental sediments are abundant in the CP-SOSB area. These have been laid down primarily by a hierarchy of drainages as coalescing alluvial fan deposits (piedmont plain) giving rise to the San Onofre Bluffs.

These continental sediments are all younger than about 125,000 years old (stage 5), for they generally overlie Terrace 1 marine deposits. Their stratigraphy, as exposed in sea cliffs and roadcuts of the San Onofre Bluffs, records a complex history of terrestrial cutting and filling, replete with channel gravels, overbank silts and clays, and buried paleosols.

Drainage Classes

The post-stage 5 continental sediments have been laid down mainly by three classes of drainages (Cleveland, 1975): (1) class I or integrated drainages, of sufficient basin area to have graded to sea-controlled changes of base level; (2) class II or modern arroyos, typically steep-walled and heading within the coastal bluffs; ad (3) class III or ephemeral streams debouching from old marine terrace and highland terrain onto the San Onofre Bluffs.

Class I

The Santa Margarita River exemplifies a class I or fully integrated drainage in the CP-SOSB area. With a drainage area of 750 sq. miles (1940 sq. km) (U.S. Marine Corp. 1975) and sufficient flow rate, the Santa Margarita has long established connection to the sea, and has periodically cut and filled its lower course responding to climatically-controlled changes in hydraulic regimen and glacio-eustatic fluctuations of sea level. This is particularly evident by the late-Wisconsinan buried channel grading to a low stand of the sea.

A second class I drainage in the CP-SOSB area is San Mateo Creek. Although well-log control is insufficient to identify distinct Wisconsinan or earlier-age channels, existing subsurface data indicate that post-Terrace 1 sediments are at least 100 feet (30m) thick near the present coast, and that the lower 25 feet (8m) (elevation -40 to -65 ft) may be remnants of a 17,000 to 20,000 year old channel. Since the mid-Holocene stillstand of sea level about 5,000 years ago, San Mateo Creek has apparently prograded about a half a mile (0.8 km) seaward.

A third class I drainage is Las Flores Creek (Fig. 1) approximately 8 miles (13 km) southeast of SO Units 2&3. As other class I drainages, sediments laid down by Las Flores Creek are in a valley incised in Terrace 1 and older deposits. Only a few well-logs are available from which to interprete the approximate thickness and grain-size of Las Flores Creek alluvium. These data, from wells approximately one mile (1.6km) from the coast, suggest the presence of a relatively thin (5 to 6 ft - 1.5 to 1.8m) gravelly unit overlain by oxidized sands and silts fining upward into organic-rich clays. The basal gravels, presumably fluvial, occur at about 32 feet (10m) below present sea level, and may be chronologically correlative to the late Wisconsinan channel underlying the Santa Margarita River.

Class II

Class II drainages are mainly steep-walled arroyos rapidly dissecting the San Onofre Bluffs, and giving rise to coastal badland topography (Figs. 18 and 19). A few, in a more advanced stage of development, have extended sufficiently headward in Tertiary marine and post-Terrace 1 continental deposits to tap small drainages heading in the San Onofre coastal mountains. In essence, class II drainages have just, or will soon become integrated and grade to sea level. A good example of a newly-integrated class II drainage is Horno Creek debouching into the ocean about 5 miles (8 km) southeast of SO Units 2&3 (Fig. 1). Topographically, Horno Creek has built up an alluvial fan on the San Onofre Bluffs (Las Pulgas Canyon Quadrangle) with radiating distributaries laying down fine-grained sediments along the distal margins. In the very recent past, perhaps within the last several hundred years, steep-walled arroyos, originating from sea cliffs, have extended headward and now tap a distributary of Horno Creek. Consequently, all Horno Creek drainage,

Figure 18. Incipient Class II drainages extending headward onto San Onofre Bluffs as steep-walled arroyos.

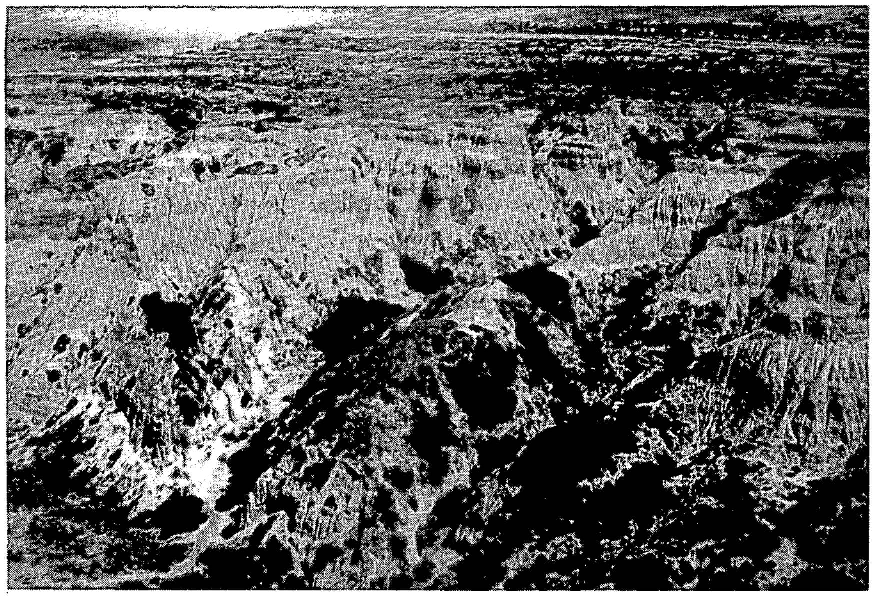


Figure 19. Class II drainages north of Target Canyon coalescing to form badland topography in continental sediments, San Onofre Bluffs.

especially that derived from high intensity, summer convective precipitation, is now funneled into one distributary causing rapid channel incision, and the dissection of the fan.

Class III

Most of the San Onofre Bluffs, from SO Units 2&3 on the northwest to Las Flores Creek on the southeast, is a composite of coalescing alluvial fans laid down by class III ephemeral streams. These fans apparently extended at least a mile (1.6km) beyond the present sea cliffs about 5,000 years ago graded to sea level in mid-Holocene time. Some 40 to almost 100 feet (12 to 30m) of these fan sediments typically overlie marine gravels and sands on the Terrace 1 platform, their thickness varying with distance from source area.

Class III drainages are typically ephemeral, head in the coastal mountains, and seldom have basin areas of more than two square miles (5 sq. km). As shown in Fig. 20, a typical class III drainage, about 1 mile (1.6km) north of Las Flores Creek, heads at an elevation of 1350 feet (405m) and has built up a Holocene-age alluvial fan at least 100 feet (30m) thick where debouching from highland terrain onto its base level, the San Onofre Bluffs. Characteristically, poorly-sorted, coarse-grained mudflow, debris flow and fluvial deposits are laid down in proximal segments of the fan or are entrained in gullies. Distal portions of the fan are fine-grained, usually clays and silts, which in some cases reach the present sea cliffs. The seaward (distal)

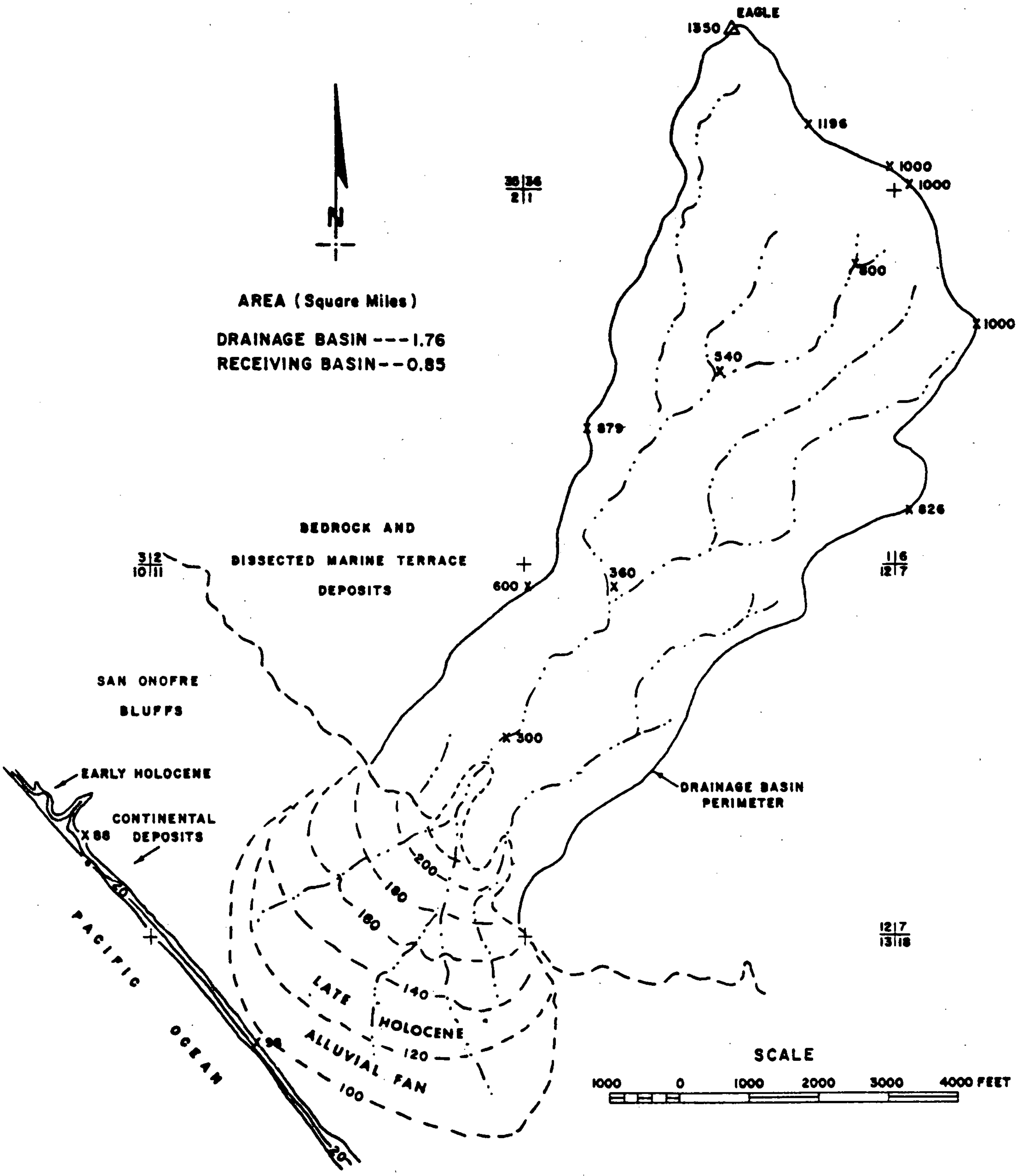


Fig. 20 San Onofre Bluffs forming base level for late Holocene alluvial fan deposits, first drainage (unnamed) north of Las Flores Creek (Las Pulgas Canyon 7-1/2' Quadrangle; T. 10 S., R. 6 W.). Latest Pleistocene-early Holocene continental deposits eroding by shoreline retreat and arroyo-cutting graded to present sea level (see text for discussion; Class III drainage).

fan sediments are often no more than a few feet (1 m) thick; their relatively undeveloped soil profile (A-C) is indicative of a late Holocene age. However, immediately under these young sediments are probable early Holocene deposits, as deduced from development of buried soils and their geomorphic position relative to Holocene sea levels.

In summation, class I drainages, such as San Mateo Creek and the Santa Margarita River, incised deep channels responding to the late Wisconsinan (Stage 2) sea level low about 17,000 to 20,000 years ago. Subsequently, these coastal valleys have been filled but have not overtopped coastal bluffs or alluvial fans. Class II drainages are of late Holocene age and perhaps no more than several hundred years old. Their channels are just entering a stage of integration and are characterized by abrupt breaks in their longitudinal profile. Class III drainages, heading in the San Onofre coastal mountains, have built out coalescing alluvial fans (piedmont plain) on the Terrace 1 platform and marine section. The present base level for class III drainages is the aggraded surface of the San Onofre Bluffs. These drainages, therefore, grade to a base level relatively fixed in elevation and independent of glacioeustatic fluctuations of the sea.

The late Pleistocene and particularly the Holocene continental deposits of the CP-SOSB area have thus been laid down at various elevations and on a wide variety of geomorphic surfaces; floodplain, channel and terrace-fill sedimentation by integrated drainages (class I), and episodic alluvial fan deposition by ephemeral drainages (classes II and III).

The San Onofre Bluffs

The San Onofre Bluffs, from approximately SO Units 2&3 on the north to Las Flores Creek on the south (Figs. 2 and 3), form the dominant coastal landform in the CP-SOSB area. The eastern margins, adjacent to the coastal mountains, are generally aggradational receiving mud and debris-flows from class III drainages. The coastal portions of the bluffs, however, are severely dissected, especially where class II drainages, modern steep-walled arroyos, are extending rapidly headward; and where coastal landslides dominate. The stratigraphy of the Bluffs records a complex history of late Pleistocene and Holocene climatic change. Radiocarbon dates have been obtained from basal portions of the section, and these permit calculation of an average sedimentation rate and of approximate ages for specific depositional units and buried soils.

General Stratigraphy

The stratigraphy of the San Onofre Bluffs is well exposed in the badland topography created by coastal arroyos (class II drainage), sea cliffs, and numerous access trails and roadcuts to beach areas. In addition, recent excavation of a "Haul Road" in the Target Canyon area (SE 1/4, sec. 14, T. 10 S., R. 6 W) has exposed over 80 feet (24m) of continuous section consisting of 44 feet (13 m) of continental sediments, several feet (2 m) of underlying marine beach deposits on the Terrace 1 platform, and approximately 33 feet (10m) of sands and silts of the Tertiary Monterey Formation (Fig. 16).

To ascertain the stratigraphy of the San Onofre Bluffs continental sediments, eleven backhoe cuts were made in the walls of Target Canyon and logged in detail (Figs. 21 and 22). These cuts clearly expose a complex, heterogeneous sequence of channel gravels, overbank sands and silts, and buried soils, providing evidence about relative climatic and base level change, and rates of sedimentation.

Depositional Units and Buried Soils

Some 32 separate depositional units and buried soils, ranging in thickness from a few inches to several feet, make up the San Onofre continental sediments exposed in Target Canyon (Table 5). Gravel channels within the section are typically lenticular with angular pebbles and cobbles reworked from San Onofre Breccia or pre-Stage 5 marine terrace deposits. Some channels can be traced laterally almost 100 feet (30m) in cuts of the "haul road" (Table 5, unit 13); where frequently they grade upward into coarse sands, silts and clays, and often terminate in a buried soil. In essence, the continental section of the San Onofre Bluffs is a series of broadly fining-upward sedimentary cycles reflecting climatic and vegetative changes in the basin of Class III ephemeral drainages.

Five distinct paleosols (buried soils) and several incipient profiles, not sufficiently developed to warrant separate identification, are exposed in Target Canyon (Figs. 23 and 24). The soils are mainly in the upper half of the section, and identify epochs of relative landscape stability

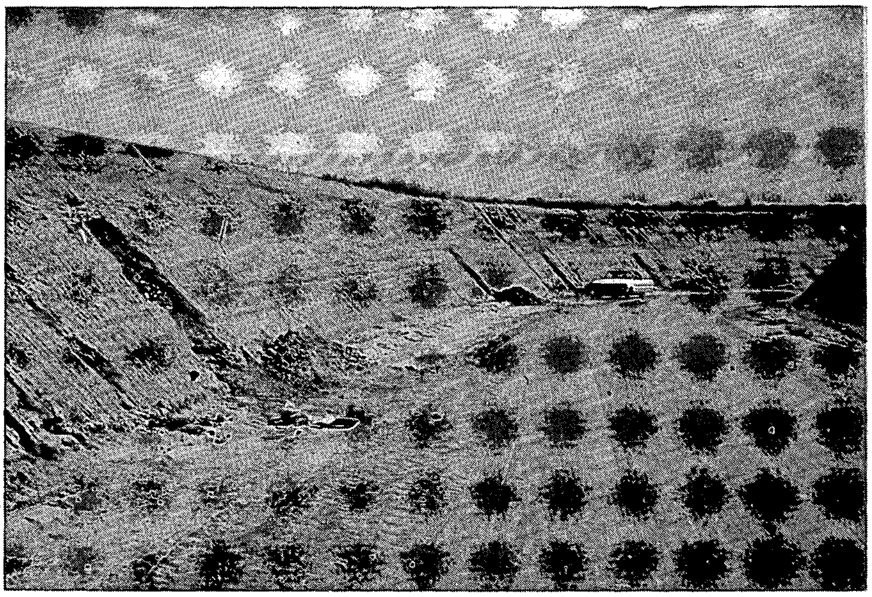


Figure 21. Cuts in the Target Canyon "haul road" exposing post-Stage 5 continental sediments and buried paleosols.

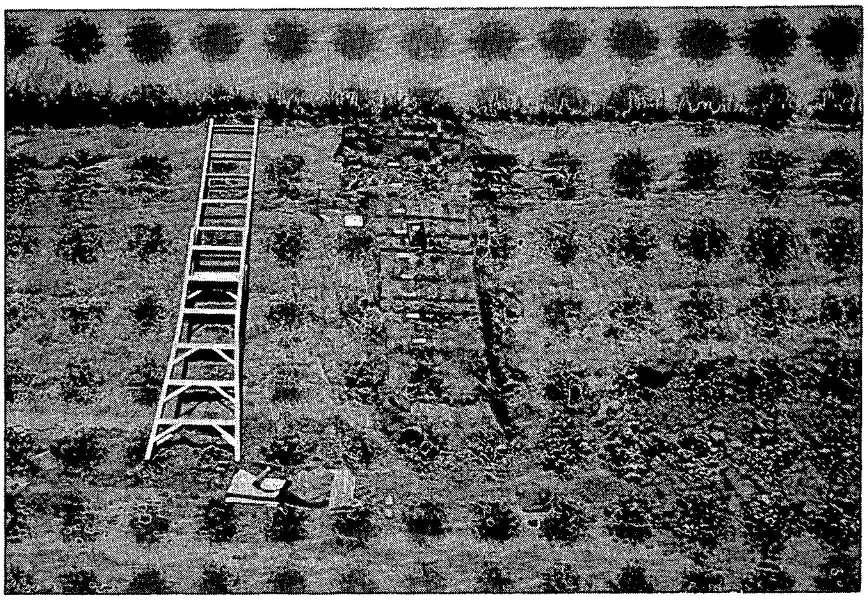


Figure 22. Cut number 1, Target Canyon, showing depth markers and horizon boundaries for depositional and buried soil units 1 through 7.

when deposition was limited to proximal segments of alluvial fans.

Because of parent material stratification, typical of ephemeral fan deposits, it is not meaningful to designate San Onofre Bluff buried soils and their enclosing sediments by Roman numerals and related nomenclature of a standard soil survey (Soil Survey Staff, 1951). More practical from a Quaternary stratigraphic standpoint is to identify separate depositional and soil units, designating each sequentially, and describing and interpreting each according to changes in grain size, color, structure, consistency, and other physical characteristics (Table 5).

The buried soils of Target Canyon are identified mainly by clay content, structural development, and presence of illuvial clay in the argillic horizon (Table 5; units 2-3, 4-5, 16, 18 and 19; Figs. 23 and 24). Other physical characteristics locally diagnostic are: (1) change of color from yellowish brown in surface epipedons to dark-brown and reddish-brown in cambic and argillic horizons; (2) presence of rootcasts, worm burrows and charcoal flecks; and (3) form of calcium carbonate accumulation (Figure 25).

As typical of most buried soils in an oxidizing environment, the original organic horizon (mollic epipedon) is not readily visible in the field, owing either to later chemical decomposition or to mechanical erosion. Thus these

TABLE 5

Late Pleistocene - Holocene (post-Stage 5) Depositional Units and Buried Soils, Target Canyon

Depositional Unit/ Soil Horizon	Depth (feet)	Description
1-A	0.0-0.2	Yellow brown (10YR 5/4) fine sandy loam; dark yellowish brown (10YR 4/4) when moist; massive structure; loose when dry, nonplastic; common fine roots; abrupt smooth lower boundary.
2-A1	0.2-1.1	Light yellowish brown (10YR 6/4) sandy clay loam; dark brown (10YR 3/3) when moist; single-grained structure; slightly hard to hard when dry, slightly sticky and nonplastic; common very fine to fine roots; clear smooth lower boundary.
2-A$_3$	1.1-1.3	Light yellowish brown (10YR 6/4) pebbly silty clay loam; dark yellowish brown (10YR 4/4) when moist; massive structure; very hard when dry; few very fine roots; abrupt smooth lower boundary.
2-B$_{21tb}$	1.3-1.6	Dark brown (10YR 4/3) silty clay loam; dark brown (7.5YR 4/4) when moist; weak angular blocky structure, coarse; very hard when dry, slightly sticky and slightly plastic; few medium roots; common thin clay films on interstitial pores; abrupt smooth lower boundary.
2-B$_{22tb}$	1.6-2.1	Dark brown (7.5YR 4/4) sandy clay loam; yellowish red (5YR 4/6) when moist, strong coarse prismatic structure; very hard when dry, slightly sticky, slightly plastic; few medium roots; common moderately-thick clay films in interstitial pores; manganese staining on tubular pores; abrupt smooth lower boundary.

Depositional Unit/ Soil Horizon	Depth (feet)	Description
2-B_{3tb}	2.1-2.4	Reddish brown (5YR 4/4) sandy clay loam; yellowish red (5YR 4/6) when moist; moderate medium blocky structure; very hard when dry, sticky and plastic; weakly cemented; few very fine roots; few thin clay films in bridges between mineral grains; continuous smooth lower boundary.
3-C_b	2.4-3.9	Yellowish brown (10YR 5/4) coarse sandy loam; brown (10YR 4/3) when moist; weak medium platy structure; hard when dry, firm when moist, slightly sticky and slighty plastic; common thin colloidal clay films, yellowish red (5YR 5/6); continuous smooth lower boundary.
4-B_{2b}	3.9-5.7	Strong brown (5YR 5/6) fine sandy loam; brown (7.5YR 5/4) when moist; medium coarse subangular blocky structure; hard when dry, firm when moist, slightly sticky and non-plastic; weakly cemented; few coarse roots; few thin dark brown (7.5YR 4/4) colloidal staining on mineral grains; continuous smooth boundary.
4-B_{3b}	5.7-6.9	Same as 4-B_{2b} above; weak medium subangular blocky structure; abrupt smooth lower boundary.
5-C_{1b}	6.9-7.1	Strong brown (7.5YR 5/6) gravelly loamy coarse sand; dark brown (7.5YR 4/2) when moist; single grain, fine granular structure; hard when dry, firm when moist, sticky and plastic; weak thin colloidal staining on mineral grains; abrupt smooth lower boundary.
5-C_{2b}	7.1-7.4	Brown (7.5YR 5/4) gravelly fine sandy loam; dark brown (7.5YR 4/4) when moist; medium coarse angular blocky structure; hard when dry, firm when moist, sticky and slightly plastic; few very fine roots; very few thin colloidal stains on mineral grains; abrupt smooth lower boundary.
6-C_{3b}	7.4-7.7	Reddish yellow (7.5YR 6/6) very fine sand; dark brown (7.5YR 4/4) when moist; massive structure; hard when dry, firm when moist, non-sticky and non-plastic; few very fine

Depositional Unit/ Soil Horizon	Depth (feet)	Description
		roots and clay films, dark yellowish brown (10YR 3/4); few thin colloidal stains on mineral grains; abrupt wavy lower boundary.
7	7.7-8.1	Light yellowish brown (10YR 6/4) sandy clay loam; brown (10YR 5/3) when moist; weak medium subangular blocky structure; hard when dry, firm when moist, sticky and plastic; abrupt smooth lower boundary.
8	8.1-9.4	Yellowish brown (10YR 5/6) loamy coarse sand grading to fine sandy loam in lower 0.5 feet; dark yellowish brown (10YR 4/4) when moist; weak massive granular structure grading to moderate medium-blocky structure near base; soft when dry, very firm when moist, non-sticky and non-plastic; weak thin colloidal staining on mineral grains, few fine roots; disseminated carbon blebs; continuous wavy lower boundary.
9	9.4-10.1	Dark yellowish brown (10YR 4/4) silty loam; yellowish brown (10YR 5/4) when moist; medium coarse subangular blocky structure; hard when dry, very firm when moist, slightly sticky and slightly plastic; few fine roots; weak thin colloidal staining on mineral grains, dark brown (7.5YR 4/4); locally coarse sand to 0.1 ft. thick along ped faces derived from unit 8; abrupt smooth lower boundary.
10	10.1-10.6	Yellowish brown (10YR 5/4) pebbly very fine sandy loam; dark yellowish brown (10YR 4/4) when moist; weak medium subangular blocky structure; hard when dry, very firm when moist, slightly sticky and non-plastic; weak thin colloidal clay films; continuous smooth lower boundary.
11	10.6-11.1	Yellowish brown (10YR 5/4) silty loam; dark yellowish brown (10YR 3/4) when moist; weak medium subangular blocky structure; hard when dry, very firm when moist, slightly sticky and slightly plastic; few fine roots; weak thin colloidal clay films; abrupt smooth lower boundary.

Depositional Unit/ Soil Horizon	Depth (feet)	Description
12	11.1-11.7	Pale brown (10YR 6/3) very fine sandy loam; yellowish brown (10YR 5/4) when moist; medium granular structure; loose when dry, firm when moist; non-sticky and non-plastic; continuous wavy boundary.
13	11.7-12.8	Brown (10YR 5/3) gravelly very coarse sand; yellowish brown (10YR 5/4) when moist; single-grained; soft when dry, loose when moist, non-sticky and non-plastic; channel gravels, lenticular; approximately 45 feet long; 0.0-1.1 feet thick; gradual wavy lower boundary.
14	12.8-14.0	Yellowish brown (10YR 5/4) silty loam; dark yellowish brown (10YR 3/4); weak medium angular blocky structure; hard when dry, very firm when moist; slightly sticky and slightly plastic, few fine roots; abrupt smooth lower boundary.
15-1	14.0-14.4	Light brownish gray (2.5Y 6/2) silty clay; grayish brown (2.5Y 5/2) when moist; moderate medium angular blocky structure; very hard when dry, extremely firm when moist, sticky and slightly plastic; few fine roots; weak thin colloidal clay films; abrupt smooth lower boundary.
15-2	14.4-15.6	Brown (10YR 5/3) sandy clay loam; brown (7.5YR 5/4) when moist; medium granular structure; very hard when dry, extremely firm when moist, slightly sticky and non-plastic; few medium roots; abrupt smooth lower boundary.
16-B_b	15.6-16.2	Strong brown (7.5YR 5/6) silty clay loam; dark brown (7.5YR 4/4) when moist; strong medium angular block structure; very hard when dry, very firm when moist, slightly sticky and slightly plastic; few fine roots; common moderately thick clay films lining tubular and interstitial pores; manganese staining, clay films reddish brown (5YR 5/3); disseminated charcoal blebs; abrupt smooth lower boundary.

Depositional Unit/ Soil Horizon	Depth (feet)	Description
17	16.2-19.2	Yellowish brown (10YR 5/4) loamy sand; yellowish brown (10YR 4/4) when dry; single-grained granular structure; loose when dry, loose when moist, non-sticky and non-plastic grades to silty clay loam lenses 0.5-0.6 feet thick in mid-section; abrupt smooth lower boundary.
18-B_{tb}	19.2-20.5	Brown (10YR 5/3) clay; dark brown (10YR 4/3) when moist; strong coarse columnar structure; hard when dry, firm when moist, sticky and plastic; common fine roots; common thin clay films lining tubular and interstitial pores; strong manganese stains on ped faces; violently effervescent, fine lime filaments; laterally extensive marker horizon; abrupt smooth lower boundary.
18-C_b	20.5-21.8	Very pale brown (10YR 7/3) silty clay; yellowish brown (10YR 5/4) when moist; massive structure; hard when dry, very firm when moist, sticky and slightly plastic; few medium roots; continuous smooth lower boundary.
19-B_b	21.8-22.9	Light yellowish brown (10YR 6/4) very fine sandy loam; yellowish brown (10YR 5/4) when moist; strong very coarse columnar structure; hard when dry, firm when moist, slightly sticky and non-plastic; few fine roots; few moderately thick clay films on ped faces; common manganese staining; continuous smooth lower boundary.
20	22.9-23.6	Light yellowish brown (10YR 6/4) loamy fine sand; dark brown (10YR 5/3) when moist; single-grained weak granular structure; slightly hard when dry, firm when moist, slightly sticky and slightly plastic; abrupt smooth lower boundary.
21	23.6-24.4	Light yellowish brown (10YR 6/4) silty clay; brown (10YR 5/3) when moist; moderate medium angular blocky structure; hard when dry, very firm when moist, sticky and slightly plastic; common very fine pores; thin manganese staining on ped faces; abrupt smooth lower boundary.

Depositional Unit/ Soil Horizon	Depth (feet)	Description
22	24.4-29.7	Very dark grayish brown (2.5Y 3/2) clay; strong very coarse angular blocky structure; hard when dry, very firm when moist; sticky and plastic; moderate manganese stains on ped faces; disseminated charcoal flecks; violently effervescent, common large irregular lime concretions abundant in upper 2.5 feet of horizon; locally decalcified; distinctive stratigraphic marker; diffuse broken lower boundary.
23	29.7-30.9	Yellowish brown (10YR 5/6) loamy sand; yellowish brown (10YR 5/4) when moist; massive structure; loose when dry, loose when moist, non-sticky and non-plastic; few charcoal flecks; transition in upper part to unit 22; continuous smooth lower boundary.
24	30.9-32.0	Yellowish brown (10YR 5/4) cobbly silty clay loam; dark yellowish brown (10YR 4/4) when moist; weak fine platey structure; slightly hard when dry, firm when moist, slightly sticky and slightly plastic; locally thin lenses of angular quartzitic cobbles to 0.3 feet diameter (San Onofre Breccia); continuous smooth layer boundary.
25-1	32.0-33.0	Brown (10YR 4/3) silty clay; dark yellowish brown (10YR 4/4); moderate medium angular blocky structure; hard when dry, firm when moist, sticky and slightly plastic; violently effervescent, common medium irregular carbonate nodules; common fine discontinuous pores; few thin clays lining tubular and interstitial pores; continuous smooth lower boundary.
25-2	33.0-33.7	Brown (10YR 4/3) clay; dark yellowish brown (10YR 4/4) when moist; moderate medium angular blocky structure; hard when dry, firm when moist, sticky and plastic; violently effervescent, common medium irregular carbonate nodules; charcoal blebs to 0.1 inches diameter, disseminated; continuous smooth lower boundary.
26	33.7-34.8	Very dark grayish brown (2.5Y 3/2) clay; moderate medium angular blocky structure; hard when dry, firm when moist, sticky and very plastic; few medium roots; disseminated charcoal flecks; gradual wavy lower boundary.

Depositional Unit/ Soil Horizon	Depth (feet)	Description
27	34.8-36.0	Pale brown (10YR 6/3) silty clay loam; yellowish brown (10YR 5/4) when moist; weak fine platey structure; slightly hard when dry, firm when moist, slightly sticky and non-plastic; weak medium roots; gradual irregular lower boundary.
28	36.0-36.5	Very dark grayish brown (2.5Y 3/2) clay; moderate medium angular blocky structure; hard when dry, firm when moist, sticky and very plastic; few medium roots; abrupt wavy lower boundary.
29	36.5-37.6	Strong brown (7.5YR 5/6) loamy coarse sand; dark brown (7.5YR 4/4) when moist; massive structure; loose when dry, loose when moist; reworked marine sand; gradual irregular lower boundary.
30	37.6-39.4	Dark yellowish brown (10YR 4/4) silty clay; dark yellow brown (10YR 3/4) when moist: grading into yellowish red (10YR 5/6) at "burned zone" near base; weak and angular blocky structure; hard when dry, firm when moist, sticky and non-plastic; common fine discontinuous roots and pores; medium charcoal flecks; gradual broken lower boundary.
31	39.4-44.0	Strong brown (7.5YR 5/6) coarse sand and interbedded silty clay; brown (7.5YR 4/4) to very dark grayish brown (2.5Y 3/2) when moist; massive structure; loose when dry, loose when moist; upper portion contains reworked clayey deposits 1.4 to 1.8 ft. long, to 0.5 ft. thick; few charcoal flecks; gradual irregular lower boundary (reworked marine sands and continental clayey deposits).
32	44.0-44.8	Light yellowish brown (2.5Y 5/4) very coarse sand; massive structure; loose when dry, loose when moist; contains well-rounded quartz grains and pebbles from San Onofre Breccia to 0.3 inches diameter; bottom of trench.

soils can be classified taxonomically only by relative development of the buried argillic horizons.

Many depositional units identified in the Target Canyon roadcuts were laid down slowly so that soil formation locally kept pace with sedimentation. This is indicated mainly by an abundance of rootcasts, fillings, and disseminated charcoal fragments. Without detailed sampling and laboratory analyses, these units cannot be assuredly classified according to the U.S. soil taxonomic system (Soil Survey Staff, 1975). It appears, however, that organic matter content and degree of oxidation (cambic horizon) are sufficient to deem these incipient buried paleosols as Entic or Pachic Haploxerolls, soils little altered from the original parent material.

In contrast to the incipient paleosols, the five buried soils specifically identified in Target Canyon (Table 5) all were in place sufficiently long for movement and accumulation of silicate clays within the subsoil. Thus, under the Mediterranean climatic/vegetation regime, these fall within the order Alfisols, and suborder Xeralfs (Soil Survey Staff, 1975). With the exception of the lowermost soil (unit 19, Table 5), the buried argillic horizons all have medium- to coarse-blocky or prismatic structure with thin films of salt (probably sodium chloride) on ped faces. From a classification standpoint, therefore, these moderately-developed paleosols appear to be mainly Haplic Natrixeralfs.

Figure 23. Argillic horizon (B_{21tb} and B_{22tb}) of moderately-developed buried soil (Haplic Natrixeralf) 2.0 feet below surface, cut 1, Target Canyon (see Table 5 for description).

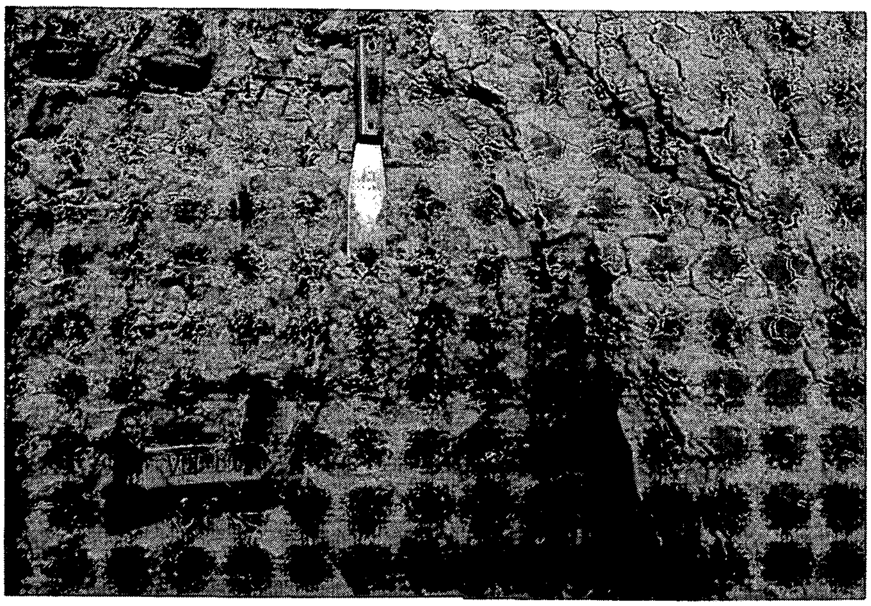


Figure 24. Buried incipient argillic horizon (B_{tb}) with strong coarse columnar structure; a clay developing on silty clay parent material, cut 7, unit 18 (Table 5), 19.2 to 20.5 feet below the surface.

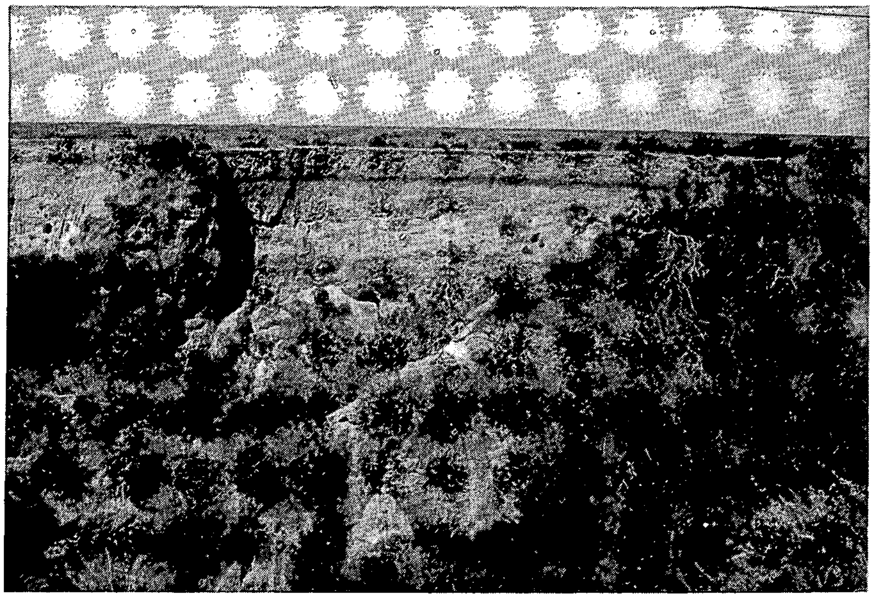


Figure 25. Argillic horizon of moderately developed buried soil (dark band) forming marker unit near top of continental section, Horno Creek area.

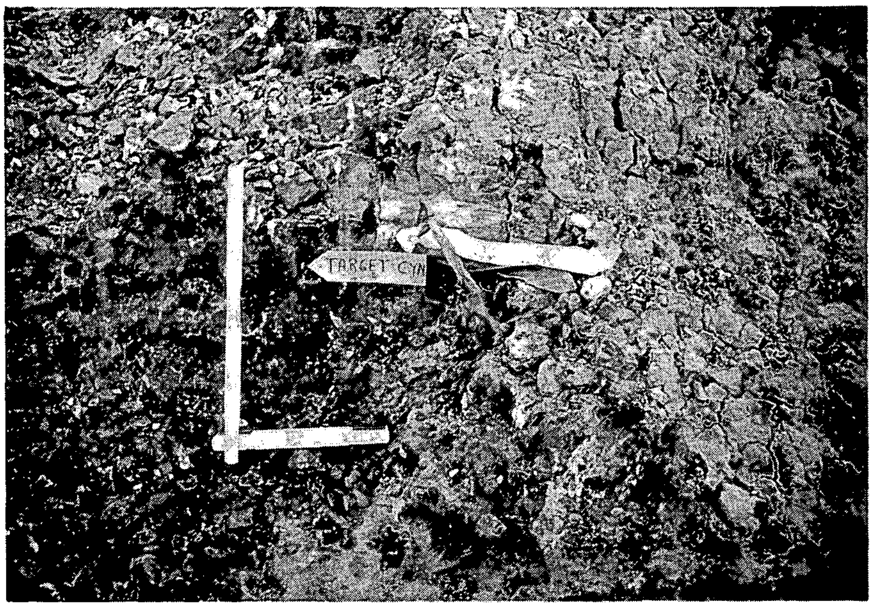


Figure 26. Primary clay (unit 22, Table 5) laid down in estuarine and distal fan environments, impeding percolation of gravitational water and causing precipitation of carbonate nodules; cut 10, Target Canyon.

Lenticular bodies of primary clay, laid down in estuarine and backswamp environments, may be initially confused with a buried soil, for expanding clays (montmorillonitic) give rise to strong prismatic and blocky structure, and impede percolation of calcium-rich gravitational water causing precipitation of carbonate modules (Table 5; units 22, 25; Figure 26). Though not buried soils, these extensive clay deposits signify paleo-environmental alteration, quite plausibly related to Wisconsinan climatic and sea level change.

Age and Origin of Continental Sediments

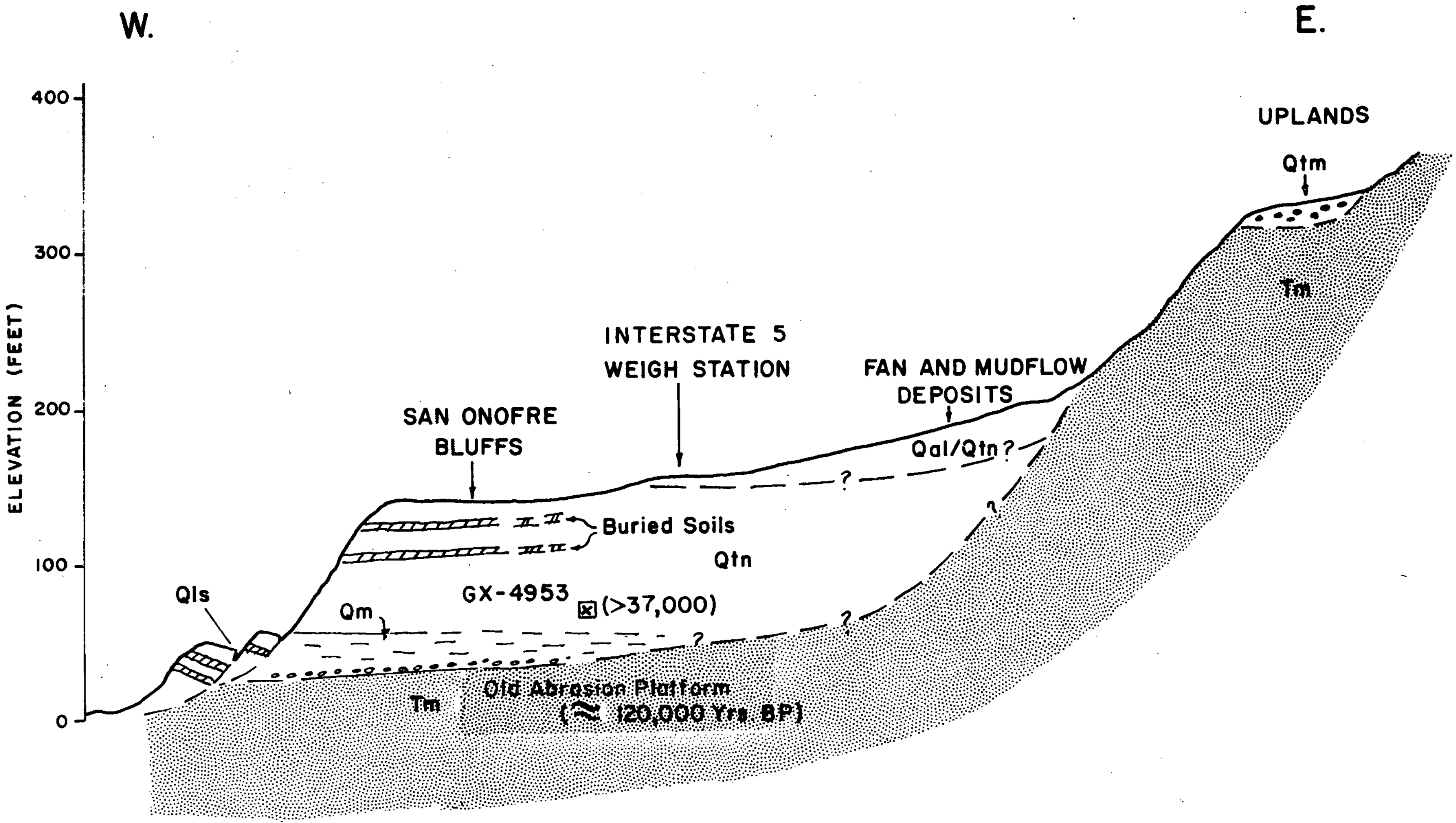
Three main lines of evidence indicate the probable age and origin of continental sediments underlying the San Onofre Bluffs; (1) stratigraphic position relative to underlying dated marine terrace deposits; (2) rate of soil profile development and interpretation of depositional environments; and (3) radiocarbon dates and extrapolated rates of sedimentation. These three lines of evidence are not mutually exclusive, but rather supplement each other, the data derived from the CP-SOSB area and elsewhere along the central and southern California coast.

Stratigraphic Position:

That the continental sediments are less than about 120,000 years old is readily apparent by stratigraphic position. As exposed throughout the CP-SOSB area, the continental section rests directly either on the Terrace 1 abrasion platform or on the veneer of overlying regressive marine gravels (Figure 27). The Terrace 1 platform by its association with the last glacio-eustatic (interglacial) highstand of the sea, was cut about 125,000 to 130,000 years ago (Table 3). Terrace 1 marine deposits have been dated both by uranium-series and amino-acid methods, and by faunal ecological associations yielding ages in the order of 125,000 years B.P. Because deposition on the San Onofre Bluffs by Class III streams is still continuing, the entire continental section has therefore been laid down throughout late Pleistocene and Holocene time. More specific ages can be ascertained from the presence and interpretation of buried soils and depositional units, radiocarbon dating, and estimated rates of sedimentation.

Rate of Soil Development:

The presence of five buried soils with field recognizable argillic horizons indictes that the continental sediments range in age from at least several to tens of thousands of years. Radiometrically-dated soils in the Central Valley of California with incipient profile development (cambic horizon) are about 10,000 to 15,000 years old; those with "weak" to "moderate" argillic horizons (Bt), similar to those in the CP-SOSB area, are probably in the order of 35,000 to 60,000 years old (Arkley, 1962; Janda and Croft, 1967; Shlemon, 1967; 1972; Marchand and Harden, 1976). These dates, however, cannot be directly extrapolated to the CP-SOSB area, for rates of soil development range widely between the interior and the coast of the Mediterranean climatic regime.



Qal/Qtn ---- Holocene Fan and Mudflow Deposits
Qtn ---- Continental Deposits and Buried Soils
Qls ---- Landslides
Qm ---- Marine Beach Deposits
Qtm ---- Marine Terrace Deposits
Tm ---- Miocene Monterey Formation
⊠ ---- Radiocarbon sample

FIG. 27 Diagrammatic sketch, stratigraphic and geomorphic relationships in the CP-SOSB coastal area. Representative radiocarbon date above base of continental deposits (Qtn) indicated by laboratory number. Vertical scale exaggerated (From Shlemon 1977)

Despite these uncertainities, two lines of evidence suggest a minimum time necessary to form the five moderately-developed buried soils (Haplic Natrixeralfs) in the upper part of the continential section. First, as deduced from gross sedimentation rates and sea level fluctuation during the last 125,000 years, described below, the buried profiles all occur above an extensive "mid-Wisconsinan" clay, about 35,000 to 50,000 years old. The buried soils comprise approximately 30 percent of the section or about 11,000 to 15,000 of the post "mid-Wisconsin" stratigraphy. Conceivably, therefore, each soil may have formed in as little as 3,000 years.

Second, buried soils with similar profile development have been observed in the continental section near San Diego (Carter, 1957) and the age of these soils may be approximated according to radiocarbon dates obtained by Carter (1957, p. 134) who pointed out that:

> ....surface soils on the alluvial cover at Bird Rock and south of the Scripps Institution of Oceanography, which have marked structural B horizons with clay accumulation, were dated 2,800 and 4,400 years old respectively. These soils...[have]...compact subsoils with distinct clay accumulation.

Within the resolution of dating afforded by gross sedimentation rates and association with radiocarbon-dated profiles near San Diego, it thus appears that the five buried Haplic Natrixeralfs in the CP-SOSB continental section could have formed in intervals between about three to perhaps five or six thousand years. This rate of formation is almost an order of magnitude more rapid than that for comparably-developed, dated profiles in the interior of California. The "accelerated" rate of soil development in coastal California may in part be due to more rapid pedogenesis in fine-grained continental overbank and distal fan deposits; to more equable seasonal temperatures and the presence of summer fog drip; and to wind influx of locally-derived salt causing rapid dispersal and migration of clays.

In addition to stratigraphic position and the presence of buried soils, the continental sediments of the San Onofre Bluffs are datable relatively by their "recording" of probable regional climatic change. Several distinctive carbonate-rich depositional units are exposed throughout the Bluffs. In Target Canyon, for example, unit 22 (Table 5), about 25 feet (8m) above Terrace 1 gravels, is a widely traceable marker, a primary clay with very coarse angular blocky structure. This clay, clearly not pedogenic in origin, has impeded gravitational water causing precipitation of large irregular lime nodules. The clay itself has been incised by younger gravel-filled channels; and is locally decalcified, suggestive of weathering and post-depositional erosion in the order of several feet (2 m), relatively high for the distal portion of a small fan (Figure 26). Other clayey stratigraphic units, above and below unit 22, contain at best only disseminated carbonate or a few small nodules. These stratigraphic relationsips thus suggest that unit 22 may have been laid down during a time of climatic amelioration; that is, during the mid-Wisconsinan interstadial (Stage 3), about 35,000 - 50,000 years ago. This was a time when sea level was rising but did not reach the present; and when only fine-grained sediments were likely carried outward onto the Bluffs, similar to the present.

Radiocarbon Dating and Sedimentation Rates:

The age of specific units within the continental section is also estimated by several newly obtained radiocarbon dates and extrapolation of approximate sedimentation rates.

Eight samples from the CP-SOSB area contained sufficient organic carbon to yield radiocarbon dates (Table 1; Figure 28). Seven of the dated samples were collected specifically for this study; the remaining for an earlier geotechnical investigation (Converse-Davis Assoc., 1971). All dates are from the lower part of the section where charcoal fragments are abundant but very disseminated. All dates must be regarded as minimal ages, for contamination by contemporary organic matter is a distinct possibility despite careful removal of rootlets in the field and special pretreatment in the laboratory.

Of the several dates obtained thus far, two are suspect: number 4 (GX-4956), taken within 10 feet (3m) from the surface and in a section now known to be slumped; and number 6 (GX-5168), collected from buried estuarine clays containing modern rootlets (Table 1). The remaining dated samples all yield infinite dates; that is, beyond the range of radiocarbon.

The accuracy of the dates must also be viewed within context of carbon recovered for laboratory counting. Thus, as shown in Table 1, all samples are lean in organic carbon, in most cases containing less than one percent of the original "selected" sample weight. Normally at least one gram of organic matter is required for counting; a lesser weight is highly susceptible to contamination by younger carbon. Accordingly, four samples less than about 0.2 grams were deemed "too small for reasonable count" (Table 1). In this regard, sample 6 (GX-5168) which yielded a finite date, is additionally suspect, not only because of probable contamination by modern rootlets, but also because only 0.21 grams were ultimately recovered for laboratory counting (Table 1).

The elevations of the dated samples, relative to the 125,000 year old underlying Terrace 1 platform and deposits, are significant, for they are consistent with an average continental sedimentation rate of about 1 ft/1,000 (30cm/1,000) years estimated in an earlier study (Shlemon, 1977, p. 8).

The thickness of the continental section in the San Onofre Bluffs varies from about 10 to 30m depending on proximity to source area. Thus gross sedimentation rates for the last 125,000 years range from about 10 to 25cm/1,000 years. These rates are also corroborated by radiocarbon dates for the basal continental sediments, and the stratigraphic position of the mid-Wisconsin marker clay in Target Canyon.

Radiocarbon ages are greater than about 35,000 years for basal sediments up to 25 feet (8m) above the Terrace 1 wave-cut platform. These "beyond the range" dates all occur in the lower 50 to 60 percent of the continental sediments, or that portion greater than about 40,000 to 50,000 years old. The approximate sedimentation rates are similarly borne out by the inferred mid-Wisconsin age (35,000 - 50,000) of unit 22 in Target Canyon (Table 5), the mid-portion of which occurs at 17 feet (5m) above the Terrace 1 platform or about two-thirds "deep" in the section. This stratigraphic position thus yields a "sedimentation rate age" of about 42,000 years B.P.

By use of the gross sedimentation rates, it is possible to determine the approximate age of any stratigraphic unit within the San Onofre Bluffs. It is only neccessary to determine the elevation of a continental unit, expressed as a percentage of thickness, relative to the underlying 125,000 year old Terrace 1 platform. For example, a silty clay horizon 20 feet (6m) above the platform in a 50 foot

(∿15m) sequence is "60 percent deep" in the section; that is, 60 percent of 125,000 or about 75,000 years old. Although the CP-SOSB coastal area has a "unique" thick section.of continental sediments, it must be strongly emphasized that ages based on gross sedimentation rates are first aproximations only which should be verified by additional radiocarbon and other dating techniques.

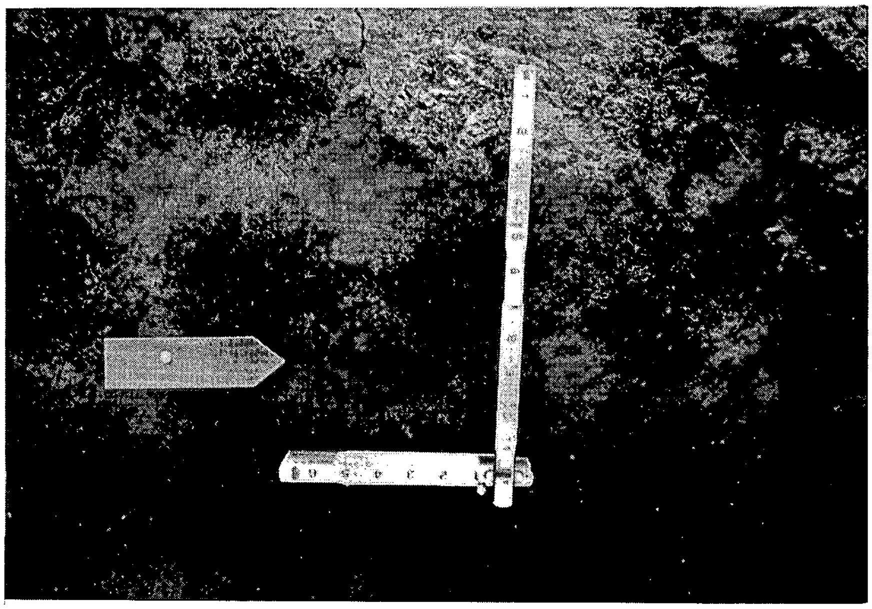


Figure 28. Charcoal sampled near the base of continental sediments, 26 feet (7.9 m) above Terrace 1 platform, "Dead Dog Canyon" [0.3 mi. (.48 km) SE of Horno Creek] yielding a radiocarbon age of greater than 37,000 years (GX-4953, Table 1).

LATE QUATERNARY STRUCTURAL STABILITY

The southern California coast has been undergoing general uplift and deformation throughout all of late Quaternary time. Questionable, however, is the rate of deformation at any particular locality. In many cases structural instability is manifest by readily-measured vertical or horizontal displacements of faults. Elsewhere the magnitude of late Quaternary deformation is deduced from geomorphic evidence; mainly tilt of marine terraces or their absolute uplift calculated against a time and elevation datum. More recently, relative structural stability has been ascertained by first and second order level surveys emanating from coastal tide-gauge stations.

Calculations of late Quaternary deformational rates have been made from several coastal localities in central and southern California (Table 6). Most are based on comparing the present elevation of the Terrace 1 shoreline angle with the Stage 5 interglacial sea level, presumed to be about +10m some 125,000 years ago. Inaccuracies in these estimates are many, for there are wide divergences of opinion about absolute elevations of sea level in Sangamonian (Stage 5) time, precision of dates, and serious question about the of Terrace 1 shoreline angles. Nevertheless, though approximate, these calculations provide a "yardstick" to measure relative structural stability in the CP-SOSB area.

TABLE 6

Late Quaternary Deformation Rates,
Central and Southern California Coast

Area	Reference	Length of Geological Record (years)	Deformation Rate (cm/1,000 yrs)
Santa Cruz	Bradley & Griggs (1976, p.144)	0 - 125,000 BP	16 - 26
Malibu Coast	Birkeland (1972, p.441)	0 - 105,000 BP	30 - 45
Bald-win Hills LA Basin	Bandy and Marincovich (1973, p.653)	0 - 36,000 BP	500 - 800
San Diego Coast	Ku and Kern (1974,p.1715) Kern (1977, p. 1563)	0 - 120,000 BP 0 - 120,000 BP	11 - 14 16 - 20
Camp Pen-dleton San Onofre State Beach	this report (Target Canyon area)	0 - 125,000 BP	4 - 5

Late Quaternary uplift and "up-to-the-northwest tilt" has been postulated for the CP-SOSB area based primarily on inferred terrace correlation by elevation from San Diego to the San Onofre area (McCrory and Lajoie, 1977). In addition, historic leveling data (1906-1932) also suggest northwest tilting of the coast in the order of 23cm/100km from about La Jolla to Dana Point (Wood and Elliott, 1977). There are, however, two alternative methods, albeit approximations, to determine an average late Quaternary uplift and tilt rate for the CP-SOSB area. These assume that lateral difference in terrace platform elevations are truly the result of structural instability, and no concessions are made for apparent uplift owing to differential coastal erosion.

First, a rate of uplift for the last 125,000 years may be approximated by projecting the Terrace 1 abrasion platform gradient inland to its postulated shoreline angle elevation at the base of Terrace 2. This yields a projected Terrace 1 elevation of 55 feet (17.1m). Assuming that sea level at stage 5 was 32 feet (10m) higher than present, then uplift during the last 125,000 years has been 17 feet (5.3m) or an average rate of 4.2cm/1,000 years. This compares with rates over the same period (Table 6) of 11-14 and 16-20cm/1,000 years for the San Diego area (Ku and Kern, 1974, p. 1715; Kern, 1977, p. 1563) and 30-45cm/1,000 years for the Malibu coast (Birkeland, 1972, p. 441).

Second, a rate of tilt in the CP-SOSB area may also be approximated by comparing (a) the gradient of the 125,000 year old Terrace 1 platform with that of the modern offshore platform, and (b) the elevation of Terrace 1 where exposed in sea cliffs at SO Units 2&3 and at the mouth of Target Canyon, 6.8 miles (11 km) to the southeast.

The Terrace 1 wave-cut platform is so well exposed in the CP-SOSB area that it has been possible to obtain a precise gradient by instrumental leveling. In Target Canyon (Fig. 16), the platform has a seaward gradient of 1° measured over a distance of 1,300 feet (390 m) (R. D. Hinkle, personal communication, 1977). This gradient is almost precisely the same as the modern offshore platform near San Clemente (Buffington and Moore, 1963) and at Santa Cruz (Bradley, 1957; 1958; Bradley and Griggs, 1976). Thus the extent and similarity in gradient of Terrace 1 and the modern platform suggest that no measurable seaward regional tilting has occurred in the CP-SOSB area in about the last 125,000 years.

However, disregarding the effect of differential coastal erosion (Fig. 14), possible "up-to-the-northwest" tilting is estimated by the elevation of Terrace 1 at SO Units 2&3 some 15 feet (4.6 m) higher than at Target Canyon; yielding an apparent maximium tilt rate of about 3.7 cm/1,000 years for the last 125,000 years.

Inspection of Table 6 shows that these approximate uplift and tilt rates are much less than elsewhere along the central and southern California coast. Inferentially, therefore, the CP-SOSB coastal area must be viewed as having been relatively structurally stable throughout late Quaternary time.

SUMMARY AND CONCLUSIONS

The late Quaternary evolution of the Camp Pendleton-San Onofre State Beach area is documented by identifying and dating some of the best preserved landforms and stratigraphic units on the southern California coast.

Nine distinct marine terrace deposits occur at elevations ranging from approximately 55 to 1,250 feet (16 to 375m) (projected shoreline angles). The youngest marine deposits (Terrace 1) are regressional, overlie an abrasion platform cut across the San Onofre Breccia and the Tertiary Monterey, Capistrano and San Mateo formations, and are dated as about 125,000 years old based on amino-acid assay, paleoecological interpretation of faunal assemblages, and on correlation with uranium-series dated corals elsewhere. The older marine terrace deposits (2 through 9) range in age from about 250,000 to at least 780,000 years, dated relatively by association with Middle Pleistocene high stands of sea level deduced from oxygen-isotope analyses of deep-sea cores (stages 5 through 22).

Two alternative hypotheses may be invoked to account for the elevation and origin of the pre-Terrace 1 deposits: (1) sea floor spreading, expansion of ocean basins, and resultant lowering of sea level since late Tertiary time; and (2) general tectonic uplift of the California coast throughout the Quaternary. The lower marine terraces owe their origin mainly to Pleistocene glacio-eustatic fluctuations of the sea superimposed on either generally falling sea levels or on a rising land mass. The magnitude of possible hydro-isostatic movement is unknown, but undoubtedly very small compared with glacio-eustacy.

Late Quaternary continental sediments are preserved mainly as channel gravels, floodplain and fluvial terrace deposits laid down by Class 1 drainages grading to glacio-eustatic fluctuating sea levels (San Mateo Creek and the lower Santa Margarita River); and as piedmont alluvial fan deposits derived from Class III streams debouching onto and building up the San Onofre Bluffs.

The base of an ancestral gravel-filled channel of the Santa Margarita River is projected to at least 210 feet (63m) below sea level; and appears to have graded to a late Wisconsinan (stage 2) shoreline about 2 miles (3.2km) off the present coast. The gravels are overlain by a fining-upward section of sands, silts and clays, thalassostatic sediments laid down as sea level rose from a glacial low 17,000 - 20,000 B.P. to its present position about 5,000 years ago.

At least two older fluvial terrace-fill deposits flank the lower Santa Margarita River about 8 miles (13 km) inland. Their absolute age is unknown, but elevation above present floodplain, gradient and relative soil profile development, suggest formation in pre-Wisconsinan time, most likely during stage 5.

Coalescing alluvial fan deposits forming the San Onofre Bluffs range in thickness from about 40 to 100 feet (12 to 30m) depending on proximity to source area; and in age from about 125,000 years to the present. Most samples of charcoal from the basal section, believed uncontaminated, yield infinite radiocarbon dates. An extensive clay (unit 22), described from Target Canyon, appears to have been deposited in interfan and on distal fan margins during a time of relative "climatic amelioration" inferred to be the mid-Wisconsinan interstadial about 35,000 to 50,000 years ago (stage 3). These data, plus the presence of several incipient and five moderately-developed buried soils (Haploxerolls and Haplic Natrixeralfs) in the upper part of the section suggest sedimentation rates during the last 125,000 years of approximately 10 to 25cm/1,000 years depending on thickness of section.

Coastal retreat of the San Onofre Bluffs by landsliding and arroyo cutting over the last 5,000 years is estimated as 0.2m/yr, a rate comparable to historical observations of coastal erosion elsewhere along the central and southern California coast.

Maximum uplift and tilt rates for the last 125,000 years are an estimated 4.2 and 3.7cm/1,000 years respectively, based on comparing the elevation of the Terrace 1 shoreline angle at Target Canyon and at SO Units 2&3 with the 10m interglacial high stand (stage 5) on tectonically stable coasts. The uplift rate, in particular, is less than half that reported for the same time period at San Diego, and about one-tenth that at Malibu. In comparison, therefore, the Camp Pendleton-San Onofre State Beach coastal area is viewed as having been relatively structurally stable throughout at least late Quaternary time.

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