# Topographic Evolution of the Southern California Borderland During Late Cenozoic Time

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## INTRODUCTION

Misconceptions about the topographic configuration and history of development of the seafloor surrounding the Southern California Islands have arisen as a result of erroneous inferences by both geologists and biologists. These mistaken opinions often are reiterated, not only in journalistic accounts, but also in scientific reports. The purpose of this paper is twofold: to help dispel misleading ideas that have been introduced in earlier literature and to describe in general terms the key events that created the present seafloor topography. Even though much conjecture remains, some of our interpretations may assist biologists who are investigating endemic evolutionary trends in the coastal and offshore region.

In recent years, a wealth of new geologic data has been gathered through shipboard and island studies on the California Continental Borderland north of 32° N latitude (Fig. 1). This work has demonstrated that the structure and stratigraphy are not as simple as previously supposed and that they rival their mainland counterparts in complexity. The history of some parts of the borderland now can be traced as far back as 100 m.y. (million years), and one isolated rock mass has been dated at 160 m.y. (Mattinson and Hill 1976).

That a large region seaward from southern California consists of extremely variable submarine topography was recognized early (Blake 1855). Few detailed descriptions of the water-covered terrain were published, however, until Shepard and Emery (1941) provided the framework upon which all later studies have been built. Two other fundamental contributions are those of Emery (1960), who described the interrelated aspects of the marine environments of the area, and Moore (1969), who demonstrated the importance of acoustic-reflection profiling in determining marine geologic processes in the same area.

Because of the fragmentary nature of the record before the beginning of late Miocene time (10 to 12 m.y. ago), the origin and development of features such as mainland shorelines, land bridges, insular platforms, and submergent ridges and basins is uncertain. The evidence that permits the reconstruction of sequential diastrophic events since the Miocene Epoch is relatively firm, even though chronologic dating of rocks older than Pleistocene seldom has a precision of better than ±1 m.y. In terms of the geologic scale, the Miocene Epoch ended a short time ago (*ca.* 5.2 m.y.); but the same span is much too great, perhaps by a factor of 10, for resolution of evolutionary and migratory patterns of the Quaternary insular biota. This disparity in the rates of natural processes is an inherent problem in integrating geologic and biologic phenomena.

A number of published paleogeographic maps of California involving different time intervals have portrayed a variety of land masses, seaways, and islands. Since Arnold's (1909) and Clark's (1921) early efforts, the most noteworthy regional paleogeographic reconstructions that include the borderland are those of Reed and Hollister (1936), Corey (1954), Clements (1955), Emery (1960), and Valentine and Lipps (1967). For the offshore area, all were based upon scant information and are highly interpretive.

The maps of Reed and Hollister (1936) and Corey (1954) are schematic representations that were compiled from mainland and island geology and sparse seafloor samples. Included are

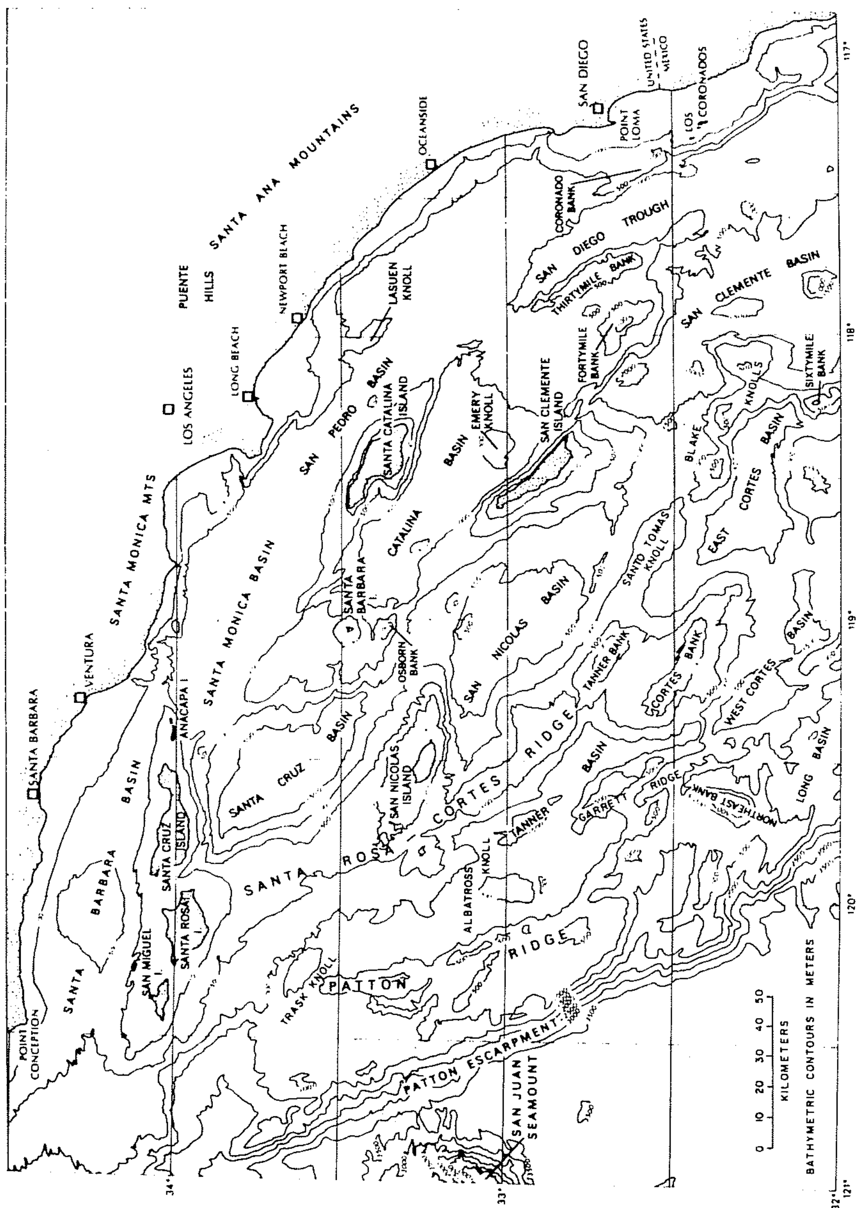


**FIGURE 1.** *Index map of the northern part of the California Continental Borderland and the adjoining mainland.*



land areas, outcrop distribution, sediment thickness, lithofacies, and faults for several episodes of Tertiary time. These workers, however, did not consider large lateral dislocations along faults and pre-uplift deposition and subsequent erosion of sediment. Emery's (1960) maps are simplified versions of Corey's (1954), supplemented by locations of offshore samples and profiles used for interpreting ancient shorelines, both emergent and submergent. Pliocene and Pleistocene shorelines depicted by Dunkle (1950) and Clements (1955) are misleading. Dunkle apparently did not apply available geologic and bathymetric criteria in his southern supplement to Reed's (1933) map. Clements used an early Pleistocene low sea-level stand of approximately minus 1,000 m, far lower than suggested by recently compiled Pleistocene sea-level curves (Curray 1965, Milliman and Emery 1968, Dillon and Oldale 1978, MacIntyre *et al.* 1978). The onshore parts of the two maps by Valentine and Lipps (1967), which also illustrate shoreline positions during parts of Pliocene and Pleistocene time, probably are nearly correct; but the offshore parts are generalized and imply high-standing areas for which there is little supporting evidence.

Axelrod's (1967) maps are simplified and slightly modified versions of Corey's (1954) for late Miocene and Pliocene time; consequently, they have the same deficiencies. The account by Weaver (1969) pertains to the northernmost part of the borderland, for which he discusses long-term Tertiary structural developments; his map of basins, uplifts, and sediment-transport directions is schematic and was not intended for use in studying Quaternary biogeography. A set of maps prepared by Fischer (1976) shows late Cenozoic shorelines, sedimentary facies, and depositional trends for the Santa Barbara Channel region as interpreted from acoustic-reflection profiles and core holes. This detailed work, however, covers only a small segment of the borderland.

## GEOLOGIC SETTING

### Geomorphology

The modern geomorphic provinces of coastal southern California (Reed 1933, Jenkins 1941, Jahns 1954) are characterized by aligned topographic entities that have two distinct directional trends (Fig. 2). The west-trending features of the long, narrow Transverse Ranges province transect the dominant northwest grain of the Coast Ranges and Peninsular Ranges provinces. As defined by Shepard and Emery (1941) and Moore (1969), the California Continental Borderland is bounded on the northwest by Point Arguello and Arguello Canyon, and on the southeast by Bahía Sebastián Vizcaíno and Isla de Cedros. Its western edge is marked by the base of the Patton Escarpment at the north and by the Cedros Deep at the south (Moore 1969, pl. 1). If the onshore provinces are extended offshore, the California Continental Borderland seems to include the submergent parts of both the Transverse Ranges and Peninsular Ranges with the result that all three provinces overlap. Although this apparent discrepancy has been a source of contention, discussion of the definitions is beyond the scope of this paper. Of greater importance is the fact that these geomorphic provinces generally reflect the underlying geologic structures and that two discrete orientations are discernible. Notwithstanding more than 50 years of study, geologists have just begun to decipher the origin and evolution of these intersecting structural domains.

North of latitude 31° N, the borderland is typified by elongate northwest- and west-trending seafloor basins and ridges, some of which protrude above sea level as islands. Offshore from southern California, the borderland differs from an ordinary continental shelf in that it encompasses large depressions as deep as 2,100 m below sea level and island peaks as high as 750 m above sea level. Topographic relief within a single ridge-basin pair is as much as 2,700 m (Santa Cruz Island-Santa Cruz Basin). Locally, the relief along the Patton Escarpment is more than 2,750 m; yet the term escarpment is a misnomer for the feature, which generally has a

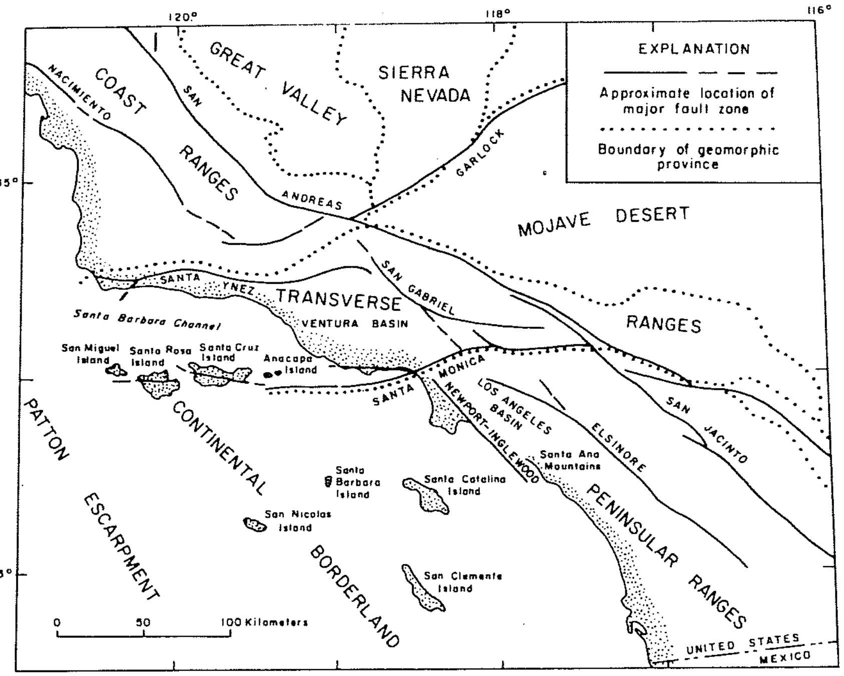


**FIGURE 2.** *Physiographic provinces and major faults of southern California. Modified from Yerkes* et al. *(1965).*

slope gradient of less than 15°. North of the Mexico-U.S. boundary, there are eight islands which range in area from 2.5 km² to nearly 250 km² (Fig. 1), and several isolated pinnacles (Richardson Rock, Wilson Rock, Begg Rock, and Bishop Rock), which range in size from 5,500 m² and 16 m above sea level to a submergent reef of about 0.2 km² and 4 to 10 m below sea level.

### Major Geologic Events

As background for the discussion of late Cenozoic history that follows, several significant geologic events are summarized. During Oligocene time, about 30 m.y. ago, a fundamental change in crustal behavior occurred in western California and resulted in a shift from a convergent plate tectonic regime to one of right-lateral shear. The new stress field was instrumental in forming a basin-and-ridge topography that replaced the pre-existing broad shelf and regionally extensive depositional aprons (Blake *et al.* 1978). At the end of Oligocene time and early in Miocene time (24 to 20 m.y. ago), an episode of igneous activity began in coastal and offshore southern California; it culminated shortly thereafter (16 to 12 m.y. ago), then diminished rapidly (10 to 7 m.y. ago). At places, borderland relief was accentuated by the volcanism, which built composite volcanoes and superimposed lava flows; some basins apparently developed in conjunction with differential subsidence that was associated with waning volcanism. Recently reported paleomagnetic measurements suggest that 75° to 90° of clockwise tectonic rotation took place in the western Transverse Ranges after middle Miocene time (Kamerling and Luyendyk 1977) and must have affected topographic alignments. Table 1



summarizes these and other geologic events and their timing. The exact tectonic mechanisms that created the vertical and lateral earth movements and that generated the volcanism have not been completely resolved, and the measured crustal rotation involves complex kinematics that are not yet understood.

## LATE MIOCENE TOPOGRAPHY

Interpretation of borderland topography before Miocene time is very uncertain because the older stratigraphic record is preserved at few places. Although early and middle Miocene events are relatively well documented, they are discussed only briefly inasmuch as they probably had a minimal influence on dispersal patterns of modern biota of the borderland region. In general, an episode of marine transgression and basin subsidence dominated in coastal southern California during late Miocene time.

Without some means of determining former water depths, inferences about pre-existing seafloor topography are unreliable. Ordinarily, bedding character, lithofacies relations, sediment composition, and fossil assemblages are used in combination to infer depth of deposition. Many of these criteria are inaccessible from shipboard, and our paleobathymetric reconstructions are based largely upon depth ranges of assemblages of fossil benthic foraminifers retrieved in cores of bedrock (Arnal 1976, Arnal and Vedder 1976). Although these assemblages may be partly time transgressive, the inferred paleobathymetry probably is valid for a tripartite division of Miocene time.

By the end of the Miocene (*ca.* 6 to 5 m.y. ago), large parts of the Ventura and Los Angeles regions were deep marine basins; a total sub-sea relief of at least 2,000 m had developed on the borderland. A few islands of unknown dimensions survived from a subsiding middle Miocene volcanic archipelago, remnants of which are preserved at Santa Cruz, San Clemente, and Santa Catalina Islands (Nolf and Nolf 1969, Fisher and Charlton 1976, McLean *et al.* 1976, Vedder and Howell 1976, 1977). In addition to the volcanic archipelago, a shallow submarine ridge at the present site of the southern Santa Rosa-Cortes Ridge (Fig. 3) seems to have subsided 300 to 500 m near the end of Miocene time (Fig. 4). Abyssal depths (> 2,500 m), not evident in middle Miocene time, developed to the south and west of this area. Even though mid-bathyal depths apparently prevailed over most of the region between the subsiding ridge and the present shoreline, the water was shallower near the northern end of Coronado Bank, where depths were less than 500 m (Fig. 4). In the Los Angeles and Ventura areas, the basin troughs subsided to lower bathyal and abyssal depths (1,000 to > 2,500 m) (Natland 1957, Ingle 1973). In the late Miocene, Los Angeles basin seafloor gradients steepened and the margins shoaled abruptly northward and eastward (Yerkes *et al.* 1965).

At most places on the Channel Islands, late Miocene strata either have been removed completely by erosion or were never deposited, leaving an incomplete record of events. The assignment of volcaniclastic strata on Santa Rosa Island to the upper Miocene (Jennings 1959) is misleading, for microfossils from interlayered shale beds are no younger than middle Miocene (Avila and Weaver 1969, J. A. Barron *in litt.* 1976). The only known island exposures of late Miocene sediments occur as thin discontinuous beds on Santa Catalina and San Clemente Islands, where fossil assemblages indicate a range of depths from middle bathyal to littoral (Vedder and Howell 1976, 1977, Vedder and Moore 1976). On Santa Catalina Island, both mollusks and foraminifers in sediments deposited on an irregular volcanic flow surface imply a steep bottom slope from an inner sublittoral environment to one possibly as deep as 1,000 m. At San Clemente Island, only shallow-water mollusks are present in correlative beds, which form thin, depression-filling veneers on the older lava surface (Vedder and Moore 1976). All of these limited outcrops are insufficiently preserved to interpret the original distribution and thickness of the sedimentary unit that they represent. Moreover, paleogeographic infer-

**Table 1.** Chronology, major events, and geologic evidence for late Cenozoic changes in topography on the southern California borderland. Ages of the epoch boundaries are from Van Couvering (1978).

| ERA | PERIOD | EPOCH Boundary ages in millions of years | MAJOR GEOLOGIC EVENTS | EFFECTS AND EVIDENCE |
|---|---|---|---|---|
| Cenozoic | Quaternary | Holocene | 10 End of rapid sea-level rise *ca.* 6,000 years ago | Drowned and backfilled drainage channels along mainland coast and at Santa Cruz and Santa Catalina Islands. |
| | | 0.011 | | |
| | | Pleistocene | 9 Beginning of post-glacial sea-level rise *ca.* 17,000 years ago | Eolianites on outer islands. Submergent surf-cut platforms around islands and along mainland coast. |
| | | | 8 Filling of onshore basins; fluctuating eustatic sea levels<br>Continuing local uplift and subsidence | Emergent surf-cut platforms around the islands and along the mainland coast. Nonmarine sediments throughout large parts of onshore basins. |
| | | | 7 Increase in tectonism with widespread intensive uplift and subsidence | Thick accumulations of marine and nonmarine sediments in onshore and near-shore basins. Deformed and deeply eroded basin margins on mainland. Faults throughout region. |
| | | 1.6-2.0+ | | |
| | Tertiary | Pliocene | 6 Eustatic lowering of sea level with onset of polar glaciation | Shallow-marine deposits on Santa Rosa, Santa Cruz, and San Clemente Islands, and along basin margins at Santa Monica Mountains, Puente Hills, San Joaquin Hills, and San Diego. |
| | | | 5 Accelerating rate of deposition in near-shore basins accompanied by local subsidence | Deep-marine deposits in central Ventura and Los Angeles basins. Basin-edge unconformities throughout the borderland. |
| | | *ca.* 5.2 | | |
| | | Miocene | 4 Encroaching seas and deepening near-shore basins<br>Diminishing volcanism *ca.* 10-7 m.y. ago | Widespread deep-marine deposits in Ventura and Los Angeles basins.<br>Local igneous intrusions, flows, and ash falls at Santa Catalina Island, Santa Monica Mountains, Palos Verdes Hills, Puente Hills, and San Joaquin Hills. |
| | | | 3 Formation of discrete basins and ridges and peak volcanic activity *ca.* 16-12 m.y. ago. Incipient rotation(?) | Shallow-marine deposits and tephra at Santa Cruz and Santa Catalina Islands. Marine-nonmarine breccias along southern mainland coast. Igneous intrusions, flows, and tephra in Santa Monica Mountains, margins of Los Angeles basin, and Santa Barbara, Santa Catalina, and San Clemente Islands. Volcanic rocks throughout inner borderland ridges. |
| | | | 2 Commencing basin development and initial volcanism *ca.* 24-20 m.y. ago | Basin-margin breccia at Santa Cruz and Santa Catalina(?) Islands. Igneous flows at San Miguel Island and Tanner-Cortes Bank area. |
| | | *ca.* 24 | | |
| | | Oligocene | 1 Plate-tectonic shift from convergent to transform regime *ca.* 30 m.y. ago | Disrupted magnetic-anomaly patterns. Transgressive shallow-marine deposits 30-23 m.y. old at Northern Channel Islands, Santa Monica Mountains, and northeast margins of Ventura and Los Angeles basins. |
| | | | Global low-standing sea level | Nonmarine deposits along margins of Ventura and Los Angeles basins and Santa Rosa and Santa Catalina Islands. Unconformities on San Miguel and Santa Cruz Islands. Marine deposits restricted to western Santa Ynez Mountains and southern Santa Rosa-Cortes Ridge. |

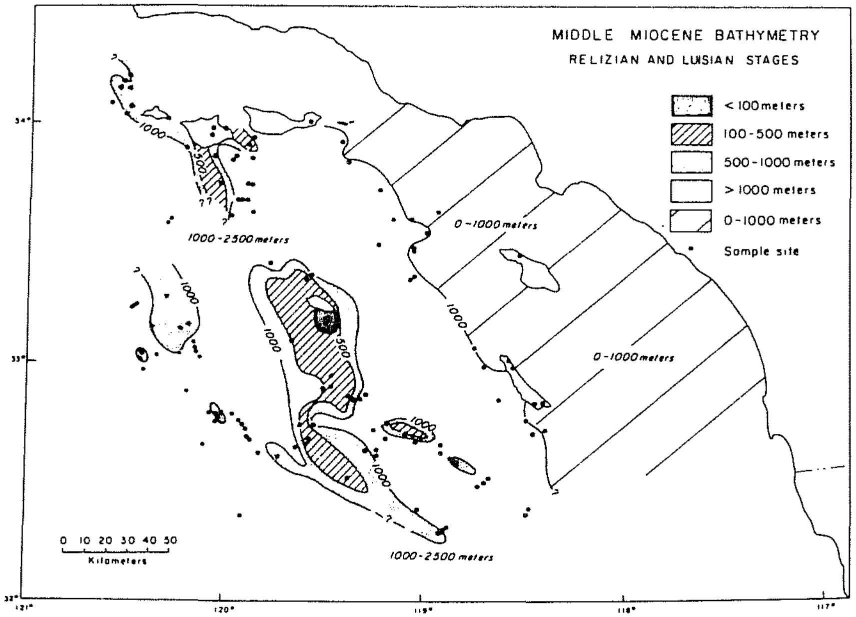


**FIGURE 3.** *Middle Miocene bathymetry inferred from selected benthic foraminiferal assemblages. Parts of the Santa Barbara Channel and the inner basins, banks, and shelf are generalized or omitted because of an insufficient number of available samples. Mainland basins are not included. Modified from Arnal (1976).*

ences based upon isolated or missing strata should be made with caution. For example, the local absence of late Miocene marine beds led Corey (1954, fig. 7) to depict several islands that otherwise are unsubstantiated. However, deep-water sediments of identical age (Vedder *et al.* 1974, 1976) have been cored on the seafloor adjoining the postulated large islands, suggesting that these strata may have completely draped the sites and subsequently were entirely eroded. Bottom samples from other places on the inner and outer ridge systems where Corey (1954) shows islands have yielded middle and lower bathyal foraminiferal assemblages (Arnal and Vedder 1976).

Beneath the seafloor, geologic structures ordinarily are interpreted from acoustic-reflection profiles, examples of which are shown in Figure 5. Growing structures that affected borderland topography and depositional patterns are manifested by unconformities that separate middle ' upper Miocene strata along the Patton and Santa Rosa-Cortes Ridges (J. K. Crouch, Arne Junge ... *litts.* 1977) and the flanks of the Santa Monica and San Pedro Basins (Junger and ... All of these discordant sequences may reflect the same episode or closely spaced uplift ... subsidence. Nearer to the former coast, similar discontinuities break the ... along the edges of the Ventura and Los Angeles basins. Identifica- ... faults ... folds that created the borderland uplift and subsidence and ... Pre-Pliocene faults that presumably contributed to ... margins and beneath many of the offshore basins ... 977, ... r 1979). The estimated maximum rate of

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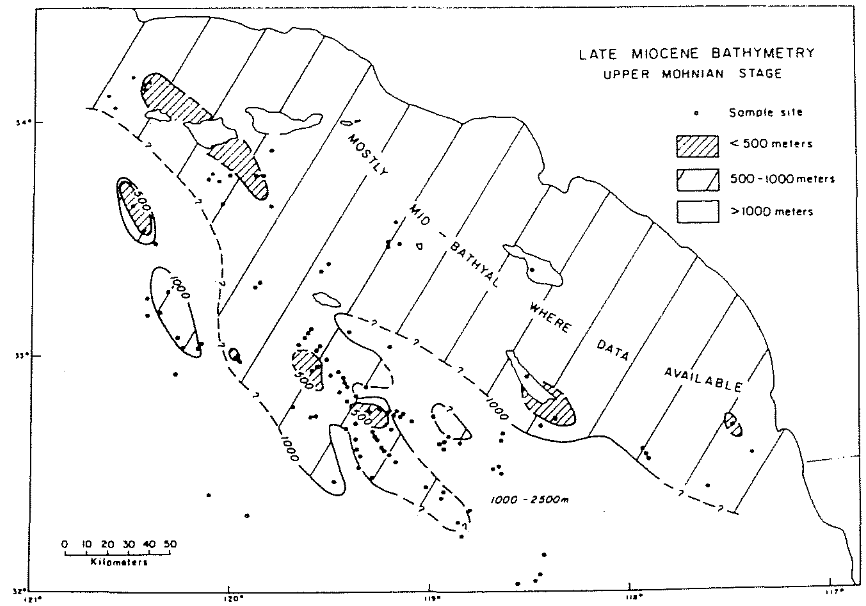


**FIGURE 4.** *Late Miocene bathymetry inferred from selected benthic foraminiferal assemblages. Mainland basins are not included. Modified from Arnal and Vedder (1976).*

late Miocene deformation in the offshore region is in the vicinity of Santa Catalina Island, where subsidence may have amounted to as much as 1.0 m per 1,000 years.

It is noteworthy that the greatest encroachment of seas and some of the deepest basins of late Cenozoic time in southern California developed near the end of Miocene time, perhaps in response to diminishing igneous activity and the concomitant subsidence that accompanied thermal cooling within the crust. This local deepening and advancing of the sea onto areas that now are far inland is well documented by the paleontologic record (Natland 1957, Ingle 1973). The shallow marine incursions combined with basin subsidence seem to be reflected in the vertical temperature gradients inferred by Addicott (1969) from coexisting marine invertebrates with different depth ranges. Shoreline configuration along the margins of these coastal basins is shown on Corey's (1954, fig. 7) map of late Miocene geography.

## PLIOCENE TOPOGRAPHY

Until a few years ago, Pliocene deposits had been recognized only on Santa Cruz Island; all other islands were believed to have been above sea level, and published paleogeographic maps omitted marine Pliocene from all of the modern ridges, banks, and islands of the borderland. However, thin remnants of nearshore marine beds of probable late Pliocene age were mapped beneath Pleistocene terrace deposits on northeastern Santa Cruz Island by Rand (1933) and Weaver and Meyer (1969). Shallow-water Pliocene strata have since been reported from San Clemente Island (Vedder and Howell 1976, Vedder and Moore 1976, Stadum and Susuki 1976), and correlative lower bathyal strata are now known to occur on Santa Catalina Island. Recent fieldwork on Santa Rosa Island has revealed the presence of calcareous sandstone beds that

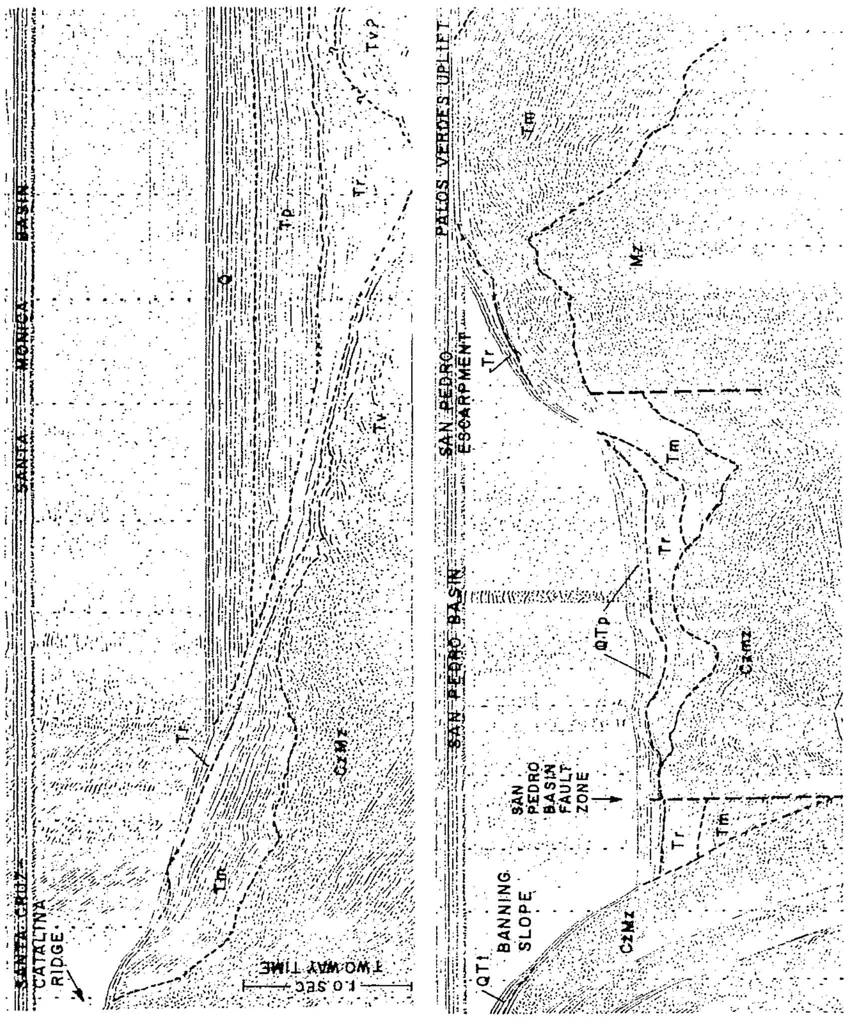


**FIGURE 5.** *Sub-bottom acoustic-reflection profiles across parts of the Santa Monica and San Pedro Basins showing interpreted rock units (letter symbols), structures, and unconformities (from Junger and Wagner 1977). Vertical exaggeration is approximately 6:1. The length of the profile across the Santa Monica Basin is about 35 km; across the San Pedro Basin, about 30 km.*

have yielded foraminifers which are assigned a late(?) Pliocene age by R. E. Arnal (*in litt.* 1977). In addition, shallow-water Pliocene mollusks embedded in volcanic detritus have been dredged from Northeast Bank (Hawkins *et al.* 1971). Outer sublittoral species of mollusks of possible Pliocene age are preserved in samples of fine-grained sandstone from southeastern Coronado Bank (Vedder *et al.* 1976). Each of these occurrences represents a stratigraphically incomplete and areally limited record that cannot be directly related to either the scattered



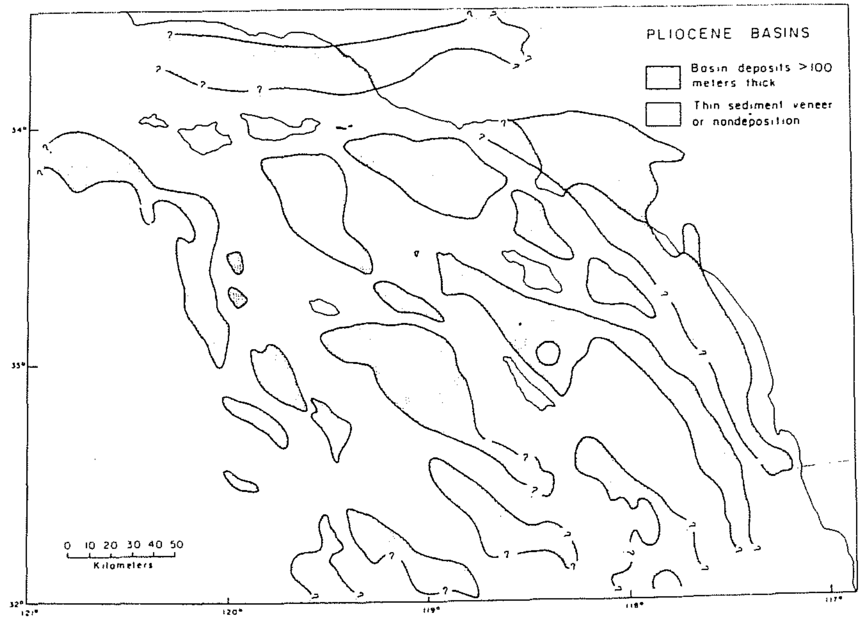


**FIGURE 6.** *Basins in which it is estimated that more than 100 m. of Pliocene and younger marine sediments were deposited. Intervening, unpatterned tracts indicate ridges and slopes where either thin veneers of sediment were laid down or where there was no marine deposition.*

outcrops on the mainland shelf or the nearly completely buried thick sequences in the deep basins. Pliocene insular platforms are difficult to identify on the borderland, because strata that might provide clues on their sites now are confined primarily to lower slopes and basins deeper than 500 m and are virtually inaccessible for study.

Along the mainland coast, very thick accumulations of marine sediments were deposited as turbidites in the now-filled parts of the Pliocene Los Angeles (4,200 m) and Ventura (3,800 m) basins, and deposition in these areas during the early part of the epoch was in water as deep as 1,500 m near Ventura and 2,500 m southeast of Los Angeles (Natland 1957, Ingle 1973). The thick, rapid sedimentation in these initially deep, down-bowing basins implies that the bordering highland areas to the north and east were being actively eroded, probably concurrently with continuing uplift and deformation (Conrey 1967, Yerkes *et al.* 1965, Crowell *et al.* 1966, Crowell 1976, Yeats 1965, 1976). In these basins, the influx of sediment seems to have kept pace with or surpassed the amount of subsidence with the result that seafloor relief may have become increasingly subdued.

Beneath the central Santa Barbara Basin, correlative strata are about 1,800 m thick; to the west and south, these beds thin and wedge out. In the Santa Monica and San Pedro Basins, maximum thicknesses of Pliocene rocks are 2,700 m and possibly 1,500 m, respectively (Junger and Wagner 1977). Equivalent sections are less than half as thick in the near-shore basins west of Oceanside and San Diego, and the basins seaward from the islands generally contain no more than 600 m of these sediments. Figure 6 shows the general outlines of Cenozoic basins in which more than 100 m of Pliocene sediment were deposited. The relatively thin sections in the outer basins suggest that adjacent submarine ridges and possibly islands impeded dispersal of terrigenous sediments and that pelagic debris and locally derived detritus from the barrier ridges was not voluminous. The geometry of these tracts of Pliocene basin deposits implies a seafloor topography that was much like that on the borderland today.

Unconformities within the basin-margin sections in the Santa Barbara, Santa Monica, and San Pedro Basins (Fischer 1976, Greene 1976, Junger and Wagner 1977) demonstrate that adjoining areas were being structurally deformed, particularly on the north and east. Pliocene unconformities have not been recognized in the outer basins where tectonism apparently did not effectively disrupt the comparatively slow accumulation of land-derived sediments.

Pliocene shorelines are preserved at few places in southern California. There is equivocal evidence for their presence on the north edges of Santa Rosa and Santa Cruz Islands, where dune deposits cap shallow marine beds on a surf-cut bench (Weaver and Meyer 1969), and on San Clemente Island, where deposition probably was in sublittoral environments not far from the surf zone (Vedder and Moore 1976). Along the mainland coast, embayed shorelines fringed the narrowing and filling Ventura and Los Angeles basins and the shoaling San Diego shelf during the latter part of the epoch, while the sea was retreating. Most of the paralic features, however, have been eradicated by subsequent erosion. Islands presumably occupied the present sites of the Santa Monica Mountains and San Joaquin Hills as delineated by Corey (1954, fig. 8), but evidence for strand lines in those places is obscure. Whether or not large islands were present on the outer borderland is conjectural. Even though the nearshore basins were receiving large amounts of sediment and the sea was withdrawing toward the end of Pliocene time, the axial parts of these basins remained as deep as 1,500 m in the vicinity of Ventura and Los Angeles, probably as a result of continuing subsidence and sediment compaction.

Late Pliocene marine strata now in water depths of 1,000 to 1,250 m near the northwest end of San Clemente Ridge contain foraminiferal assemblages that imply water depths of 2,500 m or more at the time of deposition, and early Pliocene beds on Santa Catalina Island contain species that now live in depths in excess of 2,000 m (R. E. Arnal *in litts.* 1977, 1978). These assemblages, therefore, suggest local uplifts on the borderland as much as 2,000 m since the early part of the epoch and 1,000 m since the late part; other areas, such as the San Diego shelf and perhaps the northern island platform, remained relatively stable. Maximum rates of uplift are estimated to have ranged between 0.5 and 0.7 m per 1,000 years.

Although it is possible that a Pliocene land bridge could have connected the northern island group with the mainland to the east (Greene 1976), it is unlikely that either the San Clemente or Santa Cruz-Catalina Ridges formed pathways for dispersal of the terrestrial biota because of the intervening deep water. Seafloor samples from these ridges rarely contain fossiliferous Pliocene strata, but where they do, the fossils usually indicate bathyal depths. Similarly, microfossil assemblages from discontinuous Pliocene deposits along the mainland shelf between San Pedro and La Jolla suggest water depths greater than 200 m. Because only Miocene and older rocks have been sampled from most of the Patton Ridge area, it is possible that parts of the ridge formed positive features from which Pliocene sediments subsequently were eroded.

## PLEISTOCENE-HOLOCENE TOPOGRAPHY

### Introduction

Crustal deformation and eustatic changes in sea level had a marked influence on mainland and borderland topography during the last two million years. Some of the features created by these changes were recognized as early as 1853 (Blake 1855, 1857), and they drew the attention of many early geologists. Fairbanks (1897) introduced one of his several studies on coastal and island landforms by stating, "Various interpretations of the records left by these movements have been given by different observers, but their results do not harmonize with each other, nor



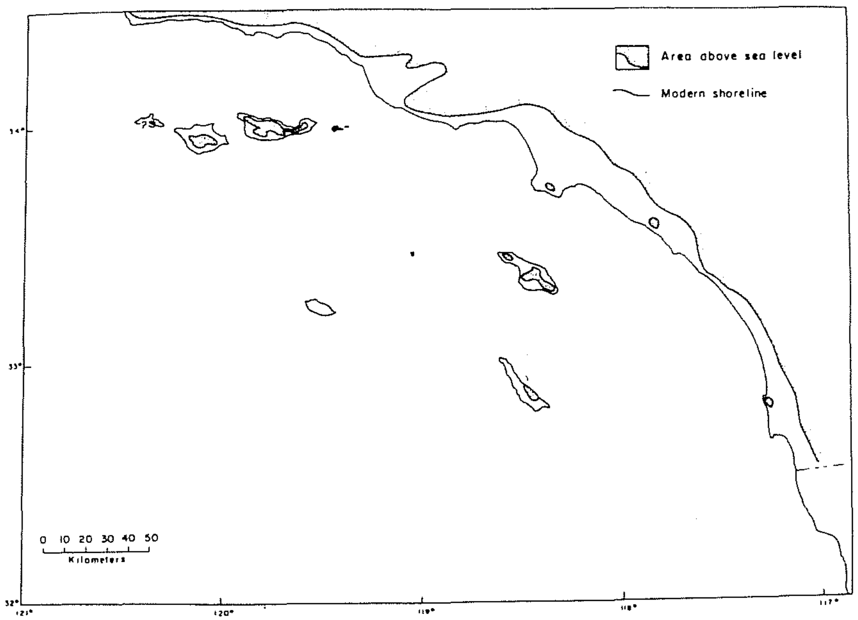


**FIGURE 7.** *Interpretive map showing maximum extent of the sea during the last 500,000 years. Patterned areas are those that presumably have been continuously above sea level. Because the geologic record is incomplete, neither a specific point in time nor a single ancient shoreline is implied.*

does any one of them appear to express the whole truth." This remark is as relevant now as it was then. In order to facilitate discussion, the effects of basin deposition, terrace development, tectonic deformation, possible land bridge sites, and submarine canyon cutting are treated under separate headings.

### Basin Deposition

Marine and nonmarine sediments accumulated rapidly in the coastal basins during Pleistocene time, while farther offshore, deposition of marine beds generally decreased with increasing distance from the mainland. Holocene deposits mantle these basin sequences nearly everywhere except along the edges of the Ventura and Los Angeles basins, but the dense spacing of wells drilled for oil in these two basins has provided substantive information on their thickness and composition, which in turn, give evidence of topographic development.

Near Ventura, the subsurface Pleistocene sedimentary section may be as much as 4,000 m thick, and near Los Angeles, about 1,500 m. Nonpersistent unconformities along the margins of these thick sequences attest to nearly continuous tectonic deformation and changing depositional trends. Similar unconformities are recognizable on acoustic-reflection profiles in the Santa Barbara, Santa Monica, and San Pedro Basins, where the sections are thinner (Greene *et al.* 1975, Fischer 1976, Junger and Wagner 1977, Nardin and Henyey 1978). In basins farther offshore, interruptions in sedimentation are less distinct, suggesting that tectonism diminished seaward. Although marine embayments reached well inland during the last 500,000 years (Fig. 7), by the end of the epoch, the mainland basins were completely filled. The comparatively thin

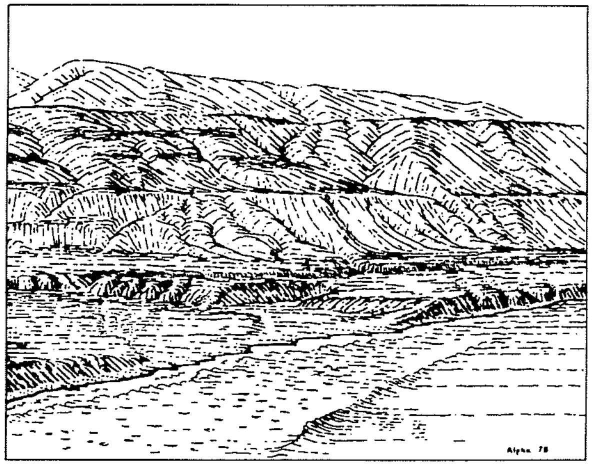

**FIGURE 8.** *Sketch of surf-cut platforms that reflect former sea-level stands at Pyramid Cove, San Clemente Island. View toward the northeast. The platform on the skyline has an altitude of about 300 m; the modern sea cliff in the foreground is 8 to 10 m high. Drawing by Tau Rho Alpha.*

sections in outer borderland basins indicate slow deposition far from source areas as well as differences in depositional mechanisms and agents. Late Pleistocene-Holocene rates of terrigenous sedimentation also diminished in the outer basins with the post-glacial rise in sea level, a change that is described by Emery (1960) and Gorsline, Drake, and Barnes (1968), although the rates vary from basin to basin. As a result of these slow sedimentation rates, the geometry of the outer basins probably has not changed significantly since the beginning of Pleistocene time.

## Terraces

Oscillation of sea level resulting from repeated growing and melting of Pleistocene polar ice caps is manifested by well-preserved marine shorelines in coastal southern California (Fig. 8). Superimposed on these eustatic changes were both provincial and local diastrophic events that may have surpassed all earlier episodes of tectonism in their amount and rate of development. Despite the fact that ancient surf-cut platforms (terraces) and their sediment cover both above and below the modern strand line provide a superb record of still-stands of sea level during the latter part of the epoch, the exact ages and correlation of many remain in doubt.

As pointed out by Putnam (1954), Sharp (1954), Vedder and Norris (1963), Bradley and Griggs (1976), and many others, correlation of terraces is difficult because of the influence of two variables: eustatic oscillation of sea level and disharmonious tectonic deformation of individual crustal blocks. These variables were not considered in most early reports, in which terrace cutting was ascribed primarily to regional uplift, and correlation was assumed to be simply a matter of matching altitudes. Figure 9 illustrates the differences between the numbers of recognized emergent terraces together with their maximum preserved altitude at selected places on the borderland and mainland coast. Other differences, not shown in the figure, are the inconsistent vertical spacing and width of platforms. Published maps and tables indicating terrace correlation must be used with caution because most of them do not specify the criteria used either for age control or for the identification of shoreline position, except in general terms.

As many as five well-defined submergent terraces between the depths of 10 and 130 m were recorded by Emery (1960), who believed that they dated from Wisconsin time and that they



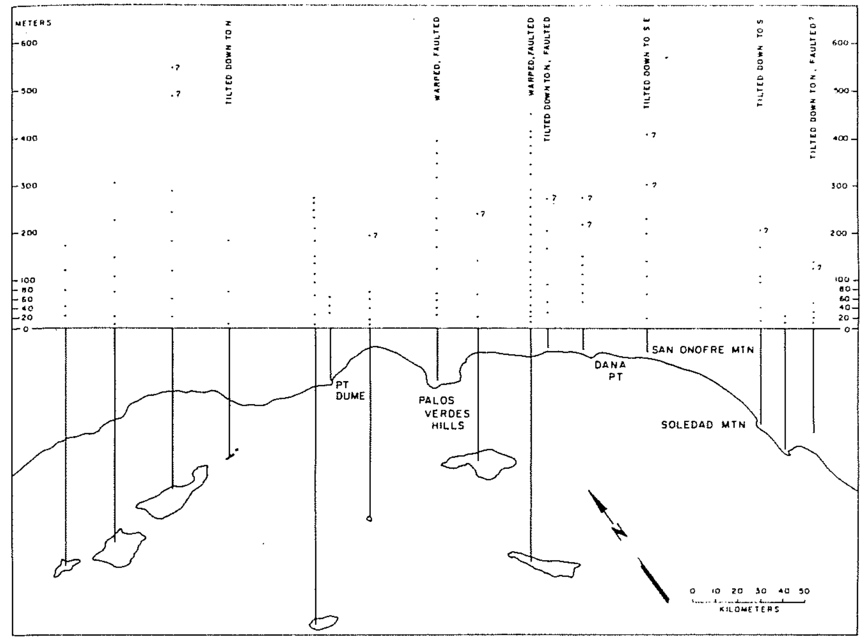


**FIGURE 9.** *Locations and altitudes of emergent terraces at selected places on the mainland and islands. The type of deformation is noted where all or part of a sequence is known to have been structurally modified. Sources of measurements are: San Miguel Island, Emery (1960); Santa Rosa Island, Orr (1960, 1967); Santa Cruz Island, Rand (1933); Anacapa Island, Valentine and Lipps (1963); San Nicolas Island, Vedder and Norris (1963); Point Dume, south side, Birkeland (1972); Santa Barbara Island, Lipps* et al. *(1968); Palos Verdes Hills, Woodring* et al. *(1946); Santa Catalina Island, Smith (1897, 1933); San Clemente Island, Lawson (1893), Smith (1898); Newport Beach, Vedder (1970); South Laguna-Dana Point, Vedder (unpubl.); San Onofre Mountain, McCrory and Lajoie (*in litt. *1978); Soledad Mountain, McCrory and Lajoie (*in litt. *1978); Point Loma, Kern (1977); San Diego Mesa, Hertlein and Grant (1954).*

since have been regionally tilted seaward. Later work indicates that some of these sub-sea platforms are likely to be local features and consequently are difficult to correlate and possibly can be attributed to other causes such as submarine slumping. It is noteworthy that the submergent terraces are both erosional and constructional in origin (Ridlon 1972, Fischer 1976, Junger 1978). M. E. Field (*in litt.* 1978) suggests that depositional terraces on the island platforms were built during regressive phases, effectively enlarging the shelves, but most of these terraces probably were destroyed during transgressive phases when erosional terraces were cut. Terraces deeper than 120 m along the Santa Rosa-Cortes and Santa Cruz-Catalina Ridges (Uchupi 1961, Junger and Wagner 1977) and elsewhere (Emery 1960) probably are older than late Pleistocene, and some may be as old as late Pliocene.

According to Curray (1965) and Milliman and Emery (1968), the sea last began to return to its present level about 17,000 to 18,000 years ago. During this low stand (Fig. 10) and subsequent

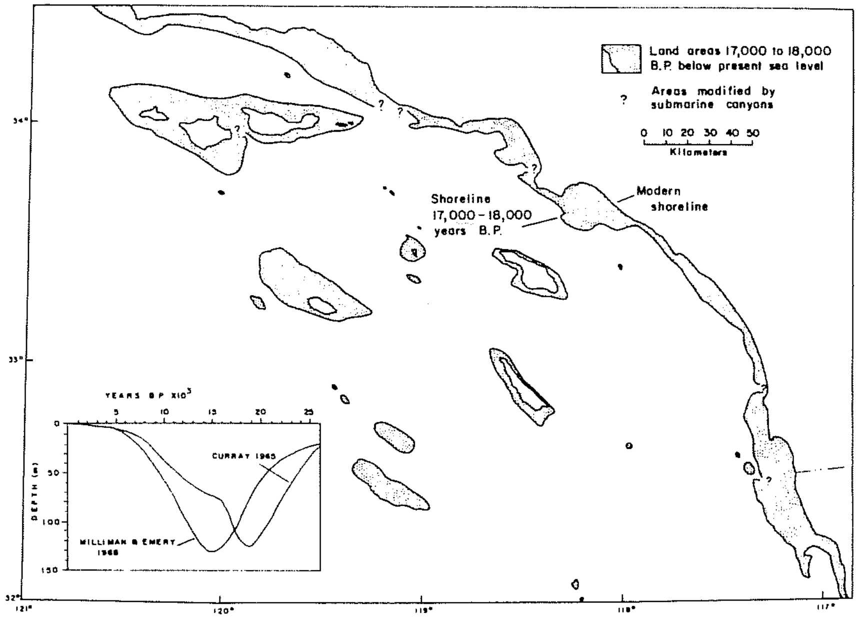


**FIGURE 10.** *Approximate position of the shoreline about 17,000 to 18,000 years ago, the time of probable maximum sea-level lowering to ±120 m. Sea-level curves adapted from Curray (1965) and Milliman and Emery (1968).*

transgression, the unusual eolianites (cemented dunes) and caliche deposits on the upper surfaces of the outer islands may have begun to form (Vedder and Norris 1963, Johnson 1967, Olmsted 1958).

Even though the Pleistocene Epoch represents a short period of time (1.5 to 2.0 m.y.), the lack of precise dating techniques, particularly for the older part, hinders accurate chronologic identification of the ancient shorelines. Recent application of radiometric and amino acid stereochemistry dating methods have been helpful (Veeh and Valentine 1967, Ku and Kern 1974, Szabo and Rosholt 1969, Szabo and Vedder 1971, Wehmiller *et al.* 1977). At present the areal coverage by these dates is spotty, and unbroken stratigraphic sequences have not been thoroughly sampled either within individual terrace deposits or through entire terrace flights.

## Deformation

Rates of tectonic deformation differed from place to place on the borderland and along the mainland coast throughout the last third of the Pleistocene Epoch. That the borderland consisted of independent structural blocks is evident from the lack of correlation between emergent surf-cut terraces on the islands and along the mainland coast (Fig. 8); these differentially moving blocks are further corroborated by seafloor faults and folds of Pleistocene and Holocene age (Vedder *et al.* 1974, Greene *et al.* 1975, Fischer 1976, Junger and Wagner 1977, Nardin and Henyey 1978). One of the most striking examples of deformation and erosion is evident in the vicinity of the Dos Cuadras and Carpinteria offshore oil fields southeast of Santa Barbara, where several thousand meters of Pliocene and early Pleistocene strata were



removed from the crest of a growing anticline during late Pleistocene and Holocene time to form a nearly flat seafloor.

Amino acid age inferences for terrace flights at San Nicolas Island, Palos Verdes Hills, and San Joaquin Hills imply different rates of uplift for each of these structural blocks as well as rate changes during the last 500,000 years (Lajoie and Wehmiller 1978). The highest estimated rate among these sites is slightly less than 1.0 m per 1,000 years at Palos Verdes Hills. Recent work by K. R. Lajoie and others (*in litt.* 1977) indicates that local tectonic uplift rates on an anticline along the Ventura coast amounted to more than 10 m per 1,000 years during the last 100,000 years. Extraordinary short-term uplift and subsidence have been measured throughout the now-active "Palmdale bulge," the effects of which have reached the Ventura area (Castle *et al.* 1977).

## Land Bridges

In the proceedings volume for the predecessor of this symposium, Valentine and Lipps (1967) reviewed the late Cenozoic history of the borderland and emphasized the implications of the Pleistocene marine fossil records on both the mainland coast and islands. Their well-documented discourse is still the commonly accepted interpretation of the Pleistocene physical geography of coastal southern California and for the occurrence of fossil land mammals on the Northern Channel Islands. They proposed that these animals migrated westward along a peninsula created by eustatically lower sea level during an interval or intervals of medial Pleistocene time, while coinciding uplift and erosion affected large parts of the mainland. Later, during the latter third of the epoch, eustatically rising sea level and local structural deformation severed the connection between the mainland and the west-trending peninsula to isolate the terrestrial organisms, which subsequently were subjected to endemic evolution. The authors concluded with the statement that sea level dropped more than 100 m below its present position with the last glaciation but not sufficiently to rejoin the northern island platform to the mainland.

Most geologists who have considered the locations of former land bridges to the southern California islands agree that the only plausible post-Pliocene link was one that projected westward from the Santa Monica Mountains through the Northern Channel Island platform. However, even this bridge has been questioned by Johnson (1973), and Junger and Johnson (1980) note that mammoth remains on San Miguel, Santa Rosa, and Santa Cruz Islands can be explained by the swimming capability of elephants and that acoustic-reflection profiles do not show evidence for a Quaternary subaerial ridge between Anacapa Island and the mainland. A bathymetric map of the area (Fig. 11) indicates a maximum water depth of about 250 m and a minimum distance of about 7 km between the 120 m isobaths in the narrows that separate the Anacapa Island shelf from the Oxnard shelf, a seaway that large mammals could have crossed (Sondaar 1977). In addition, the maps of Pleistocene sediments compiled by Fischer (1976) show that slope and basin deposits extended eastward as far as the site of Hueneme Canyon, a condition that would severely limit the bounding edge of a land bridge, if one existed.

Alternatively, Greene (1976) states that an emergent ridge connected the island platform to the Santa Monica Mountains during part of Pliocene or early Pleistocene time; however, this ridge probably pre-dated the arrival of mammoths in North America 1.3 m.y. ago (C. A. Repenning pers. comm. 1978). According to Edwards and Gorsline (1978) there is evidence of a west-directed late Pleistocene drainage network beneath the modern gap that possibly could indicate an exposed sill during lowest sea levels at the southeast end of the Santa Barbara Channel. Subsequent transgression then would have reopened the seaway. High-velocity tidal currents must have swept through the narrow passage during low sea-level stands; such currents certainly would have been a deterrent to the successful crossings of swimming animals. Slow subsidence of the southern shelf (Fischer 1976) possibly could account for the submergence of a


**FIGURE 11.** *Bathymetric map of the region between the Northern Channel Islands platform and the mainland. The 120-meter isobath is emphasized to indicate the probable configuration of the seaway and approximate shoreline position during the low stand of sea level about 17,000 to 18,000 years ago. Modified from National Ocean Survey Map NOS 1206N-16.*



late Pleistocene land bridge at the southeast end of the channel, a condition that might not be evinced from apparent structural and stratigraphic relations on acoustic-reflection profiles. In any case, if such a connection existed, it must have been a transitory feature.

Neither geological nor geophysical evidence substantiates any other Pleistocene links between the mainland and the islands or between the two island groups of the southern California borderland.

### Submarine Canyons

Nearly a century ago, bathymetric surveys along the California coast detected submarine canyons; since then, these remarkable features have attracted the interest of geologists as well as oceanographers. Not only are the canyons of the borderland one of the most striking elements of sub-sea topography, but they also are believed to be primary contributors to seafloor destruction at their headward ends and construction beyond their basinward ends. Even though the major canyons have been intensively studied, the time of origin and the erosive agents that cut them are in dispute. To describe the details of morphology and the history of development of the canyons is beyond the scope of this paper; Shepard and Emery (1941), Emery (1960), and Shepard and Dill (1966) discuss them at length.

Large canyons along the mainland shelf of southern California, such as Redondo, La Jolla, and Coronado, have walls from 250 to 500 m high and incised channels as long as 16 km. With the exception of Santa Cruz and Catalina Canyons, there are none on the flanks of the offshore ridges and banks that rival the near-shore canyons in size. Forerunners of the modern canyons may have begun to dissect newly formed borderland slopes as long ago as the Pliocene, yet the headward ends of some on the mainland shelf are actively cutting into strata as young as Holocene. It seems likely, therefore, that the carving processes endured through much of Quaternary time. Sharp bends along the courses of some canyons possibly are attributable to erosion along cross faults and straight courses of others to channeling along longitudinal faults. However, the origin of most of the southern California canyons cannot be directly related to structural deformation.

## CONCLUSIONS

Despite the obscurity of some episodes of the geologic history of coastal and offshore southern California, much more is now known about the evolution of borderland topography than was evident at the time of the 1965 symposium on the biology of the islands (Axelrod 1967, Orr 1967, Valentine and Lipps 1967). The mid-Cenozoic change in structural style that initiated basin and ridge development seems to be fairly well documented on the basis of both plate tectonic reconstructions and borderland geology. Even though we are unable to explain the kinematics of some tectonic relations, such as the inferred rotation of a large segment of the western Transverse Ranges, understanding of concurrent Miocene volcanic and sedimentary events now is fairly clear. Later phases of waning volcanism, subsidence, marine transgression, and sediment influx during Miocene and Pliocene time are recorded through interpretations of paleobathymetry based upon foraminiferal paleoecology and depositional trends. Eustatic sea-level changes and local intense structural deformation imposed a complex pattern of shoreline cutting and basin filling throughout the Quaternary. There is sufficient evidence, both geologic and geophysical, to demonstrate that land bridges were not primary features during the last half of the Pleistocene Epoch. The single possible link, which may have connected the Northern Channel Islands platform to the Santa Monica Mountains, presumably was ephemeral, if it existed at all.

Although we now have greater confidence in our reconstructions than we did a decade ago, much more work on seafloor geology is required before accurate paleogeographic maps can be compiled. Of particular significance is the need for refinement of dating techniques, which ultimately will provide a satisfactory resolution of events, especially in the Pleistocene. Exploratory drilling for petroleum, now under way, will yield valuable subsurface information as will proposed drilling solely for research purposes. Obviously, our comprehension of the geologic history of the borderland is limited, but the background furnished here may help guide future work.

## SUMMARY

Fragmentary geologic evidence suggests that coastal and offshore southern California changed from a shelf-slope setting to one of basins and ridges during late Cenozoic time. Precursory events that contributed to post-middle Miocene development of borderland features included a fundamental change from a convergent plate tectonic regime to one of right-lateral shear about 30 m.y. ago and a subsequent episode of widespread volcanism that persisted from about 24 to 10 m.y. ago. The ridge-and-basin configuration that was created by the right-shear stress field was overprinted with island-building composite volcanoes and lava flows that accompanied flourishing igneous activity. Toward the end of Miocene time (*ca.* 7 to 5 m.y. ago), near-shore basins, now on land, deepened and began to receive large amounts of terrigenous sediment derived from rising mountains to the north and east, while offshore features began to resemble their modern counterparts in shape and size. During the same time span, local subsidence was associated with diminishing and sporadic volcanism. The Pliocene (*ca.* 5 to 2 m.y. ago) was a time of rapid sediment accumulation in the near-shore basins and the beginning of accelerated tectonism that seems to have peaked during the Pleistocene to form large areas of high relief. Sea-level oscillations resulting from the waxing and waning of Pleistocene polar ice caps, combined with the differential uplift of crustal blocks, carved the mainland and islands into flights of surf-cut platforms. Although these terraces provide a remarkable record of former sea levels, they are difficult to correlate because of localized tectonic deformation. Apparent maximum uplift rates along the mainland coast exceed those estimated for the offshore region, where the highest rates probably averaged less than 1.0 m per 1,000 years throughout the late Tertiary and Quaternary.

If a Pleistocene land bridge joined the Santa Monica Mountains with the Northern Channel Islands, it presumably was an ephemeral feature, as marine geophysical data do not confirm its existence. Available geologic evidence does not substantiate any other Pleistocene connecting links between the mainland and the islands or between the two island groups.

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