SAND MOVEMENT INTO CARMEL SUBMARINE CANYON, CALIFORNIA

by

J.R. Dingler and R.J. Anima[1]

ABSTRACT

Carmel Submarine Canyon heads in shallow water near Monastery Beach at the southeast corner of Carmel Bay, California, U.S.A. Very coarse sand, shaped into large oscillation ripples, covers the narrow shelf between the beach and the canyon; when this sand enters the canyon head, it lies at angles as great as the angle of repose. In some areas, these sand slopes show evidence of active grain flows in the form of downslope-coarsening, inversely graded deposits.

The results of a dyed-sand tracer study adjacent to the canyon show that sand moved canyonward during the summer of 1979. Initially the dyed sand, which had been shaped into an oscillation ripple in the center of a 20-m by 60-m grid, moved offshore en masse. After a few days, though, the dyed sand dispersed with the center of mass moving canyonward.

As wave-transported sand accumulates along the canyon rim, the upper slopes oversteepen, thereby causing some of the sand to avalanche downslope. Systematic changes in sand levels along three lines of rods over 15 months document preferential deposition of sand along the upper slopes; the greatest change occurred at the top of the lines (12-15 m depth) and the least at the bottom (30-40 m). Greater accretion during the spring months than during the summer months probably reflects the more energetic springtime wave climate.

Between October 1981 and October 1982, 5.7 m^3 of sand was deposited per meter alongslope on the middle line, which gives a calculated depositional rate of approximately 500 m^3/yr in the study area. Although we have monitored this area for over a year, we have not yet documented any large-scale events capable of flushing sand out of the canyon head. The only erosive event we have observed was a small grain flow we generated while digging on the slope.

INTRODUCTION

Submarine canyons funnel sediment from the continental shelf

[1]U.S. Geological Survey, Menlo Park, California 94025

to deep water. Whenever a submarine canyon extends into shallow water, its head intercepts longshore-moving beach sand, removing it from the littoral zone. Inman and Frautschy (1966) described how such canyon heads terminate littoral cells along the southern California coast.

Instead of moving directly to deep water, most sand remains in the canyon head for an indefinite period of time probably ranging from months to years. Filling of the head continues until a combination of air, land, and sea conditions flushes sand into deeper water (Inman *et al.*, 1976); investigators think that the sediment entrained by such an episodic event generates a turbidity current. Although no one has observed such a current, Inman *et al.* (1976) described strong, pulsating flows that finally produced a down-canyon flow strong enough to carry off their recording sensors. Divers who inspected the sensor mounts reported large sand losses from the canyon head.

Sand slowly accumulates in the canyon head, moving downslope from the canyon rim. Dill (1964) showed that slow gravity creep takes place in fine sand and decaying kelp in the head of Scripps Canyon. Dill (1966) attributed grain flows, seen in San Lucas Canyon, to steepening of sandy slopes beyond the angle of repose (33°). Dingler and Anima (1981) showed that grain flows down angle-of-repose slopes could produce the inversely graded, sandy deposits found in the head of Carmel Canyon.

After waves transport littoral sand to the canyon rim, gravity becomes the driving force. Gravity creep or sand avalanching redistribute sand within the canyon head, and sediment gravity flows remove sand to deeper water. This paper describes how sand moves into the head of Carmel Canyon from the littoral zone, and how small grain flows redistribute the sand onto slopes that dip at angles as great as the angle of repose.

SETTING

Carmel Submarine Canyon heads in shallow water in the southeast corner of Carmel Bay, California (Fig. 1). The canyon is one of several that cut into the continental shelf along central California; it enters the larger Monterey Canyon west of Monterey in a water depth of 2012 m (Shepard and Emery, 1941). Carmel Canyon is an extension of the adjacent land canyon that contains San Jose Creek (Shepard and Dill, 1966, p. 88). Shepard and Dill presumed that the sandy shelf between the beach and canyon rim is a filled part of the ancestral canyon.

Tributaries enter Carmel Canyon along its entire length; the shallow, nearshore ones lie close to a series of coarse-grained pocket beaches, collectively named the Carmel River State Beach. At its closest point, the canyon head lies less than 200 m from Monastery Beach, the southern most of the pocket beaches within the State Beach. Wave-generated ripples cover the narrow shelf

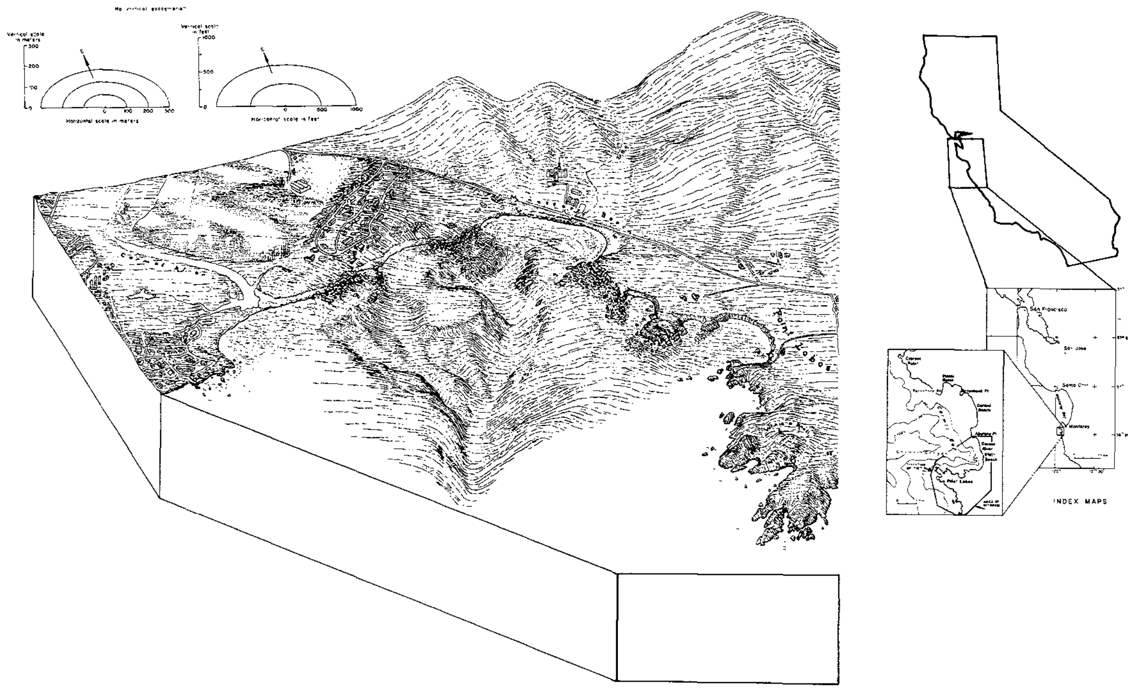

Figure 1: Section of a physiographic diagram of the head of Carmel Submarine Canyon and surrounding land (Alpha et al., 1981). Inserts show the location of the study area along the California coast.

between the beach and canyon (Hirschaut and Dingler, 1982). Water depth at the canyon rim, or shelf break, varies with location; it is less than 15 m at its shallowest point.

Although the wave climate at the canyon head is restricted by its location within Carmel Bay, storm waves from the northwest reach the area. Dingler (1981a) estimated from berm height that breaking waves higher than 3 m reached Monastery Beach too infrequently to produce a storm profile there commonly.

On land, Santa Lucia Granodiorite (Bowen 1965) is the principal rock type throughout the area. The conglomeratic Carmelo Formation (Bowen, 1965) crops out on both sides of Monastery Beach, and both the Carmel River and San Jose Creek drainage basins include other sedimentary rocks. Underwater, sand covers most of the bedrock, but granodiorite crops out in several localities around the canyon, and one sedimentary outcrop occurs along the east wall of the canyon head. Figure 2 shows the onshore distribution of rock types and the location of major underwater outcrops known to us.

Most of the sand on Monastery Beach, the adjacent shelf, and upper canyon slopes is very coarse to granular, but fine sand exists in some of the more quiescent areas. Along most shore-normal transects, grain size decreases from the beach to the rim and increases downslope to about 35 m (Fig. 3); below that depth grain size quickly drops below sand size.

A transect along the 15-m bathymetric contour from the rocks on the north passes through five zones with differing biota, texture, and surface expression before reaching the southern extent of the east wall (Fig. 4). Diopatra ornata tubes densely populate a substrate of fine sand in zone 1. The second zone has fine to coarse sand with clumps of red algae and partially exposed tubes of Platysereis bicanaliculata. This zone gradually merges into zone 3, which is different from the other zones in that it has no exposed biogenic sedimentary structures, though Platysereis exist within the sand. The shore-normal transect shown in Figure 3 passes through zone 3. When viewed from a distance, much of the sand appears to have slope-parallel stripes spaced 1 to 2 m apart. These, we believe, are the deposits of small avalanches. Zone 4 is similar to zone 2. Zone 5, which is offshore of a small kelp bed, contains both Diopatra and algae with a fine-sand substrate. Along the south wall, zone 5 terminates at granitic outcrops.

EXPERIMENTAL METHOD

Scuba divers conducted the experiments and made all the measurements and observations described herein. These included injecting dyed sand and sampling for it over time, emplacing aluminum rods and measuring them, and measuring dips on the sandy slopes. Figure 5 shows the location of the dyed sand sample area

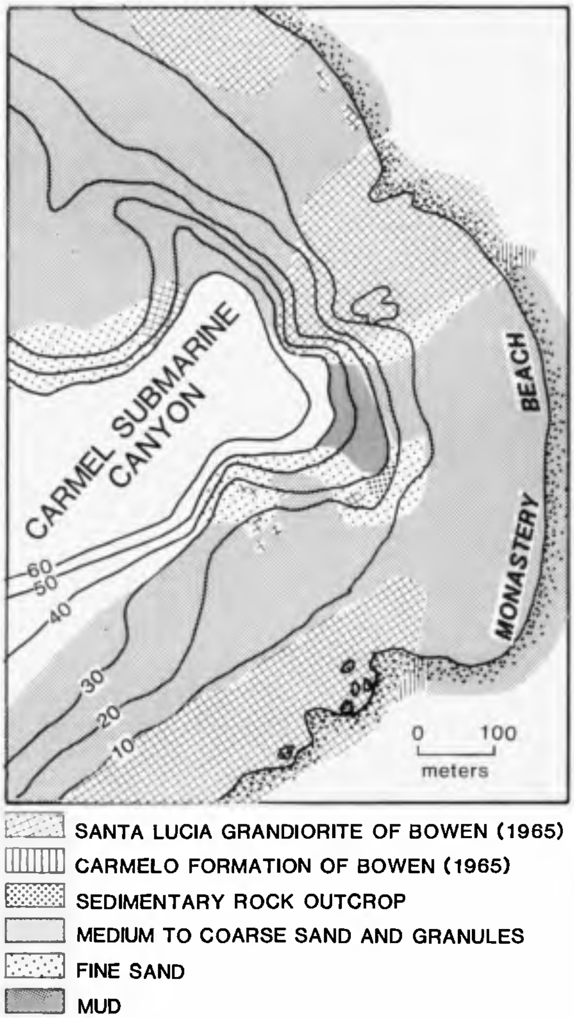

Figure 2: Distribution of rock types in the vicinity of Carmel Submarine Canyon.

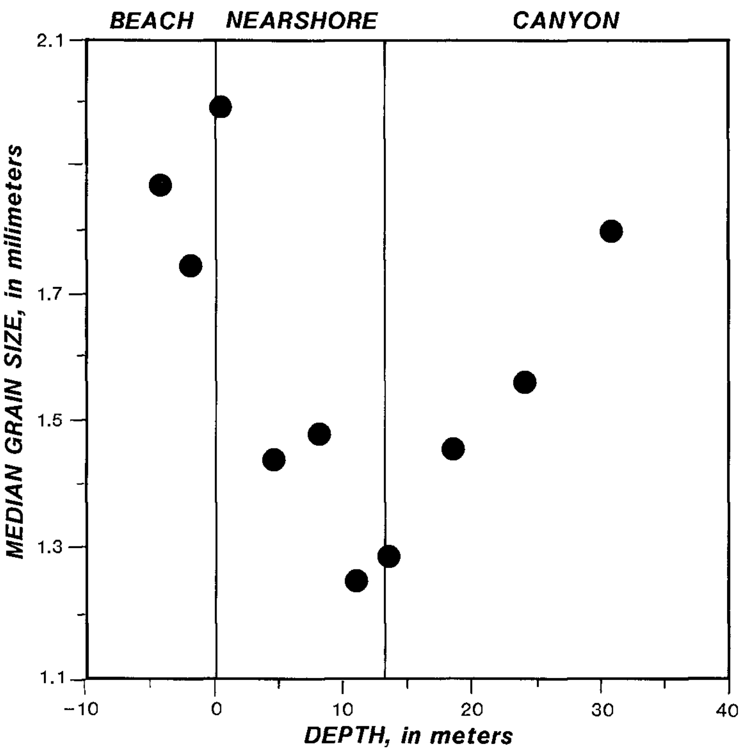

Figure 3: Grain-size distribution of sediment along a shore-normal transect that starts at Monastery Beach and ends within the canyon head. See Figure 5 for transect location.

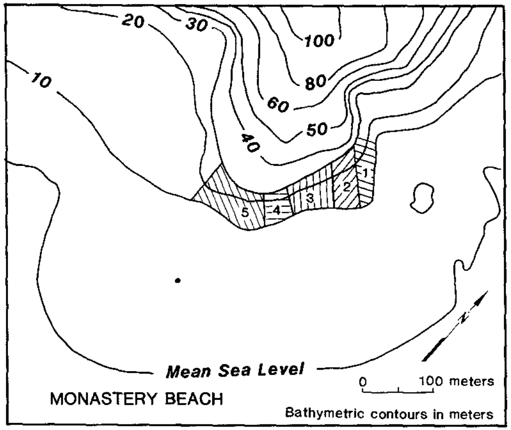

Figure 4: Bathymetric map of the head of Carmel Submarine Canyon and adjacent shelf. The east rim of the canyon is zoned on the basis of grain size and biota (lined areas). Because of this distribution we assume that active transport is greatest in zone 3 and negligible in zones 1 and 5. See text for further explanation.

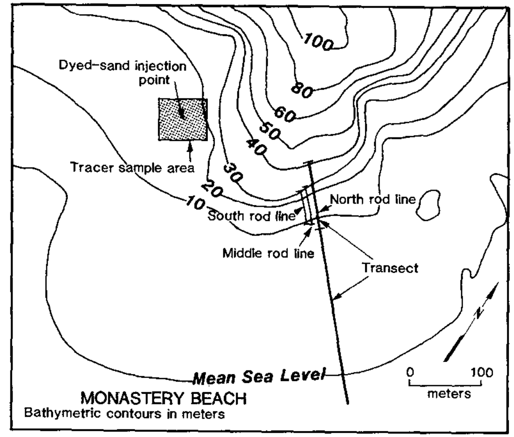

Figure 5: Location of dyed-sand tracer study adjacent to the south wall of Carmel Canyon and line of rods on the eastern slope. Line across shelf together with the north line represent the transect of Figure 3.

and the rod arrays. All measurements were made during fair weather.

To determine the transport direction of sand near the head of the canyon, we injected 161 kg of dyed sand on the shelf adjacent to the south rim prior to starting any experiments on the canyon slopes. We collected the sand from the center of a 70-m by 60-m grid, dried it, dyed it a fluorescent color, and returned it to the collection point. Injection consisted of replacing two meters of a ripple crest with the dyed sand. At irregular times, divers collected a surficial sample from each of 35 grid points; these samples were split and the dyed grains counted under an ultraviolet light.

Based on the biological and sedimentological patterns, we assumed that the most active part of the upper slope was in zone 3. To measure the rate of deposition there, divers drove aluminum rods into the sand on the slope, leaving part of each rod exposed. The rods formed lines that started on or near the shelf break and went downslope. In April 1981, we emplaced one line of 26 rods spaced 1 m apart at the site of one of our man-made avalanches (Dingler and Anima, 1981). Three months later we added a longer parallel, line about 5 m north of the first one. These two lines ended at a depth of 30.5 m. In May 1982 we added a third line about 15 m north of the second one. This last line had rods spaced 2 m apart, extending from the shelf to a depth of 36.6 m.

Two divers can measure the rods on two lines in one dive. Between the installation date and 15 October 1982, we measured the south line of rods 13 times, the middle line 12 times, and the north line 4 times. Once, the divers also measured slope angle using a dipmeter developed by Dingler (1981b). Accuracy of the rod measurements is roughly 1 centimeter and that of the dip measurements is 1 to 2 degrees. Because a dip error of 1° equals an error in elevation of 1.7 cm, we relied on the rod measurements in this study. Besides, the rod data can be used with one set of dip measurements to calculate dips at any time.

RESULTS

After injecting dyed sand on 30 April 1979, we inspected or sampled the grid on 3, 7, and 15 May, 7 June, 3 and 7 July, 3 and 16 August, and 26 September 1979. On the first two days most of the dyed sand remained in one ripple crest that had migrated about one wavelength (about 1 m) offshore. Some dyed sand also showed on the next offshore ripple and a few grains had dispersed toward the canyon. We saw no grains onshore of the injection point. The dyed-sand ripple crest had disappeared by 15 May, and dyed grains were scattered over the inner part of the grid with the greatest visible concentration being offshore and canyonward of the injection point. By 7 June, dyed grains had reached the boundaries of the study area with the highest concentration again being offshore and canyonward (Fig. 6). This pattern continued through the study period.

The curves in Figure 7, which are based on dip measurements from 11 May 1982, are the slope profiles above 30.5 m of the three lines. The slopes parallel one another; the slight deviations near the top could reflect variations in location of large ripples that extend onto the upper part of the shelf break. Figure 8 contains selected data from the middle line; the rod-height data, which are representative of data from the other lines, have been converted into net deposition by subtracting the measured heights from the initial rod heights.

DISCUSSION

Determining depositional rates in the canyon head was the goal of this study. Although our coverage of the canyon head was limited, our three lines of data show how the sand that moves into the canyon head is distributed. Assuming that the depositional rates along the lines are representative of the east rim, an average volume is calculated and seasonal fluctuation noted.

Other investigators assumed that waves drove the sand from the beach to the canyon. Our dyed-sand experiment supports this assumption to the extent that sand near the canyon rim preferentially moves canyonward through a zone of wave-formed ripples. Wallin (1968) thought that the Carmel River was a major supplier of littoral sand to Monastery Beach, but Howell (1972) concluded, using wave refraction diagrams, that sand moved south from the Carmel River and north along Monastery Beach. As shown in Figure 9, these littoral sand streams turn seaward before reaching the large rock exposure just north of the canyon.

After not finding any through paths when diving amongst the rocks and analyzing sand samples from the midforeshore along Carmel River State Beach, we also conclude that little sand crosses the rocky area north of Monastery Beach. Along the northern part of Carmel River State Beach, south of the Carmel River, grain size increases to the south (Fig. 9). This trend is opposite to the downdrift distribution produced by littoral transport. However, the observed distribution would be produced by a southward increase in the granodiorite contribution relative to the littoral contribution.

At Monastery Beach, the mouth of San Jose Creek is usually deflected to the north, indicating a northward movement of littoral sand before it moves offshore. The sources of this sand are San Jose Creek and the local granodiorite, but we do not as yet know the proportions of each.

Once the sand reaches the canyon rim, it piles up until the upper slope oversteepens. Then a grain flow redistributes the sand downslope; the distance downslope varies from a few to tens

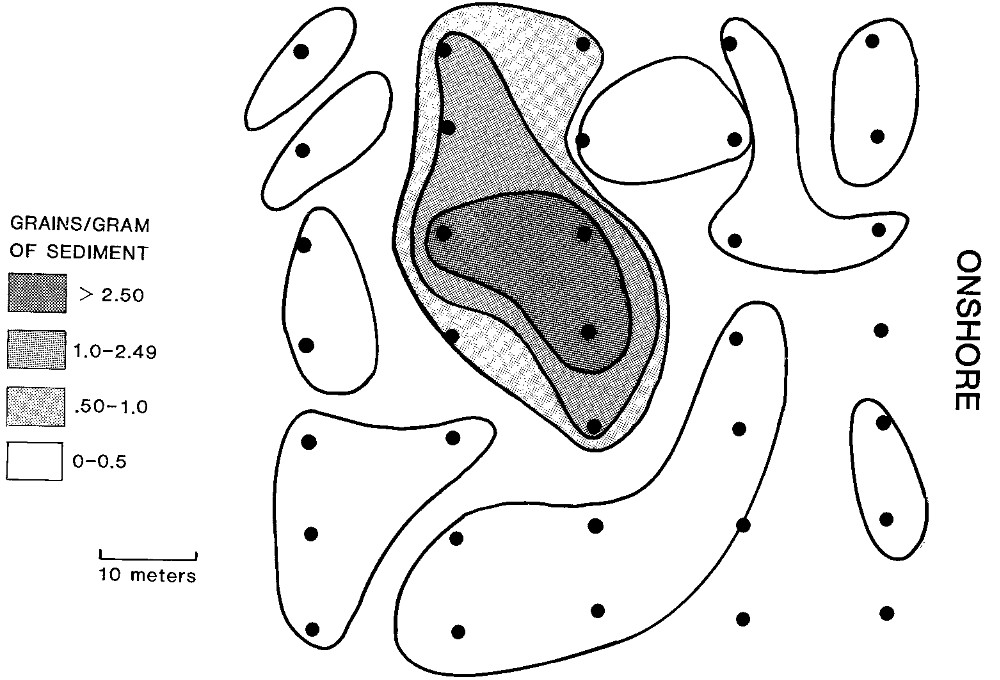

Figure 6: Distribution of dyed sand 38 days after injection on 30 April 1979. See Figure 5 for location of sampling grid.

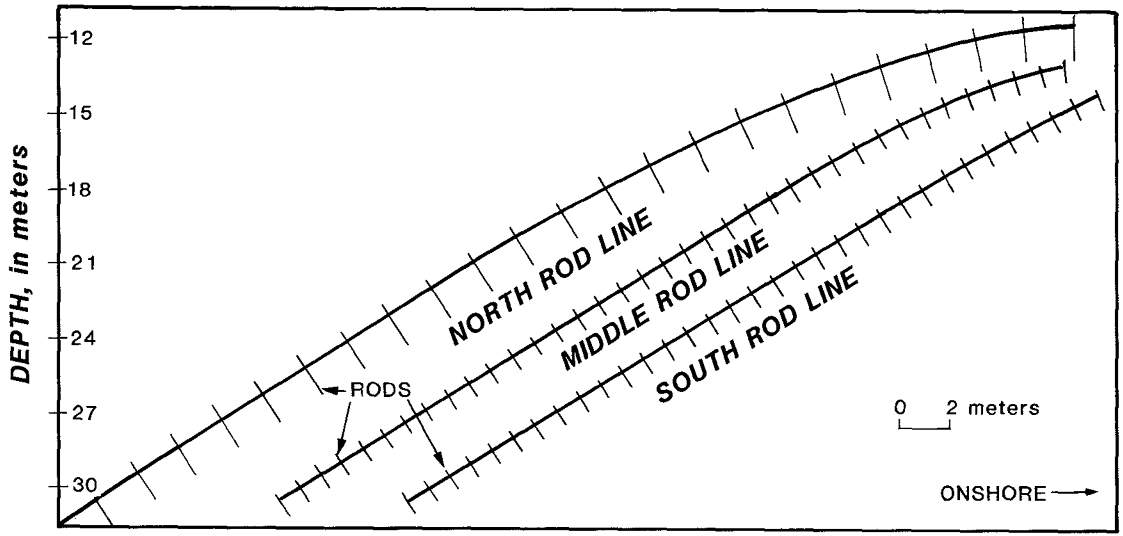

Figure 7: Bottom slopes along the three lines of rods located in Figure 5. Rods are not drawn to scale; those along the north line are 2 m apart and the others are 1 m apart.

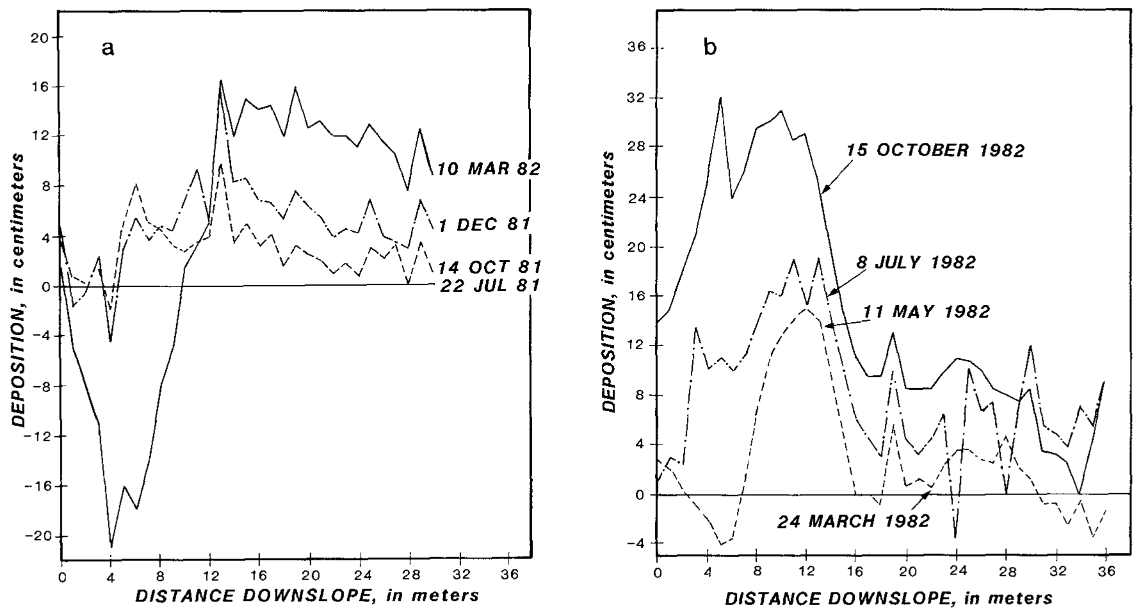

Figure 8; Net deposition at each rod on the middle line (a) from 22 July 1981 to 10 March 1982; (b) from 24 March 1982 to 15 October 1982. See Figure 5 for rod line location. Deposition between 10 and 24 March 1982 is unaccounted for because of accidentally generated grain flow on the latter data. See Figure 13 and text for more details.

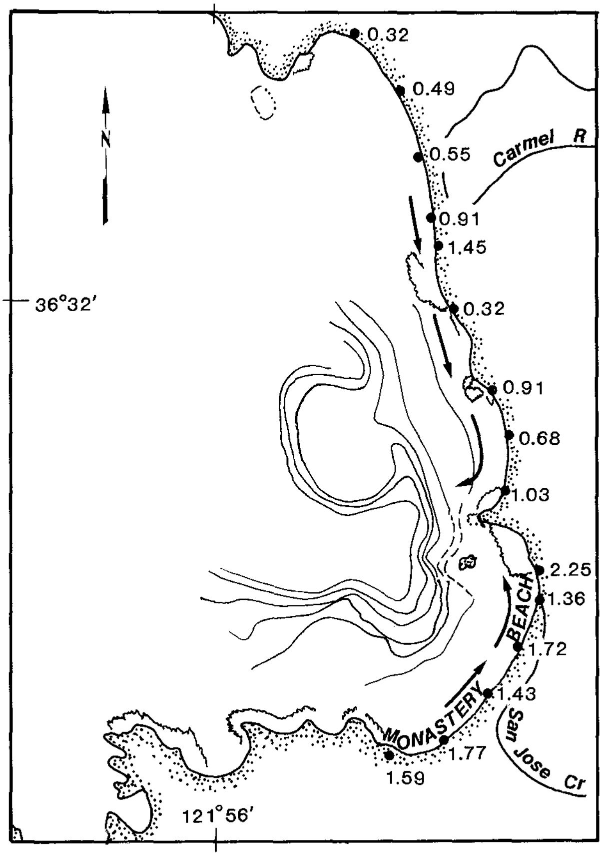

Figure 9: Littoral zone sand transport paths (arrows) into the head of Carmel Submarine Canyon (from Howell, 1972). Dots locate our textural samples, and the adjacent numbers give the mean grain size in millimeters.

of meters. We base this interpretation on systematic changes in deposition down the three lines of rods (Fig. 8). The greatest deposition takes place just over the rim (away from the ripples), and the least at the bottom. This process recurs at least on a monthly basis, and thus, the canyon rim slowly accretes.

Deposition Q_i, in units of volume per length alongslope, was calculated from the equation:

$$Q_1 = \Delta x(0.5z_1 + \sum_{i=2}^{n-1} z_i + 0.5z_n)$$

where Δx is the spacing between rods, n is the number of rods, and z_i is the amount of deposition at the ith rod. Figure 10 shows both the incremental and net deposition on the middle line, and Figure 11 recasts the incremental data in terms of average rates. These figures illustrate the seasonality of the canyon-head deposition: deposition was rapid in the late spring and early fall of 1982 and slow before and after the spring high. This trend appears on the south line, which also had relatively rapid deposition in the spring of 1981. This pattern probably mirrors the intensity of the wave climate, so fluctuations, such as between fall 1981 and fall 1982, would be expected because wave climate is variable.

Lateral variations also occur, even over the few meters between rod lines, as shown by the net deposition on the three lines between 11 May 1982 and 15 October 1982 (Fig. 12). During this time the most deposition took place on the south line, and the least on the north one. Using the data from the middle line, the depositional rate in the study area was 364 m^3/yr if all the sand moved through zone 3 (64 m wide), and 791 m^3/yr if it moved through zones 2-4 (139 m wide).

We have not found any evidence of large-scale slope erosion during our studies in Carmel Canyon. However, Shepard and Emery (1941, p. 101) speculated that erosive events must occur in the head of Carmel Canyon. They measured over 5 m of fill from 1934 to 1939, a rate that would fill the head within a few years unless there was an erosive event.

During one of our dives on 24 March 1982, we accidentally generated a grain flow along the southern line that redistributed much of the sand that had heen deposited during our study. While trying to dig out some buried rods near the middle of the line, we created a scarp-recession grain flow (Hunter, 1977). Sand fell into the upslope side of the hole and continued to flow downslope past us. Above the initiation point, previously buried rods appeared at a rate of more than one per minute; near the top of the rod array the height of the scarp had increased from a few centimeters to more than 30 cm. Figure 13 shows the approximate magnitude of erosion, assuming that a wedge of sand 25 cm thick at the top rod covered the rods before the grain flow. Although this grain flow only disturbed a small part of the slope, on a larger

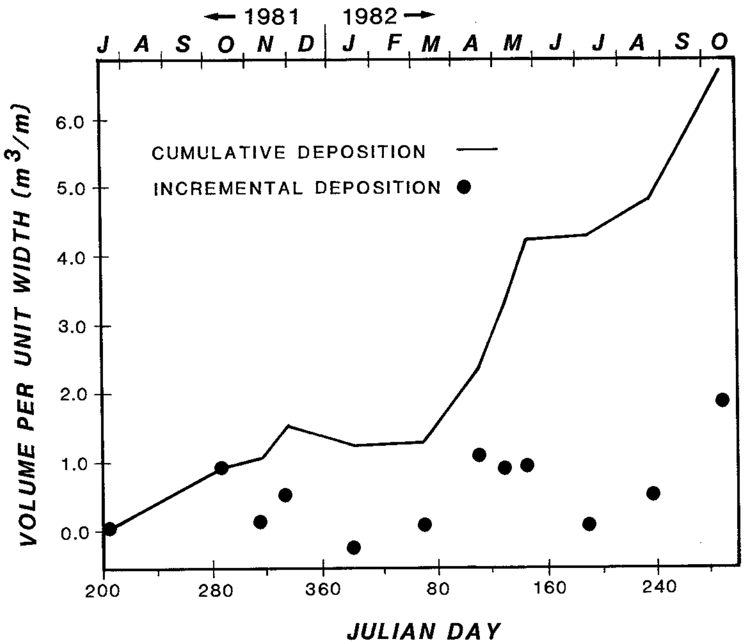

Figure 10: Net and incremental deposition along the middle rod line based on rod-height changes. See Figure 5 for rod line location.

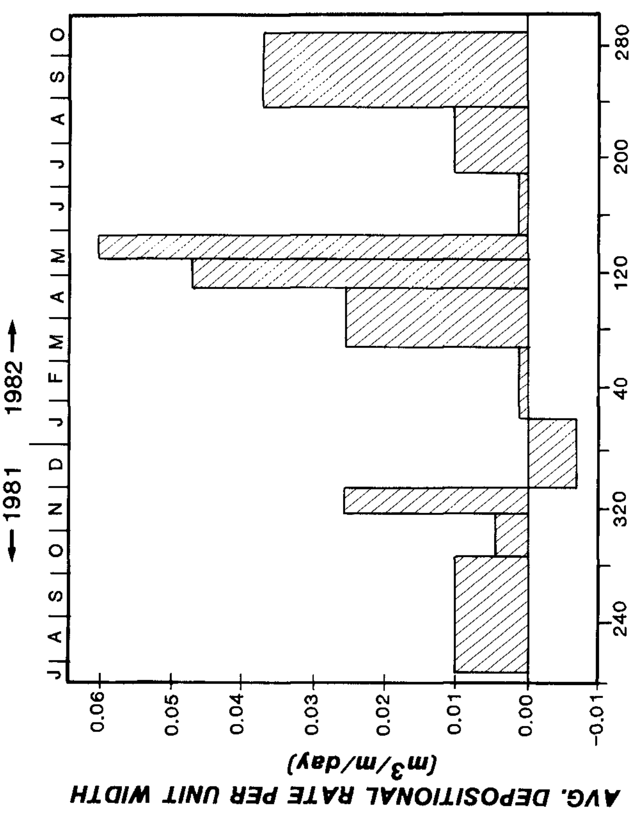

Figure 11: Average rate of deposition along the middle rod line, calculated by dividing the incremental values (Fig. 10) by the number of days between measurements. See Figure 5 for rod line location.

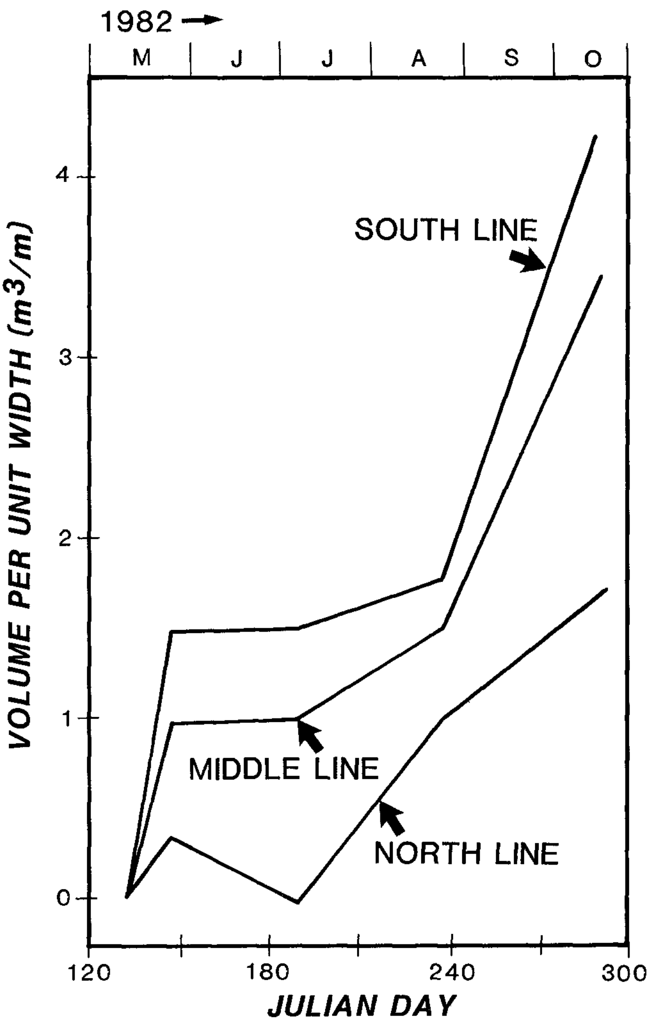

Figure 12: Net deposition on the three lines between 15 May 1982 and 15 October 1982.

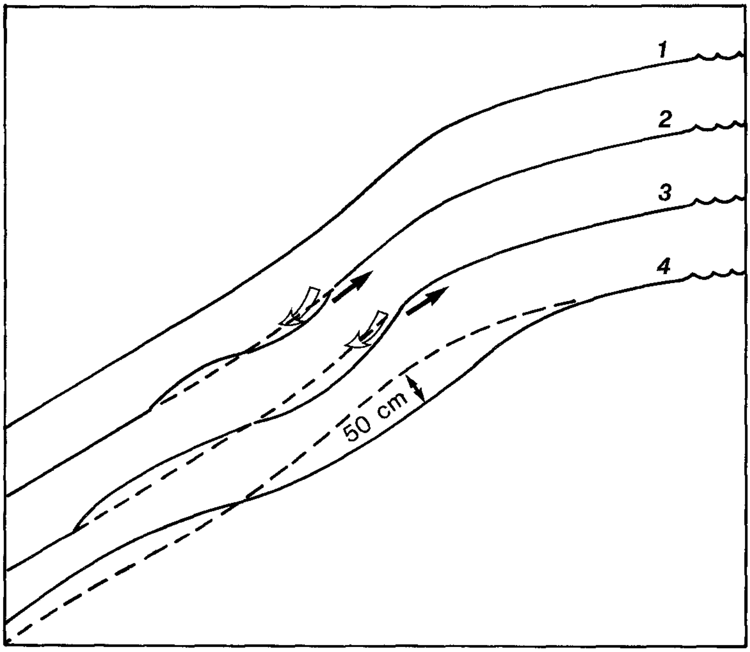

Figure 13: Changes in slope profile due to an accidentally generated scarp-recession grain flow on 24 March 1982. Maximum erosion was on the order of 50 cm. Profile 1 shows the slope before we disrupted it. Profile 2 shows sand falling into the hole we made and flowing downslope. Profile 3 shows the location of the scarp partway through the grain flow. Profile 4 shows the final profile. The dashed line in 2, 3, and 4 represents the original profile. Open arrows show the direction of sand flow; solid arrows show the direction of scarp recession. Scale is approximate.

scale this mechanism could easily initiate turbidity currents on angle-of-repose slopes.

CONCLUSIONS

1. Sand sporadically reaches the Carmel Submarine Canyon rim from the adjacent shelf. Sand entering the littoral zone comes from San Jose Creek and weathering of local granodiorite outcrops.

2. After reaching the Carmel Submarine Canyon rim, the sand collects until the slope becomes too steep. Then the sand avalanches, coming to rest farther downslope. Subsequent deposits may cause the slope below the rim to oversteepen, producing another avalanche. In this manner the slope slowly accretes seaward.

3. The depositional rate along the east rim of Carmel Submarine Canyon is on the order of 500 m^3/year.

ACKNOWLEDGMENTS

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