from distant places where high SPM concentrations have been reported.

The onset of two of the largest peaks in the LTN record are of particular interest because they coincided with the closest approach of two atmospheric storms. At 1600 hours on 14 October, hurricane Evelyn made its closest approach only 40 km from our mooring. The most intense peak in light scattering also began at this time and lasted several days. A weaker, unnamed storm made its closest approach of 250 km on 30 October. These are the only developed storms that passed within 400 km during sampling.

Experiments on the continental shelf measuring currents, pressure, light scattering, and bottom topography have shown a correlation between the passage of atmospheric storms and periods of resuspended sediments (*17*). Bottom-current velocities, which regularly exceeded the critical erosion velocity during each tidal cycle, did not increase during the storms, but there was a strong correlation between large pressure gradients measured at the sea floor and sharp increases in the turbidity of the water (*17*). Atmospheric pressure variations on time scales longer than several days and space scales of thousands of miles should not alter the isostatic equilibrium of the deep ocean, because the change in atmospheric pressure is balanced by a change in the height of sea level and the pressure on the sea floor should remain constant (*18, 19*). Pressure measurements in the Mid-Ocean Dynamics Experiment (MODE) showed low coherence between atmospheric and sea-floor pressure in both deep and shallow water (*20*). However, if nonisostatic conditions are created by a rapidly moving tropical depression and a pressure gradient is propagated to the sea floor, a corresponding mass transport of water would be required (*19*).

In the deep ocean there has not been an experiment like that of Butman and Folger (*17*) which could definitely show a correlation between atmospheric and benthic storms, but there has been a report of large increases in near-bottom current velocities coincident with the passage of atmospheric storms (*21*). In an attempt to detect any relation between atmospheric and abyssal conditions in this study, atmospheric pressure and pressure gradients above the mooring were measured from daily weather charts and plotted next to the LTN record. No correlation was apparent other than the nearby passage of the two storms mentioned.

To verify a causal relation between atmospheric conditions and conditions on the deep-sea floor, it will be necessary to simultaneously measure pressure, SPM concentrations, and current velocity near the sea floor as well as atmospheric pressure during the passage of surface storms. Whatever the cause of the benthic storms shown by our data, their frequency and intensity are much greater than previously measured in the deep ocean.

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# Holocene Sea-Level Curves for Santa Monica Shelf, California Continental Borderland

Abstract. *A curve is constructed showing changes in sea level at the Santa Monica shelf over the past 18,000 years. The curve is based on radiocarbon dates, sedimentologic data, and high-resolution seismic stratigraphic analysis of late Quaternary terrace deposits. Sea level was 117 meters below its present position about 18,000 years ago. During the first 8000 years of the Flandrian transgression, sea level rose to at least 24 meters, fell to about 46 meters, and then rose to 20 meters, all below present sea level. Subsequently, sea level rose more slowly and without discernible interruption to its present position.*

Secular change in sea level is an important process variable in models of shelf sedimentation. Consequently, marine geologists have put forth a great deal of effort to determine the detailed history of Quaternary sea-level fluctuations. As a result of the interest in constructing a eustatic sea-level curve applicable to any shelf in the world, most of the studies have been restricted to areas thought to be tectonically stable. For this reason, a program aimed at deciphering sea-level

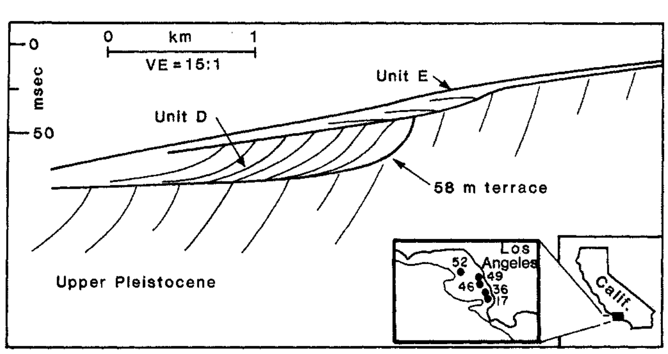


Fig. 1. Composite of inner shelf high-resolution profiles showing seismic facies and stratigraphic relations among late Quaternary units. Parallel onlapping beds of Holocene unit E and truncated clinoforms of Holocene unit D unconformably overlie upper Pleistocene foreset strata. Vertical scale is two-way travel time. Inset shows location of the study area.


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changes recorded in the shallow marine environment had not been organized for the southern California continental borderland (Fig. 1, inset). It is becoming increasingly apparent, however, that few coastal areas can be considered truly stable because, in addition to the eustatic and tectonic components of sea-level change, there appears to be a significant isostatic component related to loading of the sea floor by glacial meltwater (*1–5*). Therefore, sea-level curves appear to be valid only for the areas in which they are measured.

The California continental borderland provides a unique setting in which to study late Quaternary shelf history and sea-level fluctuations. In contrast to the intensively studied broad shelves along the western Atlantic and the Gulf of Mexico (*6*), the borderland is characterized by narrow mainland shelves and numerous insular shelves and banks formed by block faulting and folding during Neogene time. Examination of seismic reflection records representing several physiographic coastal types in the borderland suggests that a variety of coastal facies, remnants of lowered sea-level stands, have remained preserved beneath the shelves. Numerous erosional terraces and channels also can be recognized. Many of the deposits undoubtedly represent transgressive and regressive sedimentary sequences formed during periods of fluctuating sea level. It also appears likely that the ages of most of these sedimentary units and associated unconformities are Wisconsinan or younger. Thus, a study of these deposits could potentially provide information concerning the degree of late Quaternary deformation, the existence of a mid-Wisconsin high sea-level stand, the extent of reversals during the Flandrian transgression, and possibly the magnitude of the isostatic component of sea-level change.

The approach used in this study was to

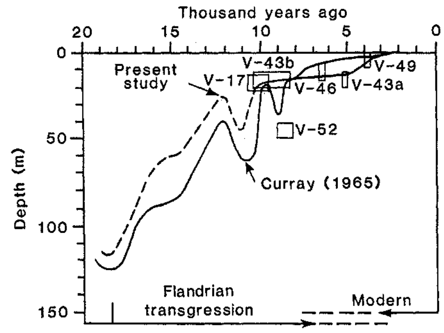


Fig. 2. Flandrian sea-level fluctuation curves for the Santa Monica and Texas shelves. Santa Monica curve is dashed where time control is lacking. Boxes represent ranges of possible time and depth errors for dated samples.

gather high-resolution (3.5-kHz) seismic reflection profiles together with vibracores to examine the stratigraphy and sedimentologic properties of the late Quaternary strata of the Santa Monica shelf. The depositional and erosional history of the shelf is discussed in the context of local sea-level fluctuations, particularly during the past 18,000 years.

The shelf, located 20 km west of Los Angeles, is a classic example of platform construction by sediment damming behind a structurally formed barrier (*7*). Strata beneath the outer shelf, between the Santa Monica and Redondo submarine canyons, are folded into a Miocene/Pliocene anticlinorium that is overlain by only a patchy veneer of sediment (*8*). In contrast, deep-penetration seismic reflection records reveal that strata beneath the inner shelf consist of thick, essentially undeformed Quaternary deposits. Sediments within the upper 200 m of the stratigraphic section are extensively cross-bedded and are contiguous with the upper Pleistocene San Pedro Formation and possibly other unnamed upper Pleistocene deposits that occur beneath the coastal plain (Fig. 1). These upper Pleistocene strata are thought to have been deposited as part of a fluvial-deltaic complex that prograded toward the western margin of the Los Angeles basin (*9, 10*). Sedimentologic, petrographic, and quartz grain-surface microtextural analyses of vibracore samples are consistent with this interpretation and show that the sediment was derived primarily from Precambrian and Mesozoic source terrains in the San Gabriel Mountains, 40 km to the east (*11, 12*). Examination of high-resolution seismic reflection profiles indicates that the upper Pleistocene strata can be divided into at least three units. These units are locally separated by unconformities that are interpreted as marine terraces possibly associated with Illinoian or Wisconsinan changes in sea level.

The Pleistocene strata are unconformably overlain by Holocene coastal and marine deposits that were largely derived from source rocks in the Santa Monica Mountains to the north as well as from reworking of Pleistocene sediment from the adjacent coastal plain and shelf (*12*). The Holocene strata locally are divisible into two units (termed D and E in ascending stratigraphic order) that are separated by an unconformity (Fig. 1). Seismic-stratigraphic analysis (*13*) of the shape and reflection patterns of the Holocene units and the erosional surfaces that bound them indicates that a major reversal in sea level occurred during their accumulation.

A datum for the maximum lowering of sea level before the Flandrian transgression (18,000 years ago) (*14*) is inferred from the base of a channel that was eroded to a depth of 117 m below present sea level at the shelf break (85 m below present sea level). This channel is filled with Holocene sediment and may be a continuation of a late Wisconsin coastal stream channel that is cut into upper Pleistocene cross-strata. However, wave-cut terraces have not been observed at this depth. The erosional sur-

Table 1. Radiocarbon ages of Holocene mollusk shells from Santa Monica shelf deposits; mbpsl, meters below present sea level.

| Sample | Depth (mbpsl) | Stratigraphic location and age (years) | Composition | Recent environmental ranges for sampled molluscan assemblages |
|---|---|---|---|---|
| V-49 | 8.5 | Basal transgressive deposit (3270 ± 120) | *Olivella pedroana, Donax gouldii, Anomia peruviana,* miscellaneous fragments | Littoral, inner sublittoral |
| V-46 | 15.7 | Basal transgressive deposit (6465 ± 160) | *Amiantis callosa*(?) | Littoral, inner sublittoral |
| V-43a | 19.5 | Basal transgressive deposit (5140 ± 170) | *Olivella pedroana, Nuculana taphria, Leptopecten latiauratus, Nassarius rhinetes,* miscellaneous fragments | Inner sublittoral |
| V-43b | 20 | Lagoonal mud (9420 ± 1120) | *Laevicardium substriatum, Tagelus subteres,* miscellaneous fragments | Littoral, inner sublittoral |
| V-17 | 20.5 | Basal transgressive deposit (10,165 ± 630) | *Polinices reclusianus* | Inner sublittoral |
| V-52 | 50.7 | Basal transgressive deposit (8590 ± 500) | *Olivella pedroana, Nassarius rhinetes,* miscellaneous fragments | Inner sublittoral |

face that separates Pleistocene cross-strata from Holocene unit D is a 4-km-wide marine terrace that dips about 0.1° across most of its width. The inner edge of the terrace is defined by a shoreline angle at 58 m below present sea level and the outer edge is defined by the shelf break. Although the terrace angle has not been dated, it is inferred from the terrace's configuration that it formed during a slow rise of sea level relative to the rate of sedimentation, perhaps followed by a stillstand near 58 m below present sea level (*15*). Landward of the shoreline angle, the dip of the Pleistocene/Holocene unconformity increases to as much as 10° and is truncated by a younger erosional surface at 24 m below present sea level. The presence of sigmoidal onlapping cross-strata in unit D suggests a rapid rise in sea level relative to the rate of sedimentation. The truncation of upper Pleistocene strata and unit D indicates a subsequent lowering of sea level. The erosional surface extends to 56 m below present sea level, which implies that sea level fell to at least 46 m below present sea level, thus allowing an additional 10 m for wave erosion (*16*). The final rise of sea level to its present position appears to have occurred without major interruption. Changes in the slope of the transgressive unconformity may reflect changes in the rate of sea-level rise. During this most recent transgression, the parallel onlapping beds of Holocene unit E were deposited.

The amplitudes and chronological sequence of Flandrian sea-level fluctuations are largely constrained by the seismic reflection data. Radiocarbon dating of Holocene shell material (Table 1) (*17*) from the coarse basal transgressive deposit of unit E and from lagoonal mud has permitted the partial calibration of a Flandrian sea-level curve (Fig. 2). All of the samples dated at less than 11,000 years and, with the exception of sample V-52, reveal that the sea-level fluctuations associated with the erosion of the 58-m terrace as well as the deposition of unit D and its subsequent truncation occurred before that time. Subsequently, sea level rose more slowly from 20 m below present sea level to its present position. Assuming that the dates for samples V-17 and V-43b are correct, sample V-52 yields an anomalously young age that is inconsistent with the seismic stratigraphy; thus contamination, reworking, or misidentification of the Pleistocene/Holocene boundary in the core is suspected (*18*).

An inspection of published late Quaternary sea-level curves shows that no single curve can be applied worldwide (*5*). However, the curve constructed from these data (Fig. 2) is similar in shape, although not necessarily in phase or amplitude, to those presented in other studies (*2, 5, 14, 19*). For example, a comparison with Curray's (*14*) Texas shelf curve shows similarities in shape for the last 18,000 years, but a second sea-level lowering in Curray's curve at 9000 years was not recognized in our study area. Differences in phase and amplitude can reflect local tectonic or isostatic conditions (*1–4, 6*). Relative to the Texas shelf, the inner Santa Monica shelf appears to have experienced uplift before 10,000 years ago and subsidence thereafter.

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18. In the less likely event that both samples V-17 and V-43b are in error and V-52 is correct, the curve would indicate that sea level was about 50 m below present sea level 8600 years ago (rather than 11,000 years ago), rose rapidly to 15 m below present sea level 5000 years ago, and rose more slowly thereafter.
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## *Riftia pachyptila* Jones: Observations on the Vestimentiferan Worm from the Galápagos Rift

Abstract. *The obturacular plume, composed of numerous tentacles, is suggested as a site for the uptake of molecular "food" by* Riftia pachyptila *(Pogonophora) from the Galápagos Rift; symbiotic bacteria are another possible source of nutrition. Differing organizations of the linings of the five major body cavities of* Riftia *demonstrate the inadequacy of "coelom" as a descriptive term.*

During investigations of the geothermal vents of the Gálapagos Rift region and the East Pacific Rise at 21°N, large worms were observed to form a major element of unique biological communities (*1, 2*).

A total of 63 worms collected at Dandelions, Garden of Eden, and Rose Garden geothermal vents in the Galápagos Rift area and from the East Pacific Rise have been deposited in the collections of the National Museum of Natural History (USNM), and these have formed the basis for a description of *Riftia pachyptila* Jones (*3*).

*Riftia pachyptila* is the only species in the family Riftiidae; the other two known vestimentiferan worms, *Lamellibrachia barhami* Webb and *L. luymesi* van der Land and Nørrevang are of the family Lamellibrachiidae. Together, the three species are the sole members of the order Vestimentifera Webb, the class Afrenulata Webb, and subphylum Obturata Jones. The trio, with the subphylum Perviata Jones (comprised of all pogonophoran worms with a bridle and lacking an obturaculum), are considered, at present, to make up the phylum Pogonophora.


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