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Distribution and Transport of Suspended Particulate Matter in Hueneme, Redondo, Newport, and La Jolla Submarine Canyons, California

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ABSTRACT

Studies of the distribution of suspended particulate matter in the waters over Hueneme, Redondo, Newport, and La Jolla submarine canyons off southern California are combined with analyses of recordings of canyon-floor currents to evaluate the influence of canyons on the seaward dispersal of fine, terrigenous sediment.

The canyon surveys were undertaken during the fall and winter months of 1971 to 1973 when suspended-sediment concentrations and composition over the mainland shelf are controlled principally by terrigenous-sediment supply. Consequently, particle concentrations at all levels generally increased toward the coast; highest values, exceeding 6 mg per l, were present in the Newport and Hueneme areas because of the relative proximity of large rivers. The vertical distribution of suspended particulate matter is influenced strongly by the density structure of the water column on the shelf and slope, and sharply bounded, midwater, turbidity maxima are well developed over the shelf where sediment supply is comparatively large. Nepheloid layers were present and ranged from a few meters to >200 m in thickness with peak particle concentrations of 5 to 7 mg per l over the inner shelf and within the steep-walled, headward portions of each canyon.

Although a nepheloid layer is a characteristic component of suspensate distribution in all sampled areas, maximum particle concentrations were <10 mg per l and therefore were far below those required to penetrate the water-column stratification and to produce significant density underflows. Nevertheless, computation by a modified Chézy formula of mean flow velocity due to suspended sediment above the canyon axes suggests that the slow, net downcanyon water transport demonstrated by Shepard and Marshall (1973) may be explained in part by the mechanism of turbid-layer flow. This conclusion is tentative, and the mechanism can only be evaluated adequately when more measurements of canyon currents and suspended sediment become available.

INTRODUCTION

Studies of processes controlling distribution and transport of suspended sediment in rivers and estuaries are numerous (see, for example, Ippen, 1966), and a relatively large and expanding body of data exists for the open ocean (Jerlov, 1968; Eittreim and others, 1969; Lisitzin, 1972; Plank and others, 1972). The intervening continental-shelf and -slope environments have received comparatively little attention. To improve our understanding of shelf-sediment transport, a research program on suspended particulate matter was initiated in 1969 off southern California (Drake, 1971; Drake and others, 1972). Recently, we focused our investigations on distribution and transport of suspended particles within submarine canyons. In particular, we attempted to evaluate the influence of canyons on seaward movement of terrigenous detritus in the light of measurements of canyon-floor currents by Shepard and Marshall (1969, 1973) and the hypothesis of turbid-layer flow or "autotransport" of sus-

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pended sediments (Bagnold, 1963; Postma, 1968; Moore, 1969; McCave, 1972).

We collected data in Hueneme, Redondo, Newport, and La Jolla canyons (Fig. 1). During surveys of the first three canyons, F. P. Shepard from Scripps Institution of Oceanography positioned two Isaacs-Shick current meters 3.6 m above the canyon floors to obtain comparative information on canyon-controlled currents.

METHODS

Our research has relied heavily on information gathered with a continuously recording beam transmissometer designed by the Visibility Laboratory of Scripps Institution of Oceanography (Petzold and Austin, 1968). This device consists of a current-regulated, 20-w, white-light source; photocell receiver; pressure transducer; and thermistor. Light transmission (0 to 100 percent) over a 1-m water path and temperature are recorded as functions of depth on a deck-mounted X-Y-Y′ recorder. Thermal drift of the electronic equipment can be monitored with an internal light path for reference. No drift has been detected over the temperature range encountered off southern California (20° to 5°C), and the instrument has been used in the Arctic Ocean with no detectable error due to thermal effects (R. Loudermilk, 1972, oral commun.).

Water layers of interest are sampled directly with Van Dorn and Niskin PVC water bottles. These samples (2 to 4 l) are filtered on shipboard through two preweighed Millipore HA 47-mm filter discs (0.45-μ nominal pore diameter), and the resulting particle-concentration data have been used to prepare a calibration curve relating light-beam transmission (percent T per m) and particle content (Fig. 2). Because beam transmission is controlled by both scattering and absorption and these parameters are in turn controlled by a host of other variables, a good correlation between beam transmission and particle density alone was not expected. If the set of values obtained in the Hueneme area in 1973 are neglected, however, the remaining points of Figure 2 show a correlation coefficient of -0.94. This excellent correlation suggests that during these surveys changes in particle-size distribution and variations in concentrations of dissolved, light-absorbing substances (see, for example, Jerlov, 1953) were minor. The points determined for the 1973 Hueneme survey generally fall ~10 to 15 percent below the curve for a given particle concentration. This survey immediately followed the largest period of precipitation and runoff for the 1972 to 1973 rainy season in southern California. Microscope sizing of particulate matter, recovered from the surface water over the canyon, yielded mean diameters (for 12 samples) ranging from 15 μ to 56 μ. Although size analyses of samples from the other canyon areas are not yet complete, the mean diameters of the Hueneme samples (1973) are typically larger at a given particle concentration. In particular, the Hueneme samples contain relatively large amounts (10 to 50 percent) of medium and coarse inorganic silt. Because light scattering increases with increasing particle size (Jerlov, 1968), it may be concluded that the 10 percent offset of the Hueneme (1973) data points is the result of a major shift in the particle-size distribution.

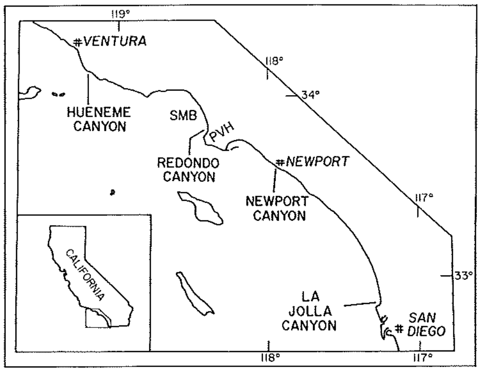


Figure 1. Location map. SMB = Santa Monica Bay; PVH = Palos Verdes Hills.

It is clear that the beam transmissometer is ideally suited for locating subsurface turbid

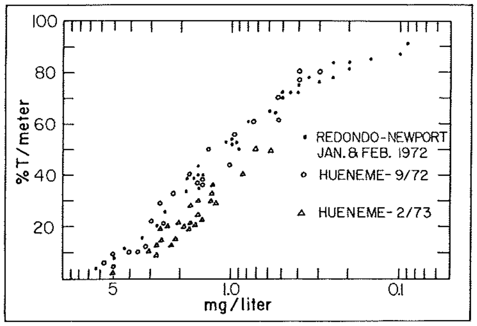


Figure 2. Scatter diagram of percent transmission per m versus total suspended-particle concentration in mg per l. Data points are based on samples collected in surface and near-bottom waters in each area. The 10 percent shift of the 1973 Hueneme data is probably the result of a change in particle-size distribution.

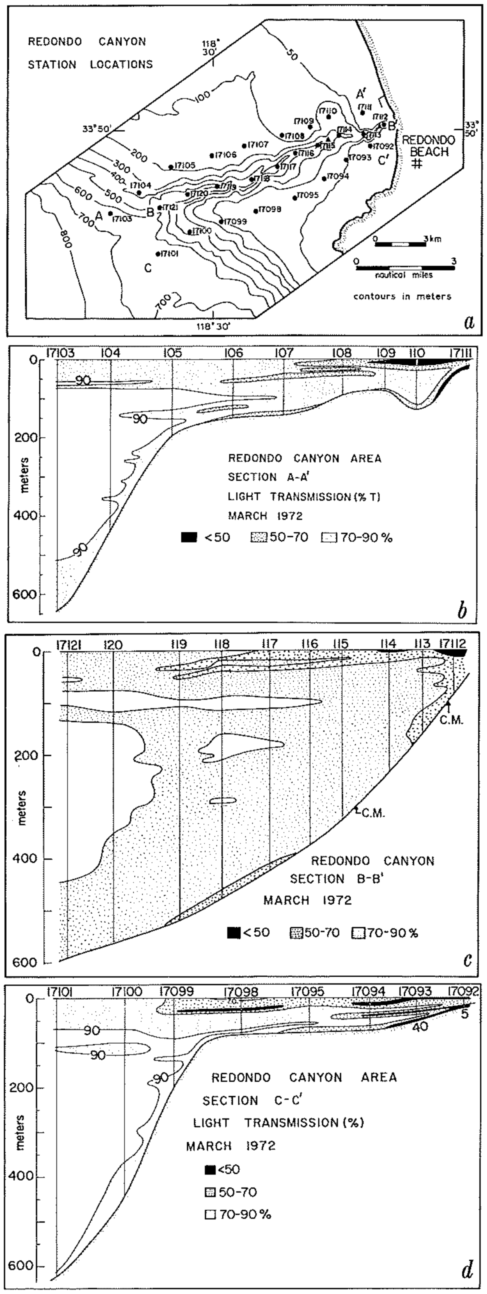


Figure 3. (a) Station locations and generalized bathymetry of Redondo canyon. Near-bottom current meters shown by solid triangles. (b) Light-transmission profile across the shelf north of Redondo canyon. (c) Light-transmission profile along Redondo canyon axis in March 1972. C. M. = current meter. (d) Light-transmission profile across the shelf south of Redondo canyon.

zones in coastal areas and can be used to estimate the particle content (particularly over the range from 0.4 mg per l to the extinction limit of the instrument), provided that particle-size changes and variations in concentrations of dissolved organic matter are not extreme. In any case, all particle-concentration values used for calculations in this paper are based on direct gravimetric analyses of recovered samples. In addition, while we believe the relation shown in Figure 2 allows us to make particle-concentration estimates from beam-transmission values, such estimates have a reliability of about ±20 percent at concentrations above 0.4 mg per l but are much less reliable at lower concentrations.

The Isaacs-Shick current meters are Savonius rotor, free-vehicle systems (Isaacs and others, 1966; Shepard and Marshall, 1973). The speed range monitored can be preset. In canyon operations, the meters have been adjusted to cover a range of ~0.5 cm per sec to 70 cm per sec.

STUDY AREAS

Hueneme, Redondo, Newport, and La Jolla canyons were studied to provide a variety of geographic and sedimentologic settings (Figs. 3 through 6). In addition, information on bottom currents is available for each canyon (Shepard and Marshall, 1973), and comparable background data on suspended sediments are available for Redondo and Newport canyons (Beer and Gorsline, 1971; Felix and Gorsline, 1971).

All of the canyons head within 200 m of sand beaches and, therefore, are potential sinks for sediment moved by longshore drift. Bottom-sediment textures along the canyon axes and surrounding the heads demonstrate that Hueneme, Redondo, and La Jolla canyons intercept a large portion of the available sand and silt (Haner, 1969; Shepard and Dill, 1966), whereas Newport canyon does not (Felix and Gorsline, 1971). Although Newport canyon heads within 3 km of the Santa Ana River and only 30 km southeast of the Los Angeles and San Gabriel Rivers, recent adjustments in stream channels and coastline orientation (combined with a predominance of long-wave swell from southern quadrants) have shifted the loci of sand input (Felix and Gorsline, 1971). Accordingly, surface sediments, even in those parts of the canyon accessible to scuba, are fine-grained, organic-rich, clayey silts containing less than 5 percent sand. Accumulation

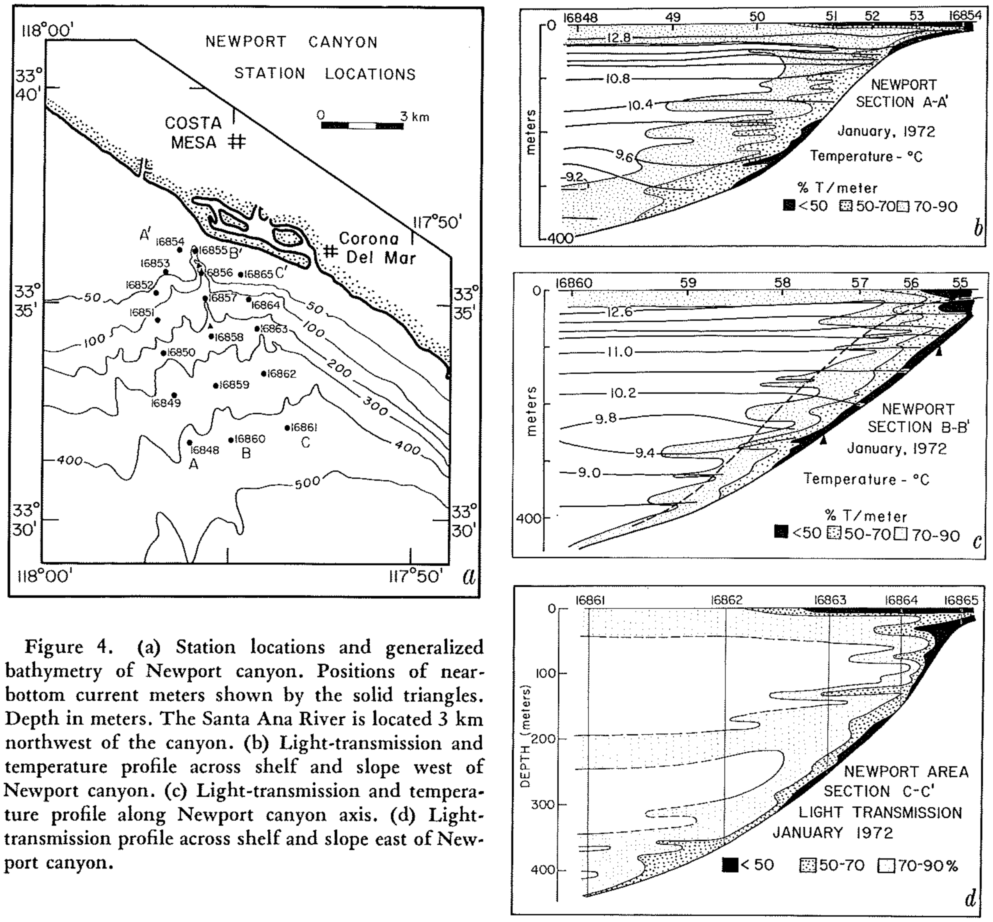


Figure 4. (a) Station locations and generalized bathymetry of Newport canyon. Positions of near-bottom current meters shown by the solid triangles. Depth in meters. The Santa Ana River is located 3 km northwest of the canyon. (b) Light-transmission and temperature profile across shelf and slope west of Newport canyon. (c) Light-transmission and temperature profile along Newport canyon axis. (d) Light-transmission profile across shelf and slope east of Newport canyon.

of stable mud in the canyon head led to the conclusion of Felix and Gorsline (1971) that the present canyon is "inactive."

While it is difficult to estimate the relative amounts of sediment available to Redondo and La Jolla canyons, both are relatively removed from large rivers, and their adjoining shelves are covered by thin deposits of fine to coarse sands (with abundant shell fragments off La Jolla) and silty sands (Emery and others, 1952; Emery, 1960; Kolpack, unpub. data). On the other hand, Hueneme canyon is located within 10 km of the Santa Clara River, the largest river in southern California in terms of discharge and suspended load. A one-year study of coastal-water transparency (Stevenson and Polski, 1961) indicated that the four canyon areas receive suspended particulate matter in the following decreasing order: Hueneme, Newport, Redondo, and La Jolla. This qualitative ranking is supported by the results of our study.

In addition to significant differences in proximity to sediment supplies, the canyons differ markedly in morphology. Newport canyon is among the smallest of the named canyons off southern California in both length and maximum relief and incises one of the narrowest segments of the mainland shelf (3 to 5 km in width). The physical settings of Hueneme, Redondo, and La Jolla canyons are similar in that they head to the north of coastal promontories and are alike in over-all dimensions. The shelf off Redondo, however, is nearly twice as wide as the shelves off Hueneme and La Jolla canyons; and, whereas La Jolla and Hueneme canyons exhibit a sinuous course typical of most southern California canyons,

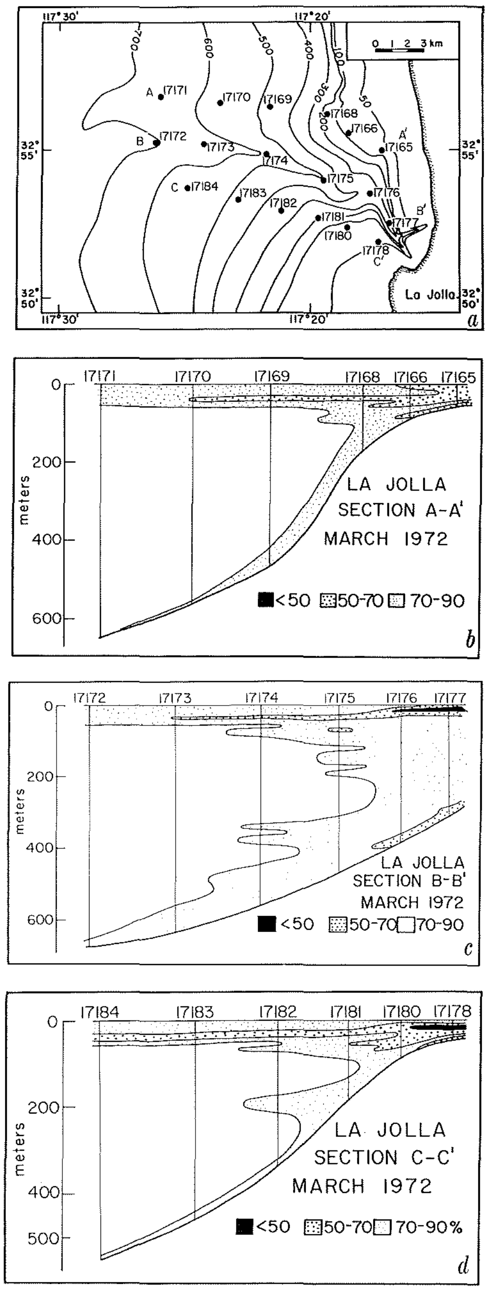


Figure 5. (a) Station locations and generalized bathymetry of La Jolla canyon. Depth in meters. (b) Light-transmission profile across shelf and slope north of La Jolla canyon. (c) Light-transmission profile along La Jolla canyon axis. (d) Light-transmission profile across shelf and slope south of La Jolla canyon.

Redondo canyon is unusually straight owing to important structural control (Yerkes and others, 1967).

All of the canyon surveys have coincided with periods of light and moderate sea breezes with maximum wind velocities reaching 26 km per hr. Wind conditions were similar during the week preceding each survey. Consequently, sea conditions were characterized by short, local waves of <0.5-m amplitude. Groundswell amplitudes also were low (0.2 to 0.5 m) with periods ranging from 6 to 12 sec (Los Angeles County Lifeguard Department, unpub. data).

F. P. Shepard (1972, oral commun.) has found that sea-state and wind variations during generally fair weather periods cannot be correlated with canyon-current variations. Therefore, it will be assumed that the small weather and sea-state variations which occurred during our surveys had no significant effect on suspended-sediment distributions seaward of the littoral zone. Extended periods of high winds (>36 km per hr) would be expected to generate significant wind-drift–circulation systems as demonstrated by the current observations of Cannon (1972) at the head of Juan de Fuca canyon and Reimnitz (1971) in Rio Balsas canyon, Mexico.

River runoff prior to and during all of our surveys except the 1973 Hueneme study was insignificant (U.S. Geol. Survey Water Supply records). The Hueneme (1973) survey immediately followed the largest rainstorm of the season in southern California. Data collected during September 1972 in the Hueneme area are considered representative of conditions of no river runoff and, therefore, provide a basis for assessment of the impact of a relatively large discharge of fluvial sediment.

CANYON-FLOOR CURRENTS

For the past four years, F. P. Shepard's group has measured canyon-floor currents along the Pacific Coast of the United States and Mexico. Based on 45 records (2- to 15-days duration) in 7 canyons, the following general conclusions are set forth by Shepard and Marshall (1973):

1. Current directions are confined predominantly to up- and downcanyon, and direction changes usually occur in <30 min.
2. There appears to be a relation between depth and frequency of current reversals. Be-

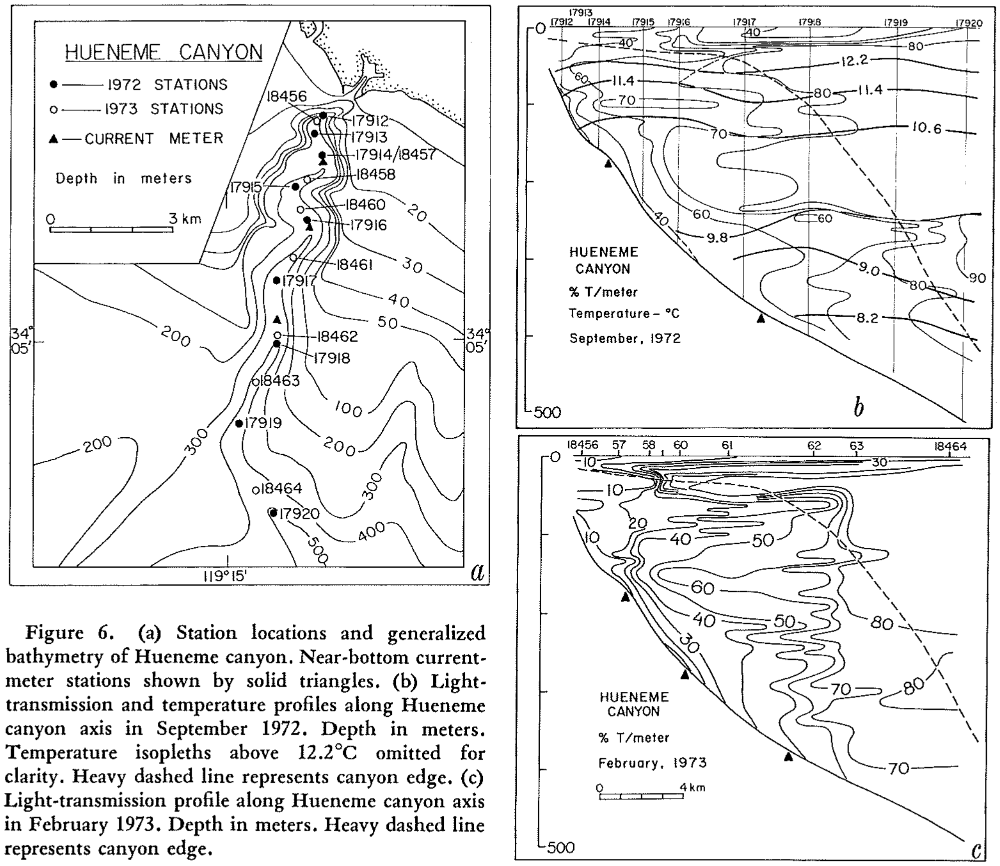


Figure 6. (a) Station locations and generalized bathymetry of Hueneme canyon. Near-bottom current-meter stations shown by solid triangles. (b) Light-transmission and temperature profiles along Hueneme canyon axis in September 1972. Depth in meters. Temperature isopleths above 12.2°C omitted for clarity. Heavy dashed line represents canyon edge. (c) Light-transmission profile along Hueneme canyon axis in February 1973. Depth in meters. Heavy dashed line represents canyon edge.

low ~250 m, reversals are less frequent and approach tidal periods, whereas shoaler stations show increasingly shorter and less regular periods (ranging from 12 min to ~4 hr). Table 1 is based on data presented by Shepard and Marshall (1973) and illustrates the apparently abrupt change in average current-reversal period between ~200 and 300 m in each southern California canyon. Reversal periods are typically twice as long in the lower reaches of each canyon; therefore, occurrence of opposed currents along canyon floors should be common. The important implications of this interpretation with respect to suspended-sediment distributions are discussed below.

3. Ninety percent of the records show that downcanyon flows typically are stronger and last longer than upcanyon flows. There is no consistent relation between depth in the canyon, current velocity, and predominance of downcanyon displacements.

4. The highest velocity measured thus far is 48 cm per sec (Hueneme canyon), and, except during storms (Inman, 1970), wind and sea conditions have no obvious effect on canyon-floor currents.

Figures 3a, 4a, and 6a show the locations of the current-meter stations in Redondo, Newport, and Hueneme canyons. Although no current data were obtained in La Jolla canyon during our survey, the typical current characteristics are well known from previous investigations (Shepard and Marshall, 1969, 1973). The current-meter data presented here were made available by F. P. Shepard, and more detailed discussions of data-reduction methods are found in Shepard and Marshall (1969, 1973).

Owing to mechanical problems, only one 2- to 4-day record containing both current speed and direction has been obtained at each of the deep stations in Newport and Redondo canyons. A relatively long record of current direction only was obtained in Redondo canyon at 283 m in October 1971. In addition, because placement of the bottom meters is accomplished

TABLE 1. CANYON-CURRENT STATISTICS*

Canyon	Depth (m)	Highest velocity (cm/sec)	Average flow length (min)	
			Up	Down
La Jolla	46	26	65.6	53.5
La Jolla	78	17	76.0	60.0
La Jolla	167	29	75.0	94.0
La Jolla	206	29	74.0	97.0
La Jolla	375	22	216.0	247.0
Newport	101	17	87.0	105.0
Newport	252	11.5	168.0	255.0
Redondo	92	27	87.5	114.9
Redondo	283	19	231.0	91.0

**Modified after Shepard and Marshall (1973).*

by free fall from the surface ship, successful positioning of deeper meters can be questioned. No direct or indirect check on this is used.

Placement of shallow meters (<150 m) is more certain and good data are available for nearly 20 days and 6 days for Redondo and Newport canyons, respectively. At 100 m in Newport canyon, the bottom currents averaged 0.92 cm per sec with a total range from below threshold to 17 cm per sec. The total time of downcanyon flow was 10 percent longer than upcanyon flow and resulted in a net downcanyon-transport rate of 34.1 m per hr. Data for the 252-m station in Newport canyon are limited to one 3-day record that shows a very low mean velocity of 0.16 cm per sec, a peak of 11.5 cm per sec, and no net water displacement. The average reversal periods are markedly different even though these stations are only 3.6 km apart: 3.3 hr at 100 m and 7 hr at 252 m.

Data from the 92-m station in Redondo canyon reveal a mean velocity of 1.97 cm per sec, a peak of 27 cm per sec (downcanyon), and net displacement rate of 34.2 m per hr downcanyon. The net displacement rates at similar depths in Redondo and Newport canyons are virtually the same. Additionally, the average reversal periods at these stations differ by only 10 min. The similarity of net displacements and flow periods in these bathymetrically different canyons suggests that canyon geometry exerts little control over these current characteristics. On the other hand, it is probable that the relative weakness of the Newport canyon currents is related to canyon size.

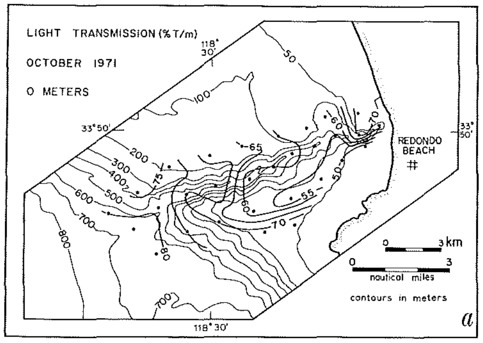
Near-bottom current-meter stations were established at 172 m and 372 m in Hueneme canyon in September 1972; in February 1973, an additional station was located at 280 m. These data have not been completely processed; mean velocities and net displacement values therefore are not available. Those portions of the current records that directly pertain to times of suspended-sediment sampling are discussed below.

Twenty-four successful bottom-current records have been obtained in La Jolla canyon at depths of 167, 206, and 375 m (Shepard and Marshall, 1969). Mean velocities range from 1.12 to 2.51 cm per sec with peak velocities approaching 30 cm per sec and net downcanyon-displacement rates ranging from 15.8 to 63.6 m per hr. Reversal periods are approximately 3 hr at the two shoaler stations but increase to nearly 8 hr at 375 m.

In all of the canyons, flows exceeding 18 cm per sec are infrequent: there were none in Newport, <0.1 percent of the total record from Redondo, and <1 percent of the total record from La Jolla. These data suggest that bottom scour and sediment resuspension should occur infrequently in the canyons (see Hjulström, 1939; Southard and others, 1971). However, samples of the nepheloid layer (1 m above the bottom) in Redondo and La Jolla canyons contain particles as large as 100 μ at depths of 375 m. The presence of significant percentages of suspended coarse silt and very fine sand above the canyon floors implies important sediment scour. These data are discussed in a following section.

DISTRIBUTION AND COMPOSITION OF SUSPENDED PARTICULATE MATTER

Suspended particles over the mainland shelf off southern California tend to concentrate within more or less distinct layers controlled by water-column stratification and proximity to the sea floor (Drake, 1971). In general, concentrations are highest within or above the main thermocline (typically developed between 30 m and 80 m) and within a nepheloid layer. The particle content of both layers increases toward the shore in response to the increasing effectiveness of wave-associated currents. Marlette (1954) and Gorsline (unpub. data) found concentrations of 0.2 g per l to >1 g per l just above the bottom at depths <7.5 m off two southern California beaches, and concentrations >20 g per l are common within the surf zone (B. M. Brenninkmeyer, 1972, oral commun.). Particle concentrations decline rapidly seaward to values that are generally below 10 mg per l throughout the water column at depths >20 m (Drake, 1972). The strong seaward gradient (particularly near the sea floor) over the depth range of ~10 m



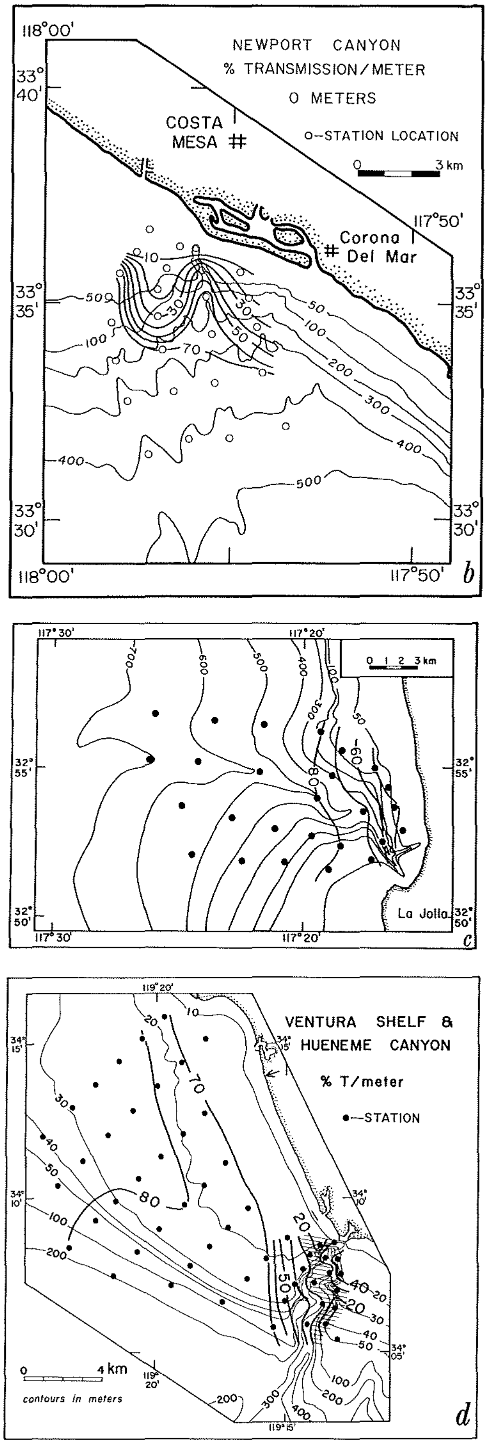


Figure 7. (a) Distribution of light-attenuating material at the sea surface over Redondo canyon in October 1971. (b) Distribution of light-attenuating material at the sea surface over Newport canyon in January 1972. Values seaward of 70 percent isopleth ranged from 71 to 78 percent. (c) Distribution of light-attenuating material at the sea surface over La Jolla canyon in March 1972. Values seaward of the 80 percent isopleth ranged from 81 to 86 percent. (d) Distribution of light-attenuating material at the sea surface over Ventura shelf and Hueneme canyon in September 1972. Areas with less than 20 percent *T*/m are lightly cross-hatched. The Santa Clara River is indicated by the arrow.

to 30 m usually coincides with those depths at which loosely deposited silt begins to blanket the shelf (Emery, 1960). The data discussed here are limited to shelf areas deeper than 20 m.

Ratios of inorganic to organic suspended particulate matter off southern California vary with season, depth, and distance from sources of terrigenous detritus. Concentrations of organic matter, determined by combustion of Millipore filters at 450°C, typically are highest in the euphotic zone but rarely exceed 60 percent (by weight) even in areas of upwelling and during spring plankton blooms within 30 km of shore (Drake, 1972). Combustible-particle concentrations in the surface waters and 1 m above the bottom were determined for several representative samples in each canyon area. Surface-water values ranged from 4 to 26 percent with the highest percentages found at the seaward limits of each survey grid. Values near the sea floor showed an inverse relation to depth, but the total range for all samples was only from 3 to 12 percent. Thus, suspended sediment at all depths was predominantly inorganic because of the low fall and winter rates of plankton productivity. These data are substantiated by microscopic inspection of Millipore filters.

Redondo Canyon

Concentrations of suspended sediment at the surface in the Redondo canyon area ranged from 1.2 mg per l to <0.3 mg per l in October 1971 and from 1.6 mg per l to 0.4 mg per l in March 1972. During both surveys and also during two surveys in 1967 (Beer and Gorsline, 1971), the highest values were observed over the shelf to the southeast of the canyon head (Fig. 7a). This consistent pattern is the result of wind-driven transport of surface water by prevailing northwesterly winds (Stevenson and others, 1956). Turbid water produced by wave agitation at shallow depths is swept southward along the coast to the Palos Verdes peninsula where it turns to the west. Seaward of the peninsula, this particle-rich water is entrained by northward-flowing offshore currents and transported back across the canyon mouth. Beer and Gorsline (1971) noted similar distributions in 1967 but attributed the higher concentrations over the canyon mouth to slightly increased plankton productivity.

Vertical profiles of light transmission over the shelves adjoining Redondo canyon show that relatively high particle concentrations extend from the surface to the main thermocline in all areas (Figs. 3b, 3d). Because of particle settling, peak concentrations within the surface layer only occur at the sea surface over the inner shelf within 2 to 3 km of the shore. Material within the surface layer is predominantly inorganic fine silt and clay that is thrown into suspension by surface waves and rip currents at shallow depths. Along with a general seaward decline in concentrations, suspended particles settle to the thermocline; this results in subsurface particle maxima over the middle and outer shelf. In detail, the character of such maxima (the sharpness of their upper and lower boundaries) is closely related to the density gradients and microstructure of the thermocline (Fig. 8).

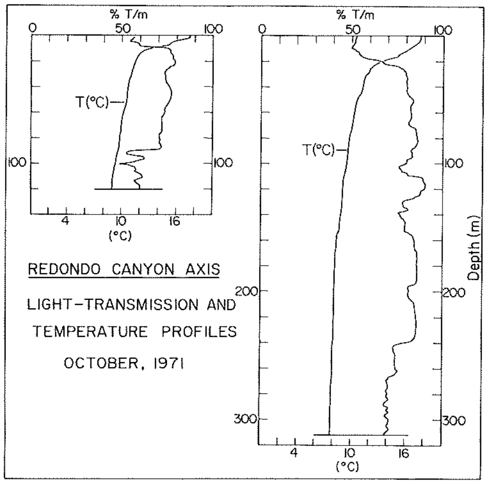


Figure 8. Light-transmission (percent *T*/m) and temperature profiles at 120 m and 310 m along the Redondo canyon axis.

Particle distributions below the main thermocline are similarly controlled by the sediment supply and the density stratification of the water column. In the simplest cases, concentrations decrease by factors of 2 to 4 near the base of the thermocline and remain relatively low and uniform before increasing again near the sea floor. In most areas, however, vertical profiles of temperature variation are composed of several nearly isothermal layers separated by abrupt, steep gradients. The density discontinuities are sufficient to temporarily retard the passage of fine particles to deeper water layers.

Nepheloid layers ranging in concentration from 5.1 mg per l to ~0.2 mg per l were present at all stations during three surveys of the Redondo canyon area. The thickness of this layer over the shelf ranged from a few meters to about 25 m but showed no consistent variation with depth.

The bulk of the water within Redondo canyon contains between 0.5 and 0.1 mg per l of suspended particulate matter (Figs. 2 and 3c). Concentrations approaching or exceeding 1.0 mg per l were observed near the bottom only in the upper canyon at depths of <200 m and in the central canyon between the depths of 300 and 500 m. Whereas the turbid water filling the canyon head can be readily attributed to particle settling from nearshore waters, the relative increase in the central canyon is not as easily explained. The axial distribution of suspended particles and water temperature in October 1971 (Fig. 9) shows an even more striking turbidity maxima at ~250 m near the canyon floor. The stations used to construct this profile (Fig. 9) were completed in 15 hr beginning at station AHF 16546. During this period, bottom currents were measured at depths of 92 and 280 m; the deep meter recorded only direction. Near-bottom currents at 92 m completed 5 up-down cycles over the 15-hr period with current speeds ranging from <0.5 cm per sec to ~18 cm per sec. Directional reversals at 280 m demonstrate 2.5 up-down cycles in the central canyon.

In particular, stations 16548 through 16550, which revealed the turbidity maxima in the central canyon at ~250 m, were sampled when near-bottom flow had been upcanyon for ~3 hr at 280 m and downcanyon at 92 m. The persistent upcanyon flow is clearly reflected in the temperature distribution (Fig. 9). The maxima marks the convergence of these opposing flows. Development of this phenomena (which is not unlike a turbidity maxima in stratified estuaries) principally between 200 and 400 m is compatible with the reversal-period data in Table 1. Other convergence zones are probable, nevertheless, and specific experiments should be designed to clarify the dynamics of these phenomena.

Newport Canyon

The southern portion of San Pedro shelf receives a relatively large supply of terrigenous sediment from the Los Angeles, San Gabriel, and Santa Ana Rivers (Rodolfo, 1970). The Santa Ana River (3 km northwest of Newport canyon) delivers an average of 6.5×10^4 metric tons of silt and clay each year. In addition to the natural supply of material from the coastal watershed, the area receives sewage effluent from the Orange County sewer line that terminates 4 km northwest of the canyon in 18 m of water. Felix and Gorsline (1971) conclusively demonstrate that a significant, but indeterminate, amount of organic-rich, particulate sewage is transported eastward to the canyon where much of it accumulates on the western canyon wall.

During two surveys of the Newport area, suspended-sediment concentrations above the thermocline over the shelf ranged from 3 to 6.2 mg per l, ~2 to 3 times higher than those observed over the Redondo shelf. Surface concentrations rapidly decrease beyond ~3 km from the shore to values that are essentially equivalent to those over the outer shelf and slopes in Santa Monica Bay (Fig. 7b). Surface water containing more than 1.0 mg per l of particles generally is restricted to within 4 km of the coast in both areas; in the Newport area, however, owing to the narrowness of the Newport shelf, surface water with high particulate concentrations extends well out over the mainland slope (Fig. 4b). The resulting rain of particles through the stratified water column leads to the formation of a large number of relatively intense particle maxima at intermediate depths (Figs. 4b, 4c, 4d). Light-transmission profiles across the shelf and slopes north and south of the canyon and along the canyon axis show no significant differences in either the intensity or number of intermediate-depth turbid layers. Thus, the entire area receives a fairly uniform supply of fine particles with little evidence of control by the canyon system. Nevertheless, consistent distributional differences do appear within the lower 20 m of the nepheloid layer. In the canyon, near-bottom concentrations are uniform at ~2 mg per l from the head to ~250 m. Between 250 and 400 m, as the canyon widens, near-bottom concentrations decline to <0.4 mg per l. In contrast to the north (and also south), concentrations of ~2 mg per l are present along the shelf break, decreasing to values of 0.6 to 1.0 mg per l on the upper slope and then increasing to 1.0 to 2.0 mg per l between 200

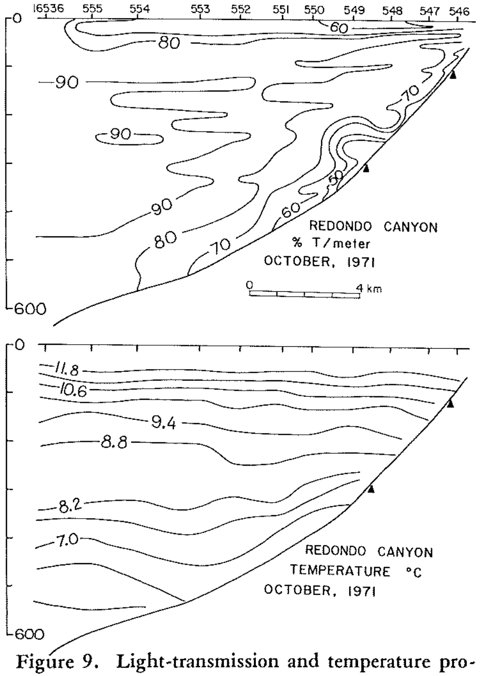


Figure 9. Light-transmission and temperature profile along Redondo canyon axis in October 1971. Current-meter positions are shown by the solid triangles, and the station locations are the same as for Figure 3c. Depth in meters. Temperature isopleths above 11.8°C omitted for clarity.

and 300 m (Fig. 4b). The uniformity of suspended-sediment concentrations within the steep-walled portions of the canyon suggests an equally uniform distribution of current energy coupled with restricted lateral diffusion. The decline in concentrations along the upper slope adjacent to Newport canyon is typical of trends recorded elsewhere off southern California (Drake, 1972). The maxima over the middle and lower slopes is unique to the Newport area, however. Because the canyon merges with the regional slope at ~300 m, it is likely that the sediment forming the slope maxima is derived by lateral spreading at the canyon mouth. In addition, Figure 4b reveals marked vertical changes in the depth of isotherms at ~300 m. If the geometry of these isotherms is the result of wave motions, the slope maxima may mark a zone of relatively high turbulence as well as the spread of canyon suspensate.

La Jolla Canyon

Owing to the limited and highly seasonal supply of terrigenous sediment to the shelf off La Jolla, suspended-sediment concentrations measured in March 1972 are lower than those present in the Newport and Redondo areas at all equivalent depths and distances from the coast. Surface-water concentrations ranged from ~1.0 mg per l over the inner shelf to 0.14 mg per l seaward of the mainland slope (Fig. 7c). As in Santa Monica Bay, drift of surface water under predominently northwesterly and westerly winds results in accumulation along the north side of Point La Jolla. Accordingly, peak concentrations of 2.0 to 2.6 mg per l were observed at the thermocline (20 to 40 m) over the canyon and southern canyon margins (Fig. 5d).

Although a nepheloid layer covers the entire area, the highest suspended-particle concentrations were present in a zone based on the thermocline (Fig. 5c). The relatively low concentrations near the sea floor reflect the generally coarse and well-sorted bottom sediments which mantle the La Jolla shelf (Emery, 1960) and indicate the magnitude of the influence of resuspension on near-bottom concentrations in the other canyon areas. The thickness of the nepheloid layer ranged from ~5 m to <200 m with the greatest thickness present within the canyon. In agreement with the distributional patterns observed in the other canyons, the nepheloid layer ranged in thickness from 5 to 28 m over the shelf and from 50 to 150 m over the upper slopes; on all transects, nepheloid-layer concentration decreased with depth and distance from the coast. Particle concentrations 1 m above the canyon floor ranged from 0.7 to 0.1 mg per l over the measured depth of 270 to 660 m.

Hueneme Canyon

Studies by Drake (1972) and Drake and others (1972) show that particle concentrations in the surface water over the Ventura shelf (adjoining Hueneme canyon on the northwest) are consistently relatively high and generally range from >5 mg per l over the inner shelf to 0.3 to 0.6 mg per l along the shelf edge. Figure 7d is representative of the distribution of beam-transmission values at the surface over the shelf and canyon. Turbidity due to terrigenous particles is high within 1 to 2 km of the coast and documents the southward transport of fine sediment from the Santa Clara River by longshore and wind-driven, inner-shelf currents. These turbid currents detach from the shore near the head of the canyon; during the September 1972 surveys, the turbid currents moved seaward along a convergence between 13°C water east of the canyon and 18°C water to the west.

Particle concentrations within Hueneme canyon (September 1972) ranged from ~0.3 mg per l to 4.6 mg per l with the highest values present just above the canyon floor in the upper 150 m of the canyon (Fig. 6b).

Comparison of the Hueneme (1972) and Newport axial profiles indicates that concentrations of suspended matter are very similar in both areas, but there are fewer midwater turbid layers in the former canyon (Figs. 6b and 4c). The vertical distribution of turbidity in Hueneme canyon is characterized by four zones of high light attenuation: a surface layer extending to the seasonal thermocline, less distinct layers centered at ~100 m and 250 m, and the canyon-floor layer. Comparison of this distribution with the water-column structure as defined by temperature (Fig. 6b) shows association of turbid and clear layers, respectively, with relatively steep and gentle portions of the thermal gradient.

Canyon-floor currents were measured at depths of 172 m (direction but no speed) and 372 m during September 1972. The records show that flow at 172 m reversed 3 times during the 13-hr period required to complete the axial transect but was predominantly downcanyon during the sampling of the canyon head. Current speeds ranged between ~2 and 10 cm per sec at 372 m but reversed only once during the sampling period. Furthermore, the sampling of stations 17917 through 17919 immediately followed a 4-hr period of upcanyon flow at 372 m (F. P. Shepard, unpub. data) and coincided with predominantly downcanyon flow in the upper canyon. Clearly, a convergence of canyon-floor currents must have existed between 172 m and 372 m. Owing to the restrictions on lateral flow imposed by the canyon walls, the escape of water from the convergence must entail seaward flow. Although current data at various levels above the canyon floor are needed to support this model, the authors believe that the turbid plume at 250 m (Fig. 6b) rooted in the nepheloid layer is the product of seaward flow necessitated by convergence of canyon-floor currents. Other midwater turbid zones may have the same origin although retarded particle settling should be important as the surface mixed layer is approached.

Figure 6c presents the distribution of light-attenuating matter in Hueneme canyon immediately following a 4-day period of high river flow in February 1973. Beam-transmission values throughout the headward and central portions of the canyon are from 10 to 40 percent lower than those recorded in September 1972. It is recalled, however, that 10 to 15 percent of this reduction probably can be attributed to a shift toward larger scattering particles (Fig. 2). In fact, water samples 1 m above the canyon floor at each station of Figure 6c contained from 6.8 to 0.53 mg per l of particles and averaged just 32 percent higher than samples recovered in September 1972. Bottom-current data obtained at 172, 280, and 372 m are not yet completely analyzed; however, preliminary inspection shows that currents were generally much faster than during 1972 with a peak of 48 cm per sec at the central station (F. P. Shepard, 1973, oral commun.). It is possible that the elevated current speeds resulted in proportionately faster dispersal of suspended matter. In any case, the concentrations of suspended matter were below 10 mg per l and differed little from those measured during the earlier period of no river flow.

Relations among Tides, Bottom Currents, and Suspensate Distributions

During each of our surveys in Redondo and Newport canyons, we obtained hourly light-transmission and temperature information at stations located in the canyon axis ~100 m

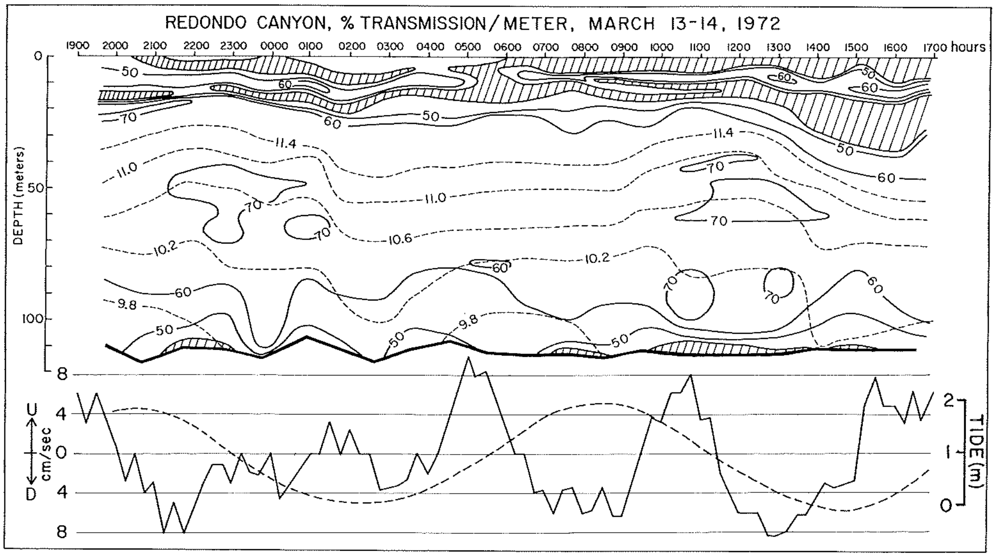


Figure 10. Time-series of light transmission, temperature, and near-bottom currents at ~115-m depth in Redondo canyon, March 1972. Temperature shown by dashed lines in the upper diagram. Temperature isopleths above 11.4°C are omitted for clarity. The tidal curve for Redondo Beach shown by the dashed line in the lower diagram. Water having <40 percent T/m is cross-hatched.

seaward of the near-bottom current meters (Figs. 10, 11). Temperature variations 5 m above the canyon floors total ~0.5 to 0.6°C and reflect the predominant bottom-water displacements. Comparison of temperature oscillations with tidal curves shows that cooler water moves upcanyon during flood tides and warmer water flows downcanyon during ebb tides. The actual bottom-current curves are more complex with short periods of flow reversal (1 to 2 hr) superimposed on the general, tidal-related currents. Shepard and Marshall (1973) tentatively concluded that short-period current reversals are produced by internal waves which would be increasingly important as the thermocline is approached in the headward portions of the canyon.

Light-transmission values near the floor of Redondo Canyon ranged from 27 percent (2.5 mg per l) to 52 percent (1.0 mg per l) over a 20-hr period in March 1972 (Fig. 10). Although these variations are considerable, there is no consistent correlation between particle concentrations and either the direction or speed of the canyon-floor currents. Particle-size data discussed in the following section show that near-bottom suspended matter is markedly coarser within each canyon. In Redondo

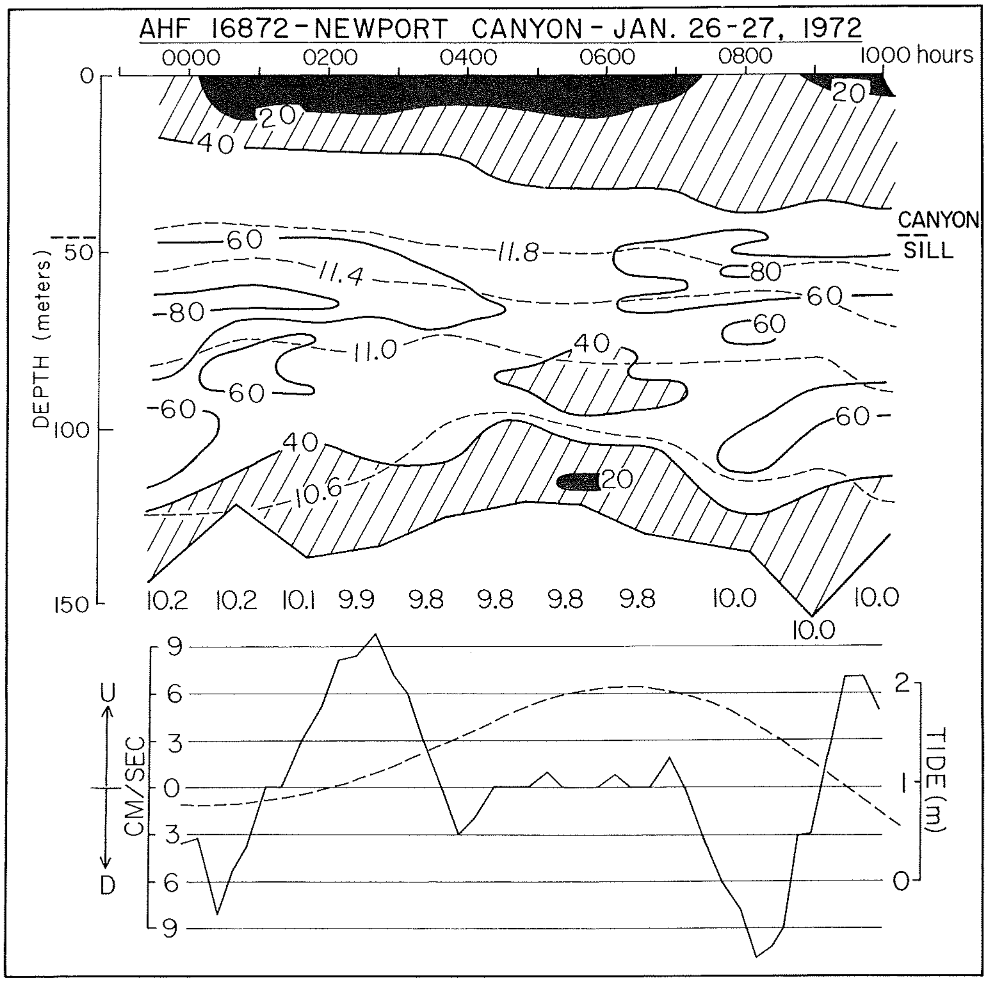


Figure 11. Time-series of light transmission, temperature, and near-bottom currents at ~130-m depth in Newport canyon, January 1972. Temperature shown by the dashed lines in the upper diagram. The temperature isopleths above 11.8°C are omitted for clarity. The tidal curve for Newport Beach shown by the dashed line in the lower diagram. Water having <40 percent T/m is cross-hatched.

and La Jolla canyons, near-bottom suspended sediment contained up to 60 percent coarse silt and 5 to 7 percent inorganic very fine sand. The presence of this material to depths of 375 m in Redondo canyon in March 1972 strongly favors a model involving active and frequent resuspension of canyon-floor detritus. In the light of these data, the lack of correlation between beam-transmission values and near-bottom current velocities is puzzling. The lack of correlation cannot be attributed to the effect of changing particle-size distributions (see discussion under Methods) because bottom scour should resuspend larger particles which would shift beam-transmission values even lower.

Temperature and light-transmission variations at intermediate depths at the two time-series stations reveal flow patterns which are opposed to the *general* bottom-layer flow (Figs. 10, 11). For example, at an axial depth of 120 m in Redondo canyon during the ebb tides between 2030 hr and 0200 hr and between 0900 hr and 1430 hr, clear and cool water was displaced shoreward between the depths of 30 and 80 m while currents were predominantly downcanyon near the bottom (Fig. 9). Current directions reverse in the two depth zones during flood-tide periods.

Whereas there is evidence showing that flow directions at different levels within the canyons are related, there is no convincing association between water transparency and temperature variations *above* the canyon sills and tidal oscillations or canyon-floor currents. Thus, in the central and headward portions of the canyons, the data suggest that the water column can be divided into three general layers: a surface layer that extends to the sill depth of the canyon and does not appear to be strongly influenced by flow patterns within the canyon; an intermediate layer from the canyon sill to 10 to 40 m above the canyon floor; and a nepheloid layer 10 to 40 m thick at canyon depths of 100 to 130 m. The bottom layer in all three canyons becomes thicker with increasing canyon depth (for example, Redondo canyon, see Fig. 8). Suspended-sediment concentrations are typically high within surface and near-bottom layers and relatively low in the intermediate layer.

From the available current-meter data, water-column structure, and axial gradients of suspended-sediment concentrations, we tentatively conclude that net flow is directed downcanyon within the bottom layer and upcanyon at intermediate depths. This simple model is only an approximation to the actual dynamics of the canyon system. Data presented earlier suggest that canyon-floor currents are commonly opposed and that midwater turbid plumes rooted in the nepheloid layer may be produced principally by seaward flow near bottom-current convergences. We envision a more complex model involving the development of cellular currents governed by water-column structure. Such a model remains highly speculative until current data are obtained from the entire canyon volume.

Suspended-Sediment Textures

In each of the canyon areas, samples of water 1 m above the sea floor were recovered using a wide-orifice, 30-l Niskin bottle modified to trigger when a lead weight strikes the bottom. Samples were taken at depths of 20, 50, and 100 m over the marginal shelves and at depths of 90, 150, 300, and 375 m in Redondo canyon; 50, 150, and 300 m in Newport canyon; and 200, 250, and 400 m in La Jolla canyon. Small amounts (0.1 to 0.5 l) of each sample were filtered through Millipore HA discs to produce a thin coating of particles for optical size analyses. Using a standard petrographic microscope, particles to 10 μ were readily resolved and sized; particles finer than 10 μ were lumped as <10 μ. Particle counts (intermediate diameters) were converted to weight percentages using a specific gravity of 2.5. In each sample, 300 to 500 particles were counted.

Size distributions in all three areas are similar; all of the grains are finer than 125 μ and most are <31 μ. In all areas, the largest particles were present over the inner shelf (20 to 30 m) and within the narrow, steep-walled portions of each canyon. Near-bottom samples over the middle and outer shelves (50 to 100 m) and samples at the sea surface had mean particle diameters which were <10 μ, although the surface-water material tended to be slightly finer. Over the inner shelves and at all depths along the canyon axes, the mean diameters were definitely larger (at a significance level of 5 percent using a Student's t distribution) and ranged from an average of ~ 12 μ in Newport canyon to 20 to 25 μ in La Jolla and Redondo canyons. Mean particle sizes within each canyon exhibited a slight, but irregular, decrease with increasing depth. Perhaps the most characteristic difference between the suspended matter in the shelf nepheloid layer and the canyon nepheloid layer is the presence of discrete quartz and feldspar particles as large as 100 μ within the canyons. Very fine sand particles only occurred in the shallowest shelf nepheloid layer (20 m). It may be concluded that energy levels near the bottom in Redondo and La Jolla canyons are of the same order of magnitude as those prevailing at shelf depths of 20 to 50 m. Mean diameters of Newport canyon suspended particles are about one-half as large as those in the two larger canyons; this is a result of weaker bottom currents and general lack of sand in the bottom sediments (Felix and Gorsline, 1971).

The presence of very fine sand 1 m above Redondo and La Jolla canyon floors to water depths of 400 m demonstrates the presence of sufficient current turbulence to maintain this material in suspension and implies significant resuspension and downcanyon transport of bottom sediments. These results agree with the numerous photographs and direct observations of current-rippled canyon-floor sediments presented by Shepard and Dill (1966).

DISCUSSION AND CONCLUSIONS

Investigations of the distribution of suspended sediment in southern California coastal areas by Rodolfo (1964), Wildharber (1966), Beer (1969), Felix (1969), Moore (1969), and Drake (1972) have demonstrated conclusively that a nepheloid layer blankets the mainland shelf and slope. Transmissometer profiles show that a slight or marked increase in turbidity always is associated with the sea floor. This ubiquitous layer is typically a few meters to 20 to 30 m thick and relatively highly concentrated over shelf areas. The nepheloid layer attains its greatest thickness of 50 to 200 m over the upper slopes and within the lower portions of submarine canyons cutting the mainland shelf. In the steep-walled portions of the canyons, particle concentrations gradually increase from the canyon edges to the floors, although secondary maxima and minima are superimposed on this vertical gradient. We envision two processes by which the midwater turbidity maxima may form and be maintained.

1. Settling of particles from the surface mixed layer (Jerlov, 1968) may be retarded. The association of particle maxima with steep portions of the vertical density gradient and with water-mass boundaries has been noted by Bouma and others (1969), Costin (1970), and Drake (1971) and is characteristic of the turbid zones in the canyons. In this regard, it is probable that shearing and turbulence "events" (Woods and Wiley, 1972) occurring along these density interfaces are important in addition to the direct effect of density increases on particle-settling rates.

2. There may be advective transport from convergence zones along the canyon floor. The bottom currents in each southern California canyon (and in others along the Pacific margin) oscillate up- and downcanyon with reversal periods which are typically short in the upper canyon part and relatively long in the central and lower canyon parts (Shepard and Marshall, 1973). Evidence presented in this paper (Table 1; Figs. 6b, 9) supports the conclusion that variations in the near-bottom concentrations of suspended matter along the canyon axes are related to current convergences formed by opposed canyon-floor flows. It follows from continuity considerations that fluid should move away from the canyon floor near such convergences leading to the seaward transport of particles within turbid zones rooted in the nepheloid layer. We cannot at present evaluate the relative importance of these processes, although we are inclined to believe that the obvious connection of the midwater and bottom turbid zones strongly suggests the importance of advective flow.

The presence of the nepheloid layer and the seaward concentration gradient within the layer prompted Moore (1969) to propose that the resulting density increase of the near-bottom water would be sufficient to initiate downslope density underflows. Similar transport mechanisms have been discussed by Bagnold (1963), Postma (1968), and McCave (1972).

Moore (1969) has suggested that the bulk of the fine-grained sediment introduced by coastal streams settles rapidly to the shelf surface as a turbid haze. Subsequently, tidal currents and wind-driven currents move this material laterally toward submarine canyons. Through particle settling or active downcanyon flow, the nepheloid layer would be intercepted by the shelf canyons and proceed to generate density flows to the canyon fans. In essence, such flows would be silt and clay turbidity currents of low velocity (on the order of 5 to 10 cm per sec depending on the particle concentrations and physical setting).

If we consider the simple case of a continuous density underflow from the littoral zone to the depth of the Redondo canyon submarine fan (a depth difference of about 600 m), the density excess must be high enough to overcome the density stratification of water column in the shelf and canyon. The water column of the shelf and slope off southern California is essentially composed of two layers, an upper mixed layer of relatively warm and less saline water and a lower layer of colder and more saline water (Emery, 1960). These layers are separated by strongly developed, seasonal thermoclines and haloclines that range in depth from ~10 to 100 m depending upon the season and distance from the coast (the mixed layer typically thins toward the coast as is shown in Figure 8). Salinity-temperature-depth data collected during our canyon surveys show that the average density change between the two layers is of the order of 10^{-3} g per cm^3. It follows that suspended-sediment concentrations of $\sim 1^3$ mg per l would be needed to penetrate the initial thermocline-halocline barrier. Our studies show that the maximum concentrations measured over the shelf surface near the canyon heads and within the canyon heads are <10 mg per l; it is clear that, under normal conditions, turbid flows originating above the shallow thermocline are impossible. In fact, the association of turbidity maxima with the main thermocline (Figs. 3 through 6) indicates that this discontinuity forms an effective, temporary barrier to the settling of fine-grained material swept into suspension within the surf zone.

Let us now consider the lower-layer suspension system. Within this layer, salinity and temperature gradients are relatively gentle and, therefore, may allow a contribution to the flow patterns by the contained particulate matter. In the canyons studied here, the average water-density gradient is $\sim 10^{-6}$ g per cm^3 per m. Thus, the density change over a depth increment of 1 m is equivalent to the introduction of ~1 mg per l of mineral suspensate. Therefore, under normal conditions, suspended-sediment concentrations in the canyon heads could initiate underflows which would move downward a vertical distance of only a few meters before encountering water of equal density. Clearly even within the less restrictive situation presented by density gradients below the main thermocline, the generation of *throughgoing* turbid-layer flows is not possible during normal periods. Consequently, this model of density-excess flow requires atypical conditions such as flood discharge of terrigenous sediment or strong shelf-sediment resuspension by storm waves. Our data from Hueneme canyon indicate, however, only a small change in particle concentrations following moderate river flow. A brief summary of work carried out during the record floods of 1969 is appropriate at this point.

Records of precipitation and runoff for the southern California coastal watershed show that rainfall is largely restricted to winter and spring months (U.S. Dept. Commerce, Weather Bureau Statistics). Furthermore, it is not uncommon that the bulk of the total rainfall for a year will come in one, or a few, brief but intense storms. Extremely heavy rainfall and serious flooding are infrequent events in southern California, however. In this century, two such storms occurred (1938 and 1969). During the 1969 flood, the Santa Clara and Ventura Rivers at the eastern end of Santa Barbara Channel delivered more than 50×10^6 metric tons of sediment to the coast, ~50 times higher than their combined average annual discharge (U.S. Geol. Survey, unpub. discharge records). Samples of surface and near-bottom suspended sediment were obtained seaward of these rivers during and in the months following the floods (Drake and others, 1972). The highest particle concentrations of 50 mg per l occurred within 1 m of the sea floor and within 2 km of the rivers; concentrations declined seaward to <10 mg per l at the shelf edge (100 m depth) 15 km from the coast. Subsequent bottom sampling of the shelf by box core showed that >70 percent of the silt and clay delivered during the floods was deposited at depths of 20 to 100 m (Drake and others, 1972). With time, this disequilibrium lutum deposit was resuspended. During this process, suspended-sediment concentrations over the shelf never exceeded 50 mg per l (Drake, 1972). In view of these data, it is probable that concentrations approaching or exceeding 10 mg per l are rarely reached seaward of the 10-m isobath off southern California. Furthermore, during floods, density overflow of sediment-laden fresh water spreads particulate matter well beyond the littoral zone and thereby limits the peak concentrations nearshore.

In summary, the initiation and maintenance of throughgoing density underflows from the canyon heads to the fans would require un-

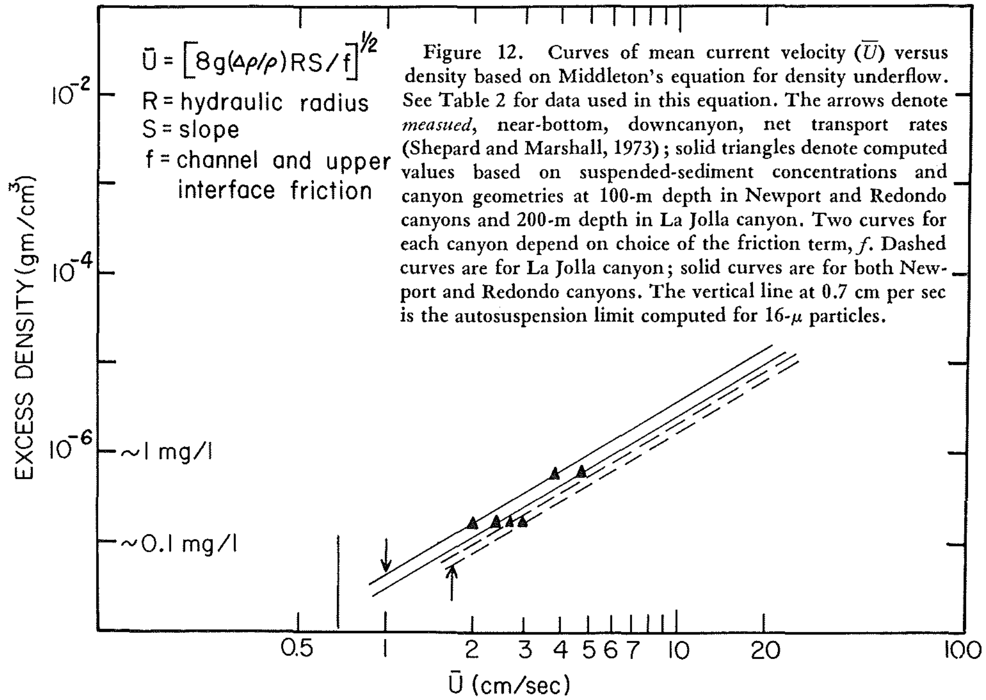


Figure 12. Curves of mean current velocity ($\bar{U}$) versus density based on Middleton's equation for density underflow. See Table 2 for data used in this equation. The arrows denote *measued*, near-bottom, downcanyon, net transport rates (Shepard and Marshall, 1973); solid triangles denote computed values based on suspended-sediment concentrations and canyon geometries at 100-m depth in Newport and Redondo canyons and 200-m depth in La Jolla canyon. Two curves for each canyon depend on choice of the friction term, *f*. Dashed curves are for La Jolla canyon; solid curves are for both Newport and Redondo canyons. The vertical line at 0.7 cm per sec is the autosuspension limit computed for 16-μ particles.

reasonably high suspended-sediment concentrations. In fact, the bottom-current records indicate that the principal water displacements in the canyon are the result of driving forces that periodically reverse, such as tides and internal waves. Although transport by *continuous* turbid-layer flows is not supported, the possibility remains that the permanent canyon-floor nepheloid layers may add a *net* downcanyon component of water transport of the proper magnitude to explain the net downcanyon-transport rates measured by Shepard and Marshall (1973).

Downcanyon-transport rates in those canyons for which we have suspended-sediment data range from 0.5 cm per sec to 1.8 cm per sec (Shepard and Marshall, 1973). To determine the possible current components which might result from turbid-layer density excesses we used an equation developed by Middleton (1966). This equation (see Fig. 12) is a modified Chézy formula relating mean flow velocity to channel geometry and excess density. Reasonable flow velocities have been computed with this equation using the known characteristics of density underflows in Lake Mead. In Figure 12, we have added the "autosuspension limit" of Bagnold (1963), which states that the sea floor must fall away faster than the particles settle from the density flow. The limits shown in Figure 12 are computed for mean particle sizes of 16 μ using the Stokes' law settling velocity for 15°C water.

TABLE 2. DATA FOR DENSITY-EXCESS FLOW CALCULATIONS

Canyon	Depth (m)	Hydraulic radius (m)	Slope	$\frac{\Delta\rho}{\rho}$	Thickness layer (m)
Redondo	100	20	4°	3×10^{-7}	20
Newport	100	20	4°	8×10^{-7}	20
La Jolla	200	20	7°	3×10^{-7}	20

In Middleton's equation, we are able to specify $\Delta\rho/\rho$, the density excess; *S*, the slope; and *R*, the hydraulic radius. Values for these parameters are based on the suspended-sediment concentrations and channel characteristics at depths of 100 m in Redondo and Newport canyons and 200 m in La Jolla canyon (Table 2). These depths were selected in light of the availability of records of canyon-floor currents. The most difficult parameter to evaluate is the term for bottom and upper-interface friction, *f*. Middleton (1966) shows that the bottom resistance can be evaluated using the so-called Moody resistance diagram for closed-conduit flow. The bottom resistance depends on the Reynolds number and the ratio of roughness elements (such as sand ripples and boulders) to the depth of flow. The thickness of the nepheloid layer in all the canyon heads ranges between 10 and 40 m. For this analysis, 20 m is taken as a typical thickness for the canyon-floor layer; this thickness choice is supported by current measurements in La Jolla canyon which indicate that net downcanyon flow is largely restricted to the bottom 30 m of the water column (Shepard and Marshall, 1969). The Reynolds number for a flow of 1 cm per sec and flow depth of 20 m is $\sim 5 \times 10^5$, and the flow should be fully turbulent. The size of bottom-roughness elements is difficult to estimate without direct examination of the canyon floors. A large error in this factor produces only a relatively small change in the bottom-friction term, however. Using 5 cm as the thickness of bottom-roughness elements yields a relative-roughness ratio of 0.0025 and a friction factor of 0.025.

The frictional resistance of the upper interface can be estimated from diagrams given by Middleton (1966), which relate the Froude number to the ratio of upper-interface resistance to the bottom-friction value. For a 20-m-thick flow of 1 cm per sec with excess densities of 10^{-6} and 10^{-7}, the Froude number ranges from 0.7 to ~2.0. This range yields a corresponding range of from 0.005 to 0.02 for the upper-interface resistance and 0.029 to 0.04 for the *total f*.

Figure 12 shows calculated curves of mean flow velocity versus excess density using the above values for f and the canyon-channel characteristics shown in Table 2. We have indicated with arrows the average net downcanyon-transport rates measured by current meter at each station. For Redondo and Newport canyons, the rates are nearly 1 cm per sec, whereas La Jolla canyon shows a net rate of ~1.8 cm per sec at 206 m. These values are based on ~15 days of continuous current-meter records at 92 m in Redondo canyon, 6 days at 100 m in Newport, and ~50 days at 206 m in La Jolla canyon. The values for Redondo and, particularly, La Jolla canyons are well established. The solid triangles represent the velocities computed for a 20-m-thick bottom flow in each canyon based on the actual excess densities due to suspended detritus. All of the theoretical values are higher than the measured downcanyon rates by factors of 2 to 4. In view of the large number of assumptions and approximations which are of necessity incorporated in this analysis, however, the agreement is reasonably good. It is perhaps noteworthy that the largest discrepancy is between the actual and computed values for Newport canyon where we have the least data.

The permanent nepheloid layers apparently produce density increases which should be sufficient to explain the measured net downcanyon drift in each canyon. It is equally evident that other mechanisms to explain the net canyon-floor flow are not excluded by our results. In particular, Lafond (1962), Cacchione (1970), and Southard and Cacchione (1972) have presented evidence showing that flow patterns associated with progressive internal waves should produce net downslope transport on continental margins. A complete understanding of the mechanics of fluid flow and suspension transport in canyons must await the time-series measurement of flow patterns, suspended-sediment concentrations, and internal wave characteristics in the entire canyon volume.

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