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SEDIMENTATION IN SUBMARINE CANYONS
IN SAN DIEGO COUNTY, CALIFORNIA, 1984 - 1987
Ref. No. CCSTWS 88-2

Coast of California Storm and Tidal Waves Study

U.S. Army Corps of Engineers
Coastal Engineering Research Center
Waterways Experiment Station
Vicksburg, Mississippi

April, 1988

prepared by

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EXECUTIVE SUMMARY

Three submarine canyons have an effect on the coast north of San Diego, California. Scripps and La Jolla Canyons extend almost to shore and permanently trap sand at the south end of the Oceanside Littoral Cell. They are also responsible for enhancing the local, long-term shoreline retreat rate as evidenced by the embayed shoreline adjacent to each. Carlsbad Submarine Canyon, in the central portion of the Oceanside Cell, extends shoreward across the Continental Shelf to a water depth of about 100 ft. Littoral sand is not carried to the canyon head at that depth. The effects of wave refraction over Carlsbad Canyon have resulted in a reduction in the local rate of shoreline retreat and produced a slight bulge in the nearby shoreline.

The first objective of the field investigation described in this report was to quantify the rate at which littoral sand was carried to and deposited in the shallow heads of Scripps and La Jolla Canyons between December 1984 and June 1987. The second objective was to establish, for the same period, the rate at which the deposited material was flushed down the axes of the canyons. Littoral sand, once it is flushed to deep water, is unrecoverable. The frequency, magnitude and duration of storms, the characteristics of the local longshore sediment transport regime, and the location and shape of the heads of the canyons control the entrapment rate, how much sand the canyon head can hold before it is flushed out, and the frequency of flushing.

Sand Entrapment Rate. Scripps Canyon has at least 6 shallow-water tributaries that trap sand. The most active four were investigated in this study. La Jolla Canyon has a single, but much larger, 0.7-mi long, shallow-water head. Canyon heads filled when sand moved seaward from the littoral zone into near-coast sediment depressions. Depressions are shallow, relatively steep, saucer-shaped regions located above canyon gorges. Gorges are comprised of rock headwalls, rock sidewalls that in some places are vertical or even overhanging, and rocky, seaward-sloping floors.

Sand that had the same size distribution as sediments in the nearby littoral zone was deposited in the depressions. Very fine-grained sands, micaceous, and organic debris passed over the depressions and were deposited in the gorges. As the prograding deposits in the depressions of Scripps Canyon were funnelled into the narrow (10 to 200-ft wide) gorges, they moved on top of the finer, lower-specific-gravity material. Relatively little passed over the sidewalls. In La Jolla Canyon about equal amounts of sand passed into the gorge over the rim of its wide headwall, and through several chute-like depressions or reentrants that pierce the headwall.

Sumner and South Branches are presently the most active tributaries of Scripps Canyon. The upper boundaries of their depressions are closest to shore and they intercepted more sand than tributaries that began in deeper water. Sumner and South Branches are located near the north end of the tributary system of Scripps Canyon and preferentially filled when longshore sediment transport was to the south. The north re-entrant of La Jolla Canyon was the most active part of that canyon, even though the gorge there is farther from shore than it is elsewhere.

In both canyons a much larger volume of littoral sand was initially deposited in the depressions than in the gorges. The ratio was about 20:1 in Sumner and South Branches.

Over 80 percent of the sand was transported seaward into the canyon heads between November and May during wave storms, probably more the result of storm-induced downwelling than transport in rip currents. Shore-normal transport was dominant. A relatively small quantity of sand entered the canyon heads parallel to shore. Only small amounts of littoral sand were carried into the depressions during the summer and autumn, but large quantities of mica and especially kelp and sea grass debris was deposited in the gorges at all times of year. Organic debris was transported by rip currents over the headwalls, and by longshore currents over the sidewalls.

An average of about 29,000 yd³/yr of littoral sand was deposited in the shallow heads of the canyons between December 1984 and June 1987. Only about 1,000 yd³/yr of that was trapped in La Jolla Canyon. In Scripps Canyon an average of about 22,000 yd³/yr was deposited in Sumner Branch; about 2,000 yd³/yr was deposited in South Branch. The long-term rate of littoral sand entrapment in or adjacent to Scripps and La Jolla Canyons appears to be approximately equal to the net longshore sediment transport rate at the south end of the Oceanside Littoral Cell.

Sand Flushing Rate. Once littoral sand passed over the upper edge of the depression it was carried downslope in small surface slumps and by wave-induced bottom oscillations coupled with gravity. In this way a critical slope of about 18 degrees was maintained at the seaward face of the prograding deposit. The normal load created by this deposit increased greatly as its toe prograded onto the steeply-dipping deposit in the gorges of Sumner and South Branches. When the normal load exceeded the internal shear strength of the deposit a massive downslope movement of sediment occurred. The slumps and slides were also controlled, in part, by the decomposition of organic debris that reduced the strength of the deposit near the floor of the gorges. The heads of Scripps Canyon apparently reach a critical volume of sand at which time the deposit is susceptible to failure. In Sumner Branch the critical volume is about 50,000 yd³ while in South Branch it is about 5,000 yd³.

Flushing occurred when storms moved large quantities of sand onto the upper part of the depressions, thereby increasing the normal load. Sumner, South and Shepard Branches flushed on 13 December 1984. Sumner and South Branches filled and again flushed in early spring 1987, so their flushing frequency during the field investigation was 0.4/yr. The flushing frequency of other Scripps Canyon tributary valleys is estimated to be 0.025+/yr.

Flushing occurs most often in gorges with steeply-sloping floors that fill rapidly because they head close to shore. Wave loading may be a factor in reducing the strength of the deposit during storms.

PREFACE

This field investigation of Submarine Canyons in San Diego County, California, was administered by the Waterways Experiment Station, Corps of Engineers. Joan Pope was the technical monitor.

The report was prepared by Dr. Craig H. Everts of Moffatt & Nichol, Engineers and Dr. Robert F. Dill. The investigation was done for the Coast of California Storm and Tidal Wave Study, Los Angeles District, Corps of Engineers. At the time the report was prepared Mr. Thomas Dolan was project manager. The present project manager is Dr. A.L. Kadib. Mr. Dolan and Ms. Pamela Castens, the contract monitor, offered helpful review suggestions that significantly improved the report.

In addition to the authors, Kevin Kelly, Anthony Jones, Thomas Lorensen, Richard B. Wilkins, Thomas Judy and Peter Dutton provided diving assistance. Moffatt & Nichol, Engineers managed the investigation and supported the preparation of the report. Boats were provided, under contract, by the Hubbs Marine Laboratory, San Diego State University through Mr. Don Kent.

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SEDIMENTATION IN SUBMARINE CANYONS
IN SAN DIEGO COUNTY, CALIFORNIA,
1984 - 1987

I. INTRODUCTION

Submarine canyons are found worldwide. Many along the U.S. Pacific Coast almost cross the Continental Shelf and extend sufficiently close to the coast to affect the shape of the shoreline. Some also act as sinks or traps for littoral sand. Steep canyon slopes prevent sands carried into shallow canyon heads from naturally returning to the littoral zone. This loss becomes permanent when the material is subsequently moved gradually or catastrophically down the canyon into very deep water where it cannot be artificially recovered. The shoreline adjacent to a nearshore canyon will usually either retreat or advance relative to the regional trend of the coast depending on: (1) the proximity of the canyon head to shore, (2) the consequences of a local longshore sediment transport gradient created by wave refraction over the canyon head, and (3) the volume of littoral sand trapped in the canyon head.

Fifteen California submarine canyons identified in Figure 1 approach close enough to the coast of California to affect the plan shape of the shoreline and/or to be sinks for littoral sand. These canyons are clustered in three groups. Four are in the north near Point Delgada; three are located in and near Monterey Bay; and eight are concentrated in the southern part of the state. The southernmost of those eight canyons, La Jolla, Scripps, and Carlsbad, are located in San Diego County and affect the shape of the shoreline. La Jolla and Scripps Canyons also act as sinks for littoral sand in the Oceanside Littoral Cell.

The field investigation described in this report addressed the submarine canyon component of the sediment budget of the Oceanside Littoral Cell. Scripps and La Jolla Submarine Canyons are located at the southern end of the Cell (Fig. 2). Carlsbad Submarine Canyon is located in the central part of the cell. The investigation had two objectives:

- (1) to establish which canyons in the Oceanside Littoral Cell are active traps for littoral sand at the present time, and

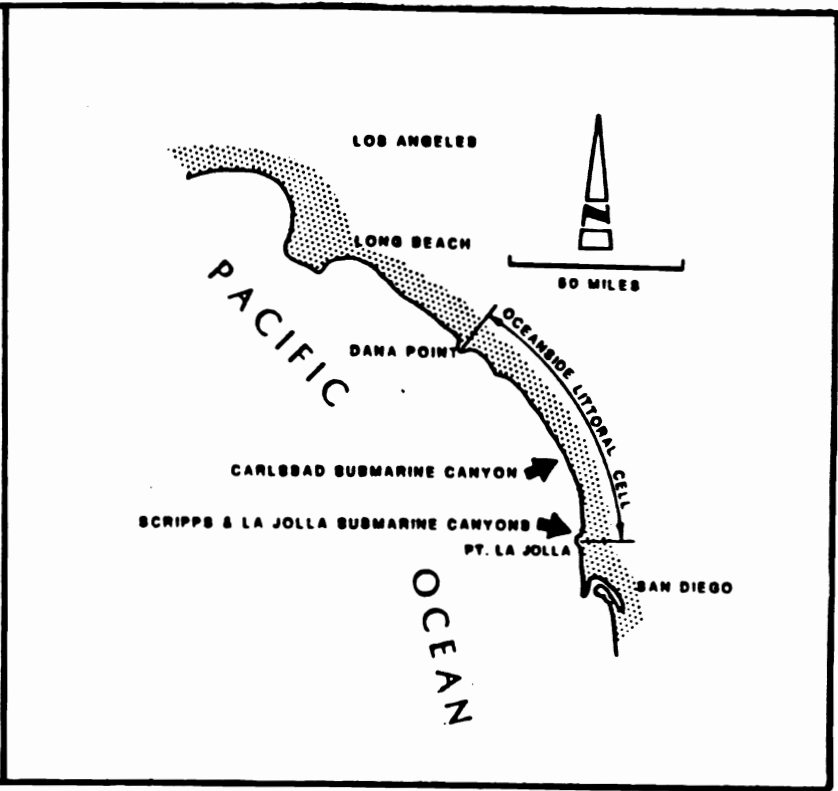
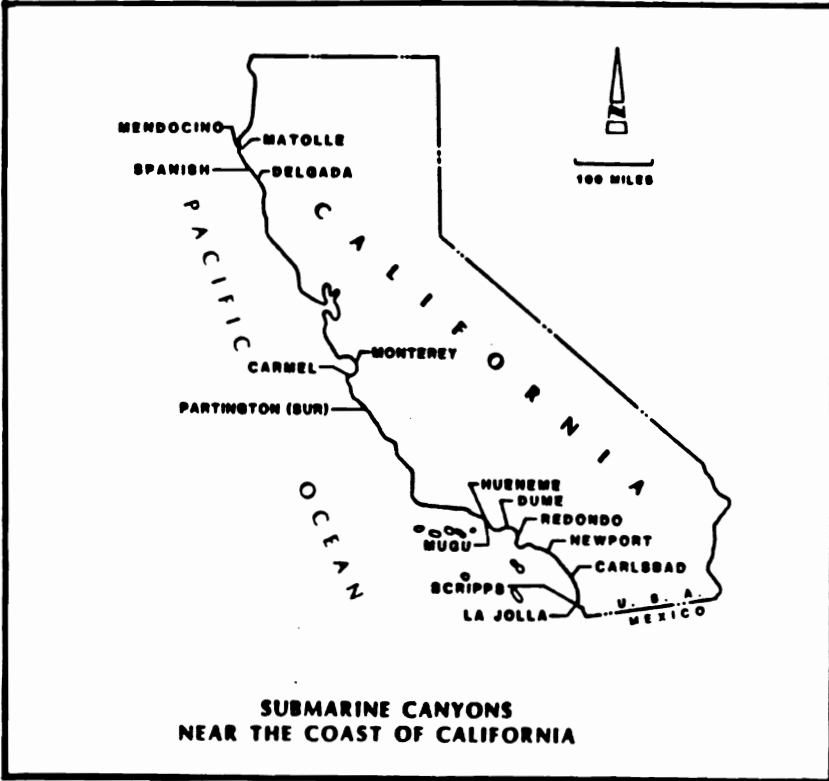


Figure 1. Submarine canyons near the coast of California.

Figure 2. Location map, submarine canyons in the Oceanside Littoral Cell.

(2) to quantify the volume rate that littoral sand was deposited in and subsequently discharged down the active canyons during the period of the field investigation.

II. SETTING AND FIELD MEASUREMENTS

1. Setting. For the purposes of this investigation an "active submarine canyon" is defined as one into which littoral sand, gravel and/or cobbles are being deposited. This diversion of littoral material to the canyon depression constitutes a net loss of material from the littoral cell which must be considered when the sediment budget of the cell is computed.

Three quite distinct regions as shown in Figure 3 comprise the littoral zone in the vicinity of an active submarine canyon in San Diego County. The beach and shoreface regions of the littoral zone have a shape and gradient similar to or perhaps a bit steeper than the beach and shoreface nearby. Sediment moving alongshore in the littoral zone either passes landward of an active canyon head or it is carried seaward into the steep canyon-head depression. Once sediment reaches the upper boundary of the depression it is lost to the littoral zone. The surface slope of the depression is so steep that sand-sized material is not naturally returned shoreward. Typically, the depression fills in a seaward direction. Consequently, its upper edge is not fixed, but progressively moves away from shore. Conversely, the boundary of the gorge is fixed and well-defined by the canyon rim. Most sediment moves into the gorge at the apex, i.e., the most landward part of the gorge. The rim of the gorge may be defined by a scarp or a change in bedrock slope. The headwall at the apex is usually buried, as illustrated in Figure 3. Most sediment transport is from the depression into the gorge. Away from the apex the rim of the gorge is usually exposed.

Scripps Canyon has eroded closest to shore and is the most active canyon in San Diego County. It has at least six shallow-water branches located about 1 mile north of the broad head of La Jolla Submarine Canyon (Fig. 4). Both canyons are at the downcoast end of the Oceanside Littoral Cell. Littoral sand from upcoast regions reaches the shoreface and beach adjacent to the shallow heads of Scripps Canyon first, and must pass by them before reaching the beach and shoreface near La Jolla Canyon. Scripps Canyon captures more littoral sand from upcoast regions than La Jolla Canyon because of the greater availability of sediment at Scripps Canyon, and because its branches extend closer to shore and are shallower than the single broad head of La Jolla Canyon.

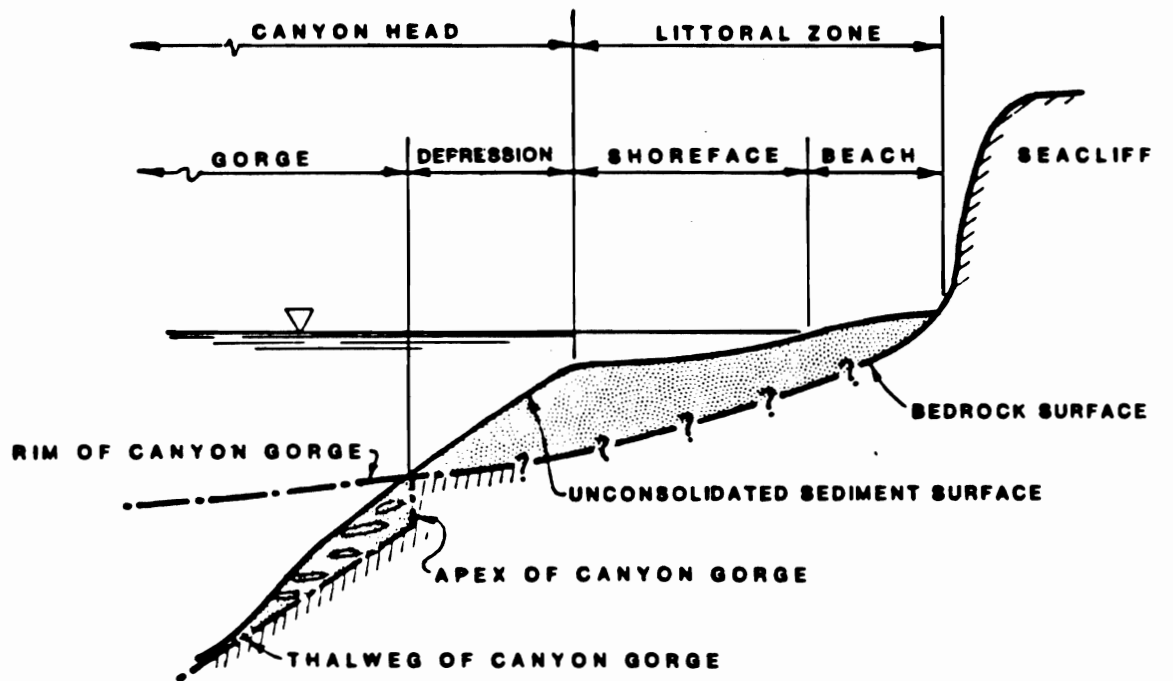
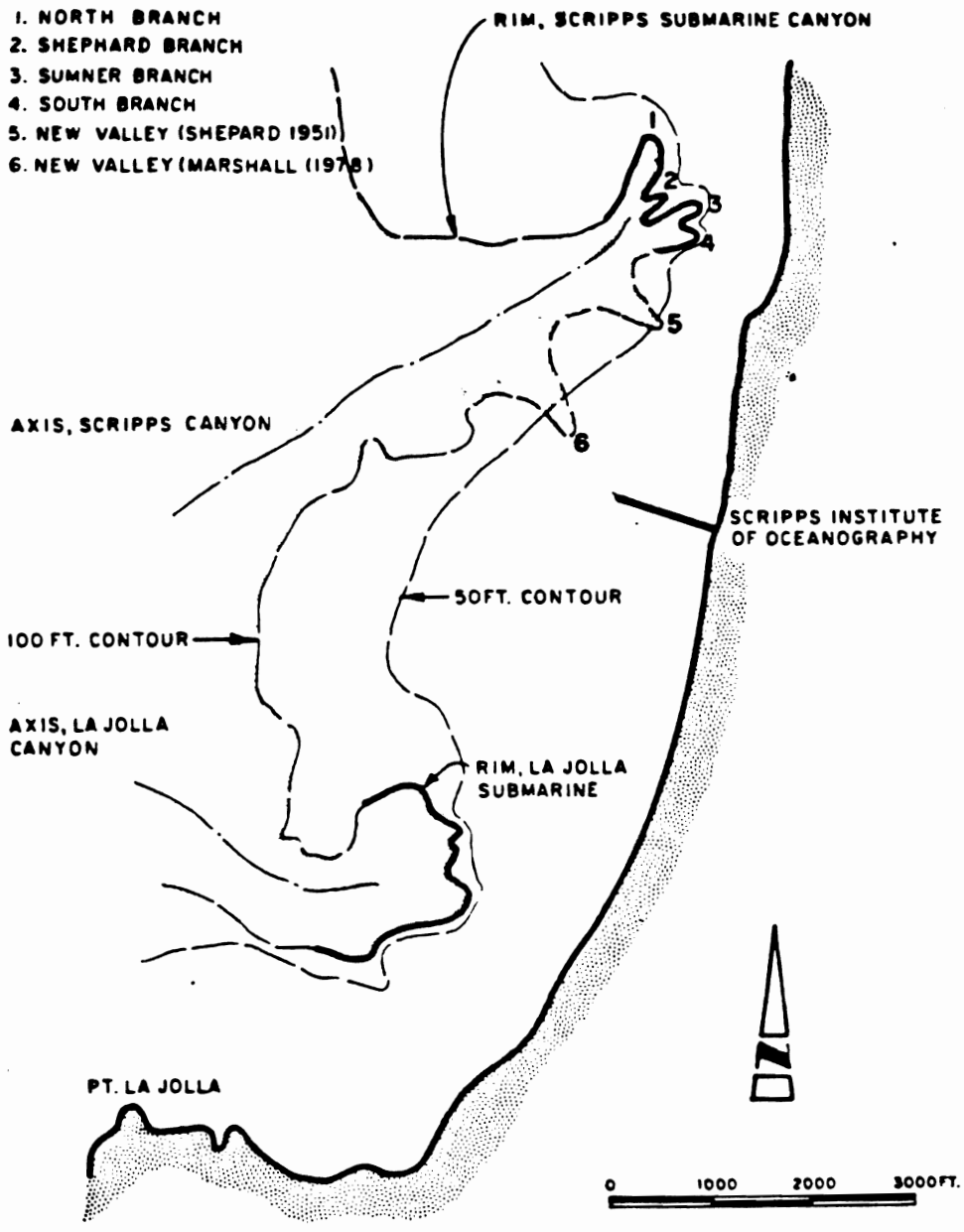


Figure 3. Idealized cross-section of inner-Continental Shelf at a head of Scripps Submarine Canyon (not to scale).



RIM LOCATIONS, SCRIPPS AND LA JOLLA SUBMARINE CANYONS

Figure 4. Map showing the general location of the canyon-head rim in Scripps and La Jolla Submarine Canyons.

Scripps Submarine Canyon is the northern extension of the La Jolla Canyon System defined by Dill (1964) and Shepard and Dill (1966) and shown in Figure 4. It has a relatively straight trend with narrow and steep to overhanging rock walls. It is oriented downslope in a southwesterly direction. The distance from the upcoast shallow-water heads of Scripps Canyon to where it joins La Jolla Canyon at a depth of 900 feet is about 1 mile. The canyon slope in that reach is approximately 7 degrees.

La Jolla Submarine Canyon forms the southern leg of the La Jolla Canyon system. It is at the southern longshore boundary of the Oceanside Littoral Cell. It has a broad bowl shape with minor, but broad tributaries or reentrants. Sand that passes landward of the heads of Scripps Submarine Canyon is either deposited on the beach and shoreface near the outlet of Soledad Valley or it is lost into the shorewardmost tributaries of La Jolla Canyon. A marked change in grain size and composition of beach sands indicates large quantities of Oceanside Littoral Cell sand apparently does not move southward around Point La Jolla and into the Mission Bay Littoral Cell. The shoreline, embayed adjacent to the head of the canyon, changes orientation from about 020 degrees at La Jolla Shores, along the north part of the canyon, to about 300 degrees east of Point La Jolla adjacent to the south part of the canyon (Fig. 4). The La Jolla Canyon System ends in the San Diego Trough after cutting across the Continental Shelf with an overall length of about 23 miles. From its rim to the intersection with Scripps Canyon the axial slope of La Jolla Canyon averages about 8 degrees.

Scripps and La Jolla Submarine Canyons were mapped in the past using echo sounders. While it was not the intention of this study to remap their deeper regions, for the purposes of establishing the volume of littoral sand lost to the canyon heads it was necessary to conclude a very specific mapping effort to establish the fixed upper boundary for the canyon gorge, i.e., the position of the rim. The location of the rim was located to: (1) determine the volume of sand that can be held in the depression, (2) quantify the infilling rate of the depression and gorge, and (3) establish the frequency at which the depression and gorge discharge their sediment load to deep water.

The mapped location of the nearshore rim in Scripps and La Jolla Canyons is shown in Figure 4. Figure 5 shows the position of the rim at the shallow-end of Scripps Submarine Canyon. Canyon rims were mapped using divers tethered to

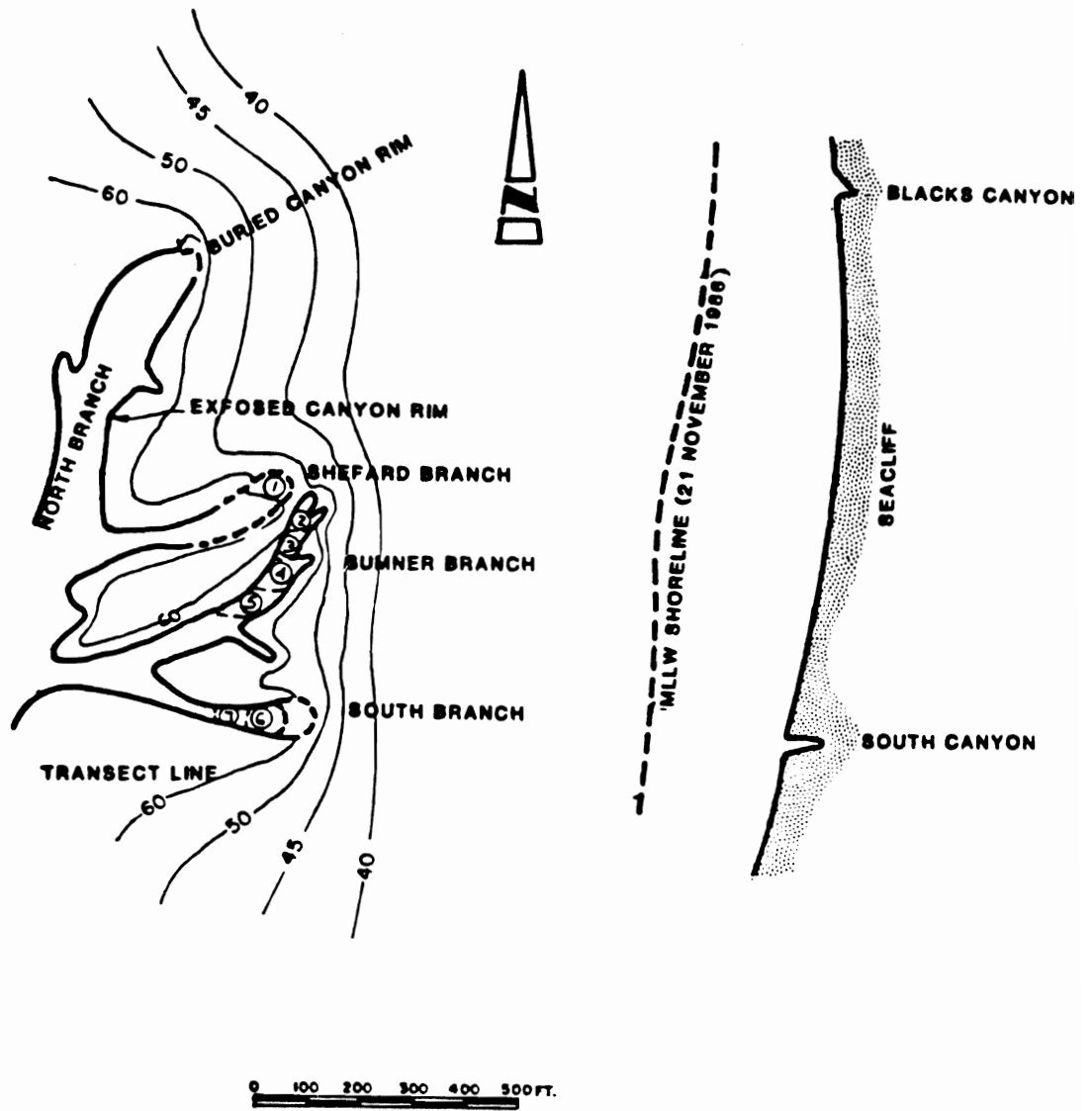


Figure 5. Location of rim, most active branches of Scripps Submarine Canyon.

the surface by a thin line and a float. The divers swam along the rim and recorded the depth of the rim and any significant features they observed. At frequent intervals horizontal sextant angles were taken from a small boat to locate the position of the float. A minimum of four prominent local landmarks were used for horizontal control purposes. Horizontal positions were also established at the stationary position of the float when the divers stopped and signalled the surface after they encountered a change in rim configuration.

At least six shallow-water heads of Scripps Submarine Canyon approach the littoral zone seaward of and north of Scripps Institution of Oceanography (Fig. 4). Below the exposed rock rim, the gorges of North, Sumner and South Branches are steep-sided, U or V-shaped, 100's of feet long and 10's of feet wide. Landward of the rock-rimmed gorge the depression of each branch is characterized by a shallow bedrock trough. Each of the three steep gorges is defined by a rocky rim at a depth of 45 to 70 feet. The rims are continuous and do not connect with a land canyon. However, the head of some of the branches, if extended, can be traced to a land canyon incised in the seacliffs. By probing the sediment cover with a water jet in the depressions of Sumner and South Branches, Chamberlain (1960) found the bedrock surface was also trough-shaped and extended toward the land canyons. The rock-walled gorges of valleys described by Shepard (1951) and Marshall (1978) and of Shepard Branch, described in this report (Fig. 4), have mild slopes. Like North, Sumner and South Branches the thalwegs of the valleys are 100's of feet long, but the thalweg slopes are milder. Geometric characteristics of the heads of Scripps Submarine Canyon are given in Table 1.

Dill (1964a, b) categorized rocky shallow-water features below the rim of Scripps Submarine Canyon according to size. He defined branches as first order features 100's of feet long, and second-order features as tributaries 10's of feet long. Dill (1964a, b) considered four tributaries to be the primary conduits by which sand enters Sumner Branch (Fig. 5). Sediment chutes and surge channels are third-order features first defined by Chamberlain (1960). Just a few feet long, these notch-like features break the branch and tributary rims, usually most extensively on the shoreward side.

TABLE 1. Geometric Characteristics of Submarine Canyon Heads in San Diego County

CANYON HEAD	SLOPE IN UPPER CANYON GORGE, degrees	DIS-TANCE TO APEX OR RIM, FT from MLLW Shoreline	DEPTH AT APEX OR RIM ft (MLLW)	DISTANCE TO UPPER BOUND-ARY OF DEPRES-SION, FT from MLLW Shoreline	DEPTH AT UPPER BOUNDARY OF DEPRESSION ft, (MLLW)	SLOPE ABOVE CANYON DEPRES-SION, degrees	DIS-CHARGED DURING STUDY? Yes-No	Remarks
Carlsbad	6			4400	100	1	No	Canyon rim not exposed
Scripps								
(1) North Branch	7	1240	64	1170	54	3	No	
(2) Shepard Branch	13	900(?)	80(?)	600	23	4	No	Broad shallow trough, rim not well defined, shares depression with Sumner Branch
(3) Sumner Branch	17	800	61	600	23	4	Yes	
(4) South Branch	25	700	66	520	18	3	Yes	
(5) new valley (Shepard, 1951)	4	1680	100-130(?)	780	30?	2	No	Rim not well defined
(6) new valley (Marshall, 1978)	6	1400	?	1200	30	1	No	
La Jolla								
(1) North Re entrant	9	1690	61	1530	43	2	No	
(2) Central Canyon	10	830	53	715	31	2	No	
(3) South Canyon	12	1200	56	1030	20	1	No	

La Jolla Submarine Canyon begins in water depths of 40 to 80 feet as a sharp scarp eroded in Holocene (last $8-10 \times 10^3$ years) lagoonal sediments (Fig. 6). The head of the canyon is broad and bowl-shaped, reaching its nearest position to the coast (approximately 800 ft) near the center of its 4000-ft long, nearly shore-parallel boundary. Three of the five fixed locations on land used in horizontal positioning are identified on Figure 6. Others were the cupola of the Valencia Hotel in La Jolla and the end of the 1986 Scripps pier (a new pier has since been constructed). Measurements of rim characteristics were made at 47 locations and recorded (Table 2). The slope immediately above the scarp averages 8-20 degrees. Four sand-filled reentrants pass through the scarped rim as shown on Figure 6. The major reentrants are those located between Sites 1 and 2 at the north end of the canyon, near mid-canyon, and between Sites 34 and 35 at the south end of the canyon. The North Reentrant is the most active. Geometric characteristics of La Jolla Canyon are given at Table 1.

Carlsbad Submarine Canyon is located about 30 mi north of San Diego, 6 mi south of Oceanside Harbor, and about 12 mi north of Scripps and La Jolla Submarine Canyons (Fig. 2). The canyon head is offshore the Pacific Gas and Electric generating station and the south outlet of Agua Hedionda Lagoon at Carlsbad, California. Contours deviate from shore-parallelism in the vicinity of the canyon at a depth of about 120 ft, approximately 4450 ft from shore (Fig. 7). This depth and distance from shore are considerably greater than the first bathymetric expression of the canyon heads of Scripps and La Jolla Canyons which are known active traps for littoral sand. Bedrock was not found cropping out on the sides of Carlsbad Canyon.

2. Approach. Field investigations were made between December 1984 and June 1987 in Scripps, La Jolla and Carlsbad Submarine Canyons. A reconnaissance investigation was made in Carlsbad Canyon early in the study to determine whether it was recently active. After it was determined Carlsbad Canyon is presently not a significant active trap for littoral sand, the field effort concentrated exclusively on Scripps and La Jolla Canyons.

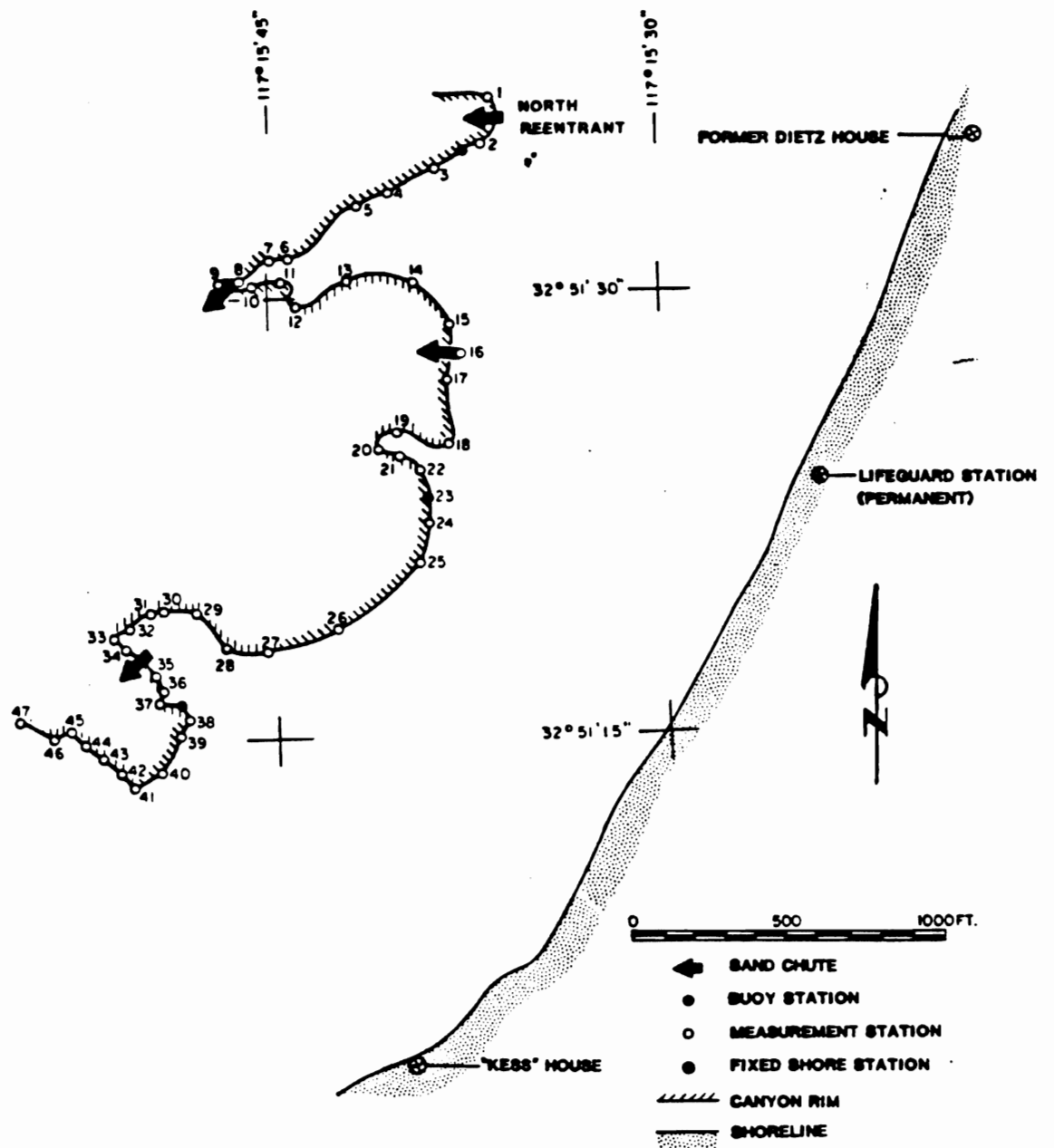


Figure 6. Location of rim, La Jolla Submarine Canyon.

TABLE 2. Characteristics of Canyon Rim, La Jolla Submarine Canyon

(1) Location	(2) Sediment Slope above Rim, degrees	(3) Depth at Rim, Feet	(4) Rim Characteristics
1	12	64	CHUTE extends west to deeper water
2	17	66	3 ft vertical scarp
3	13	61	4 ft vertical scarp above 60-degree slope
4	10	61	10 feet scarp at 60 degrees
5	18	63	18 ft vertical scarp
6	16	70	18 ft vertical scarp
7	18	70	20 ft vertical scarp
8	20	75	20 ft vertical scarp
9	20	78	nose, CHUTE-SAND Slope at 20 degrees, scarp below
10	0	80	20 ft vertical scarp
11	0	68	20 ft vertical scarp
12	20	75	20 ft scarp
13	16	62	20 ft scarp, not vertical
14	8	50	3 ft vertical scarp ABOVE 8-ft scarp at 58 ft
15	17	53	2 ft vertical scarp
16	22	51	CHUTE 60-ft wide
17	15	48	5 ft vertical scarp
18	10	52	5 ft vertical scarp
19	12	56	6 ft vertical scarp
20	20	60	nose with two scarps
21	19	51	14 ft vertical scarp
22	16	51	8 ft vertical scarp
23	17	51	8 ft vertical scarp, plus lower rim
24	15	50	nose, 2 ft high scarp
25	28	45	rounded rim, 0.5 ft scarp
26	5	54	5 ft near vertical scarp
27	15	60	rounded rim, 0.5 ft scarp
28	20	60	5 ft vertical scarp
29	25	65	5 ft near-vertical scarp
30	26	65	5 ft near-vertical scarp
31	27	67	10 ft vertical scarp
32	25	70	10 ft vertical scarp
33	22	64	rounded, indistinct 0.4 ft high scarp, large chain crosses rim here
34	26	61	0.4 ft vertical scarp
35	17	49	0.4-ft vertical scarp CHUTE 60-ft wide between 34 and 45
36	13	50	1 ft vertical scarp
37	15	49	1 ft vertical scarp
38	16	50	2 ft vertical scarp
39	14	46	14 ft vertical scarp
40	10	55	8 ft high vertical scarp (Rose Canyon Fault)
41	10	30	5 ft high vertical scarp (Rose Canyon Fault)
42	20	35	3 ft wide sand chute
43	20	40	10 ft vertical scarp
44	35	42	
45		60	
46		50	
47	20	50	

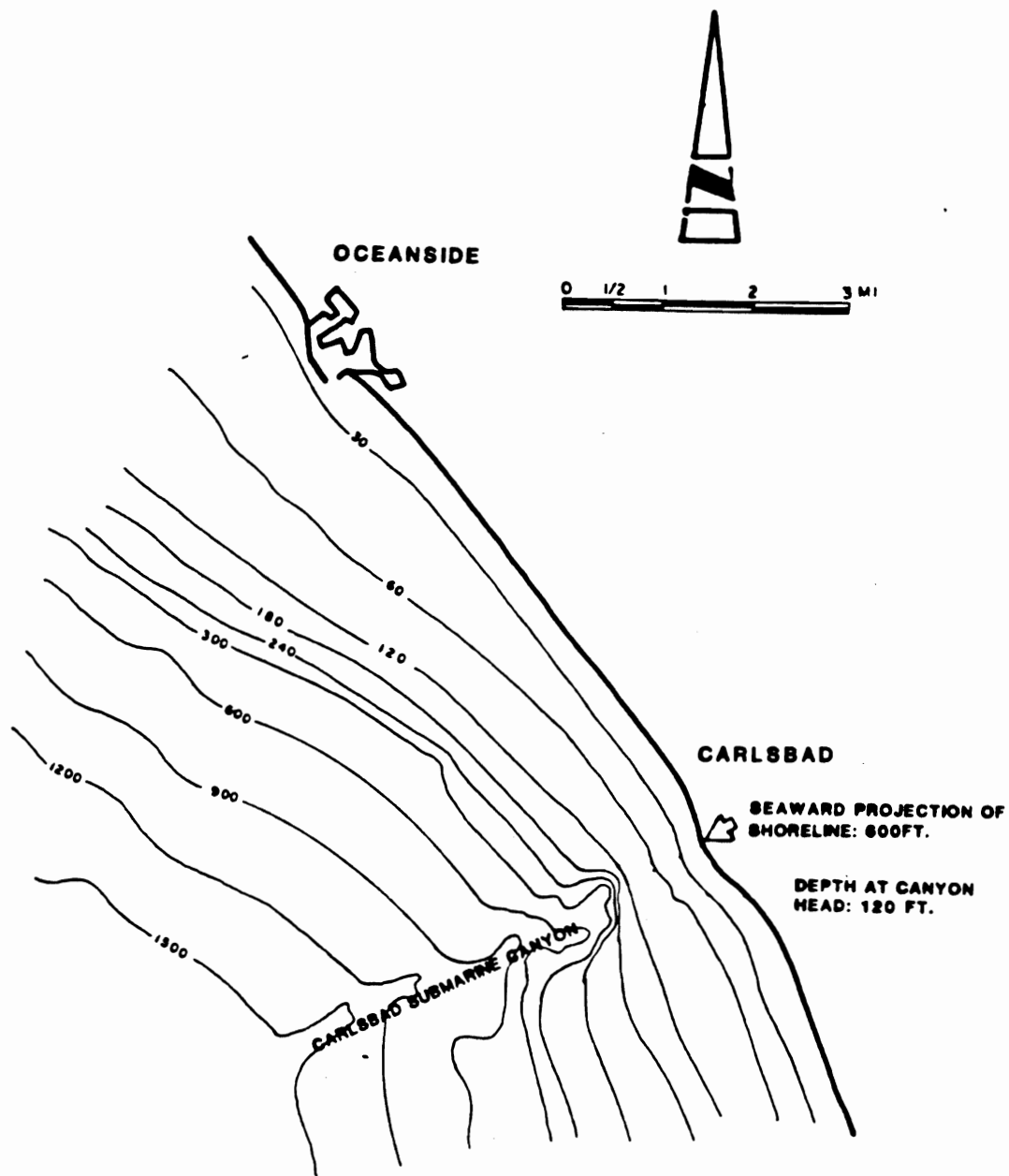


Figure 7. Bathymetry, Carlsbad Submarine Canyon.

Three survey devices were used to measure the flux of littoral sand into and down the canyon heads: (1) survey markers (rods) to determine sand level changes, (2) survey transect lines for the same purpose, and (3) sediment traps to determine the sand transport rate across the canyon rims. Sediment traps worked well where there was a well-defined canyon rim. In the canyon-head depressions and at the apexes of the canyon gorges, however, traps were not useful because the sediment infilling rates were too great. At those locations sediment infilling rates were obtained from bottom surveys that established changes in sediment level.

On-bottom or near-bottom survey methods were used. While more labor intensive than acoustic procedures applied from a boat, they offer a number of desirable features. Most importantly, they are more accurate. Direct measurements of sand level changes eliminate problems and inaccuracies inherent in reducing acoustic records. Acoustic survey data obtained from a floating platform are subject to errors introduced by sea and swell and inaccuracies in tidal corrections. Horizontal positioning problems are also eliminated using bottom or nearbottom survey techniques because fixed survey lines on or near the bottom can be reoccupied. Steep slopes, including vertical walls, can be accurately surveyed, which is an impossibility using a wide-beam acoustic signal that averages bottom depth below the boat. On-bottom surveys allow observations of sediment type and bottom configuration. Small-scale slump scars, and variations in organic, mica, and sand content cannot be differentiated on an acoustic record. Acoustic sounding may or may not define an organic layer. The state of decomposition of the organics, an important consideration in determining the strength of the accumulated sediment in the gorge, can only be established by direct observation.

a. Survey Markers. Rods, either 3/8 or 1/2-in diameter reinforcing steel bars cut in 5-ft lengths, were inserted in a vertical position along sand transport paths in two regions: (1) the depressions and leading to the gorges (Fig. 3) in North, Sumner and South Branches of Scripps Canyon, and the depression at the North Reentrant of La Jolla Canyon, and (2) within the gorges of those canyon heads plus the head of Shepard Branch. Half-inch rods lasted two or three times longer than 3/8-in diameter rods without losing significant dimension to corrosion. Survey markers were placed in single, straight lines and in crossing lines. A rod spacing of 10 ft was used so divers could find the rods and follow the lines under most visibility

conditions (Fig. 8). Rod lines were usually extended shoreward in the depressions to the assumed landward limit of the depression. Rod lines were established in sand and where possible the rods were driven to bedrock to give an absolute stake reference depth.

Survey markers were used to measure the movement of sand parcels from shore to and into the canyon heads by determining: (1) sand level changes with respect to the top of the rod, (2) mass downslope transport near the sediment surface as evidenced by rod tilt, and (3) transport of the mass of sediment in depth as evidenced by rod displacement in a horizontal direction when the rod location was referenced to other rods and to fixed locations on the bottom, i.e., rock outcrops. The survey-marker method does not provide information on the uniform or near uniform movement of sand directly to the canyon head. It does, however, show the progradation of sand lobes toward the canyon gorges, and it is useful in cataloging slumps above the thalweg of the gorges.

Survey markers were placed so they had different beginning top elevations above the sand bed. This facilitated establishing individual locations using the rod elevation sequence in poor-visibility conditions. When rods were covered to within about a foot of the top a new rod was placed next to it so the station was not buried and lost. This was necessary at Sumner and South Branches in Scripps Canyon and the North Reentrant of La Jolla Canyon.

With the exception of Sumner and South Branches, sand level measurements referenced to the top elevation of the survey markers proved a useful technique in the canyon gorges. At Sumner and South Branches, however, so much sea grass and kelp entered the gorges that the rods could not be kept in place or easily found over a reasonable length of time. These sites required a different survey approach.

b. Line Transects. Lines were strung from rim to rim across the gorges of Shepard, Sumner and South Branches to get absolute changes in sediment level at deep sites where movements of organic material precluded the use of survey markers. Tags on the lines at 4-ft spacings (except at an existing cable in South Branch) were used as survey stations. Divers measured the vertical distance from the fixed line to the sediment surface in the gorge using a lead line on a reel as shown in Figure 9. The survey result is a sequence of canyon axis profiles that define changes in sediment level. Bottom type was



Figure 8. Measurement of survey marker in the North Reentrant of La Jolla Submarine Canyon; note organic growth on rod being measured and on rod in background; bottom is well-packed littoral sand.

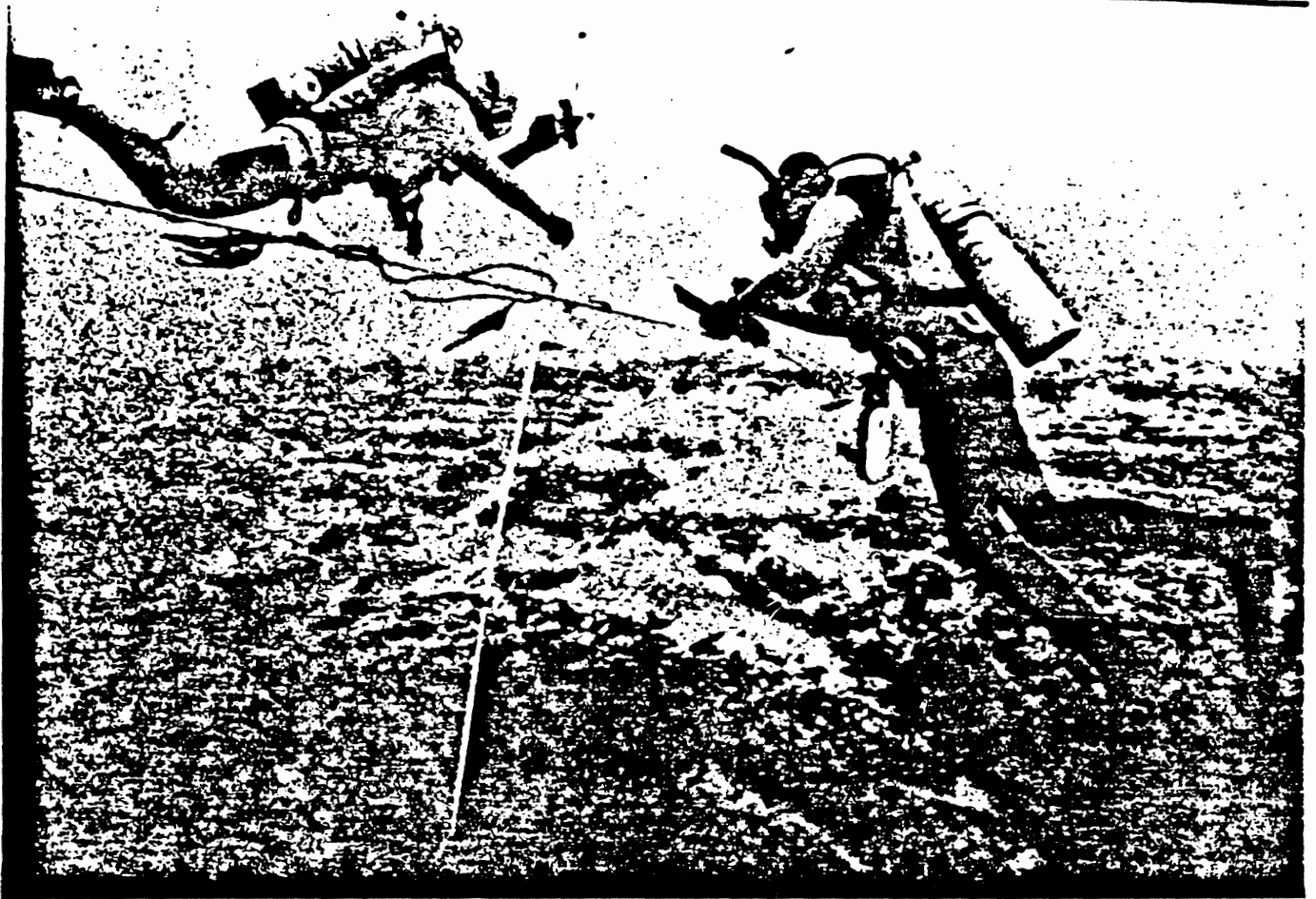


Figure 9. Measurements in Sumner Branch on Line Transect No. 3 looking northeast; depth is 68 ft; east sidewall of gorge is in background with sparse, discontinuous covering of littoral sand.

noted because the buildup was partly and often wholly sea grass and kelp which sometimes entered and exited the gorge quite rapidly and produced large bottom level changes.

All lines were 1/4 inch polypropolane (floating) rope. They were fixed to the canyon rim using lag bolts or (better) 10-in long spikes driven into the rock rim. A second spike was placed at each end so when lines were lost to dragging anchors or other causes they could be reestablished at the same site. Transect lines provided an excellent means to obtain gorge profiles at a reasonable depth. The depth at the base of the gorges would have precluded diver measurements even if it had been possible to maintain rods there.

c. Sediment Traps. Rectangular plastic buckets 11-in deep and 9.9-in by 5.5-in wide were used as sediment traps (filled volume = 0.3 ft^3). They were fastened near the canyon rim using 10-in long steel spikes driven through pre-drilled holes in the buckets (Figs. 10 and 11). Buckets were numbered in indelible black ink and the number was also engraved (scored) in the plastic. With time, after the inked markings became illegible, the engraved markings were used to identify the trap when the organic layer (Fig. 11) was scraped off. Aluminum foil was used to fill the irregular space between the rim and bucket in cases where the canyon rim was too irregular to get a continuous seal with the pliable rim of a bucket.

Bucket traps worked best where the region below the rim was nearly vertical and the rate of sediment transport was such that the traps did not completely fill between field visits. In La Jolla Canyon the buckets were especially useful because sand transport rates were relatively low and the transport velocity over the rim was such that sand passed into the trap, not over it. Traps usually filled first on the side next to the rim when the trap was placed on a vertical scarp. This suggests filling was by sand dribbling over the rim, not sand carried over in an arc. Where the rim was not vertical, or the slope above the rim was steep, sand was usually directed along the slope into the trap, not over it (Fig. 11). Because the inside of the trap is a stagnant area, the trap affects the flow at and in its vicinity. This did not seem to be a major problem on the canyon slopes where downslope sand flow rates were low (perhaps less than 0.5 ft/sec, as observed). Sediment traps sometimes filled with grass and other organic material. When emptied the infill volume and percent sand was determined to establish the sand flux.



Figure 10. Sediment trap fastened to sloping bedrock above the rim of South Branch at a depth of 63 ft.



Figure 11. Growth-encrusted sediment trap fastened to the vertical sidewall of the gorge below the rim of Sumner Branch; depth is 71 ft (June 1986).

III. SEDIMENTATION IN CARLSBAD SUBMARINE CANYON

The first objective of this investigation was to establish which of the canyons in San Diego County are presently active. Previous studies clearly documented activity in La Jolla and Scripps Submarine Canyons (Shepard and Emery, 1941; Chamberlain, 1960; Dill, 1964; and Shepard and Dill, 1966). Shepard's pioneering field work indicates those two canyons have been active at least as far back as the early to mid-1930's, and, no doubt, were active long before then. While several previous investigators considered Carlsbad Submarine Canyon to be inactive, their investigations did not specifically focus on littoral sand entrapment in the canyon head. The possibility of present-day littoral sand losses to Carlsbad Canyon is addressed in this section.

1. Previous Studies. Carlsbad Submarine Canyon was reported inactive but not completely filled at the present time by Fischer et al (1983). Their interpretation of seismic records obtained shoreward of the canyon head (0 to 100 foot depths) indicated the shoreface and Continental Shelf bottom was bare rock or covered with a very thin layer of sediment. North of the canyon Fischer et al (1983) reported the sediment volume above bedrock and out to a depth of 100 feet to be about 4×10^3 yd³/per lineal alongshore foot. South of the canyon they found it to be only one-fifth that value, or 0.8×10^3 yd³/ft. They attributed this large north-to-south decrease in shelf sediment volume to entrapment in estuaries south of Oceanside. However, it could also be the result of canyon infilling at a previous time or at the present time. Emery (1960), and Inman and Frautschy (1966), identified Carlsbad Canyon as a currently inactive feature that they considered to have been the downcoast end of a littoral cell when sea level was lower.

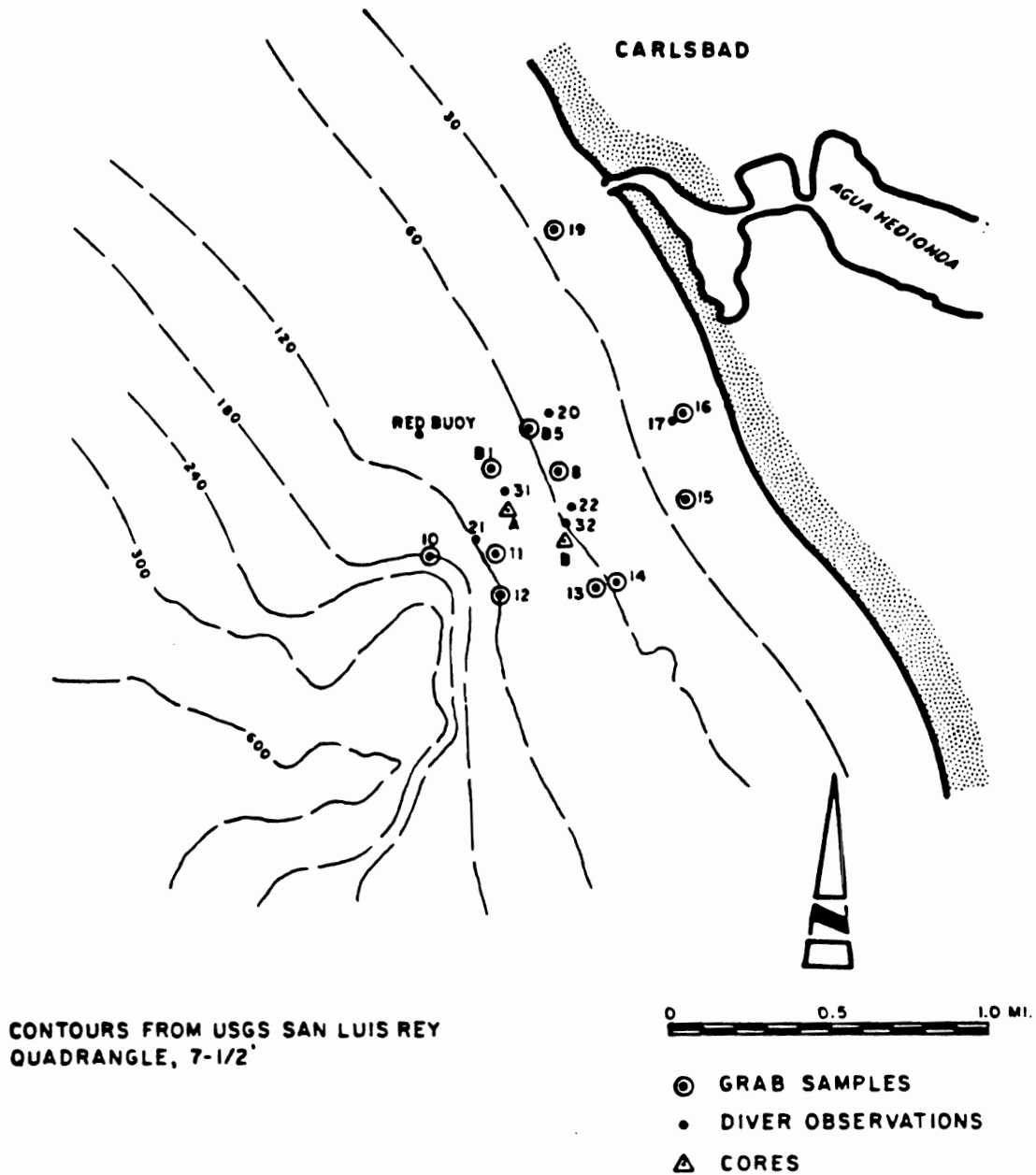
When littoral sand and gravel is trapped in quantity in the shallow, steep head of a submarine canyon, that material may be later moved down the axis of the canyon to a final deepwater depositional site. Shepard and Emery (1941) found active canyons that extend to near the present coast have hard-packed channels in deepwater composed of sand, gravel or rock. They found inactive canyons were located a greater distance from shore and their deepwater channels were partially filled with mud. The axis of Carlsbad Submarine Canyon contains relatively soft mud and Shepard and Emery (1941) assumed it was presently inactive based on that sedimentologic evidence.

2. Bathymetric Evidence. Contours deviate from shore-parallelism in the vicinity of Carlsbad Submarine Canyon at a depth of about 120 ft, approximately 4450 ft from shore (Fig. 3). This depth and distance from shore are considerably greater than the first bathymetric expressions of active heads of Scripps and La Jolla Canyons.

Inman and Nordstrom (1978), in a study of sand level changes on the inner-Continental Shelf north of Scripps Canyon, found seasonal changes decreased with water depth and were less than 0.1 ft at a depth of 36 ft. Larger seasonal offshore and onshore movements were not detected in greater water depths. The highly-seasonal volume of littoral sand transported to the head of Scripps and La Jolla Canyons, as shown in later sections of this report, is inversely proportional to the depth of the canyon head. Canyons that head in deeper water trap less sand. Although sequential bottom level data are not available at Carlsbad Canyon, it is unlikely littoral sand is seasonally carried out as far as a depth of 120 ft, or 4450 ft from shore.

3. Sedimentological Evidence. Two vibra-cores and 11 surface grab samples were taken using the San Diego State University vessel "Pelican" on 8 December 1984 at the sites shown on Figure 12. Both cores penetrated 1.5 ft of hard, consolidated, sandy sediments, but they did not penetrate to bedrock. All sediment samples were analyzed using 1/2 phi sieves. Dives were made at the seven observation sites shown in Figure 12.

Sediment sizes do not decrease in a uniform manner from shore to and into the canyon head (Table 3). The median size of beach sands is in the 0.2 to 0.3 mm range onshore the canyon. In depths of 15 to 25 ft, the median grain size is about 0.11mm, or the size one would expect in that depth interval on a shoreface that was actively tied to the beach. At sites 13 and 14 in deeper water the surface sediment is much coarser, suggesting it is relic material and that the zone between depths of perhaps 30 ft and the canyon head is no longer supplied with significant quantities of beach sand. Sediments in the canyon head are very fine sands and silts which are not a major component-size of the beach material. In active canyons, as shown in subsequent sections, sediments taken on a line from the shoreface into and within the canyon head do not vary greatly in size.



CONTOURS FROM USGS SAN LUIS REY QUADRANGLE, 7-1/2'

Figure 12. Grab sample, vibra-core and diver-observation stations in the vicinity of Carlsbad Submarine Canyon, field investigation of 8 December 1984.

Relic material was found just below the surface at many locations where a buildup of littoral sand would be expected early in the storm season of 1984-1985. While the shallow, relic layer does not preclude transport across it, its occurrence in a number of mid-depth locations supports the contention that littoral sand had not recently moved to depths of 50 to 100 ft. At Site 22 (Fig. 12), for example, in a depth of 55 ft, coarse sand and granules were found 0.3 ft below a fine-sand veneer.

TABLE 3. Sediment Size Data, Carlsbad Canyon

LOCATION (Figure 12)	GRAIN SIZE 50th percentile, in mm	GRAIN SIZE 84 percent larger than this size, in mm	GRAIN SIZE 16 percent larger than this size, in mm	WATER depth, feet
<u>SAMPLES FROM CLOSE TO SHORE</u>				
15	0.11	0.077	0.14	23
16	0.10	0.070	0.13	13
9	0.12	0.080	0.18	26
<u>SAMPLES FROM MID-DEPTH REGION</u>				
Buoy 5	0.10	0.065	0.14	62
Buoy 1	0.10	0.075	0.14	88
13	0.45	0.28	0.72	62
14	0.20	0.085	0.50	56
8	0.10	0.065	0.14	56
<u>SAMPLES FROM CANYON HEAD</u>				
10	0.070	0.045	0.11	180
11	0.090	0.055	0.13	110
12	0.080	0.050	0.13	120

4. Surface Morphology. Inactive bedforms found on the seabed during observation and sampling dives reflect conditions that prevailed when they were formed as well as post-formation modifications that include bioturbation. Bottom observations of these inactive and decaying features made by divers after two previous months (October-November, 1984) of severe wave events did not suggest sand transport to the head of Carlsbad Canyon. At Scripps Canyon much sand-sized littoral material was moved into Sumner and South Branches in the same 2-month period. Between depths of 50 ft and 125 ft, there was no

indication of significant offshore-directed flow that moved littoral sand to the head of Carlsbad Canyon in the pre-dive period of high energy wave conditions.

5. Shoreline Projection. As shown in Figures 7, 12 and 13, the shoreline adjacent to Carlsbad Submarine Canyon is presently about 600 ft seaward of the general trend for that coastal reach. In an alongshore direction the coastal bulge is about 8,000 ft long. The bulge has been created by differential shore retreat (Fig. 13). Wave refraction causes a divergence of wave orthogonals over the canyon head and a consequent reduction in wave energy impinging on the shoreline in the vicinity of the bulge. The reduced wave energy coupled with a reduction in the longshore sediment transport rate at the projection resulted in a lower shoreline and seacliff retreat rate with respect to the adjacent coast.

The most seaward part of the projection (Fig. 13) was relatively stable between 1888 and 1972 (USACE-LAD, 1988 drafts), moving within a shore-normal sweep zone of less than 80 ft (4 surveys: 1888, 1934, 1960, 1972). About 8,000 ft north and 4,000 ft south of the canyon the shoreline appears also to have been stable, but less active, in recent times. The shoreline in the region outside the control of the canyon advanced and retreated in a sweep zone of less than 50 ft between the four surveys. The longshore influence of canyon-induced wave refraction on the shoreline thus appears to be about three times the distance from the shoreline to the canyon head.

6. Sedimentation in Canyon Head. An interpretation of seismic profiles of the area led Osborne et al (1983) to conclude 15 to 50 ft of sedimentary material had been deposited in the shallow part of the canyon axis during the past 3000 to 5000 yr. Similar sediment infill deposits are absent in the heads and channels of active canyons in southern California.

Osborne et al (1983) also found a channel that is now filled with over 60 ft of sediment landward of the present bathymetrically-defined head of Carlsbad Canyon. The channel trends normal to shore and directly into Agua Hedionda Lagoon. A river channel apparently crossed the Continental Shelf at this site and discharged down the Continental Slope before sea level rose to near its present level approximately 3000 yrs ago. During the rise, the river gradient would have flattened near the coast. Sediment discharged by the river, and

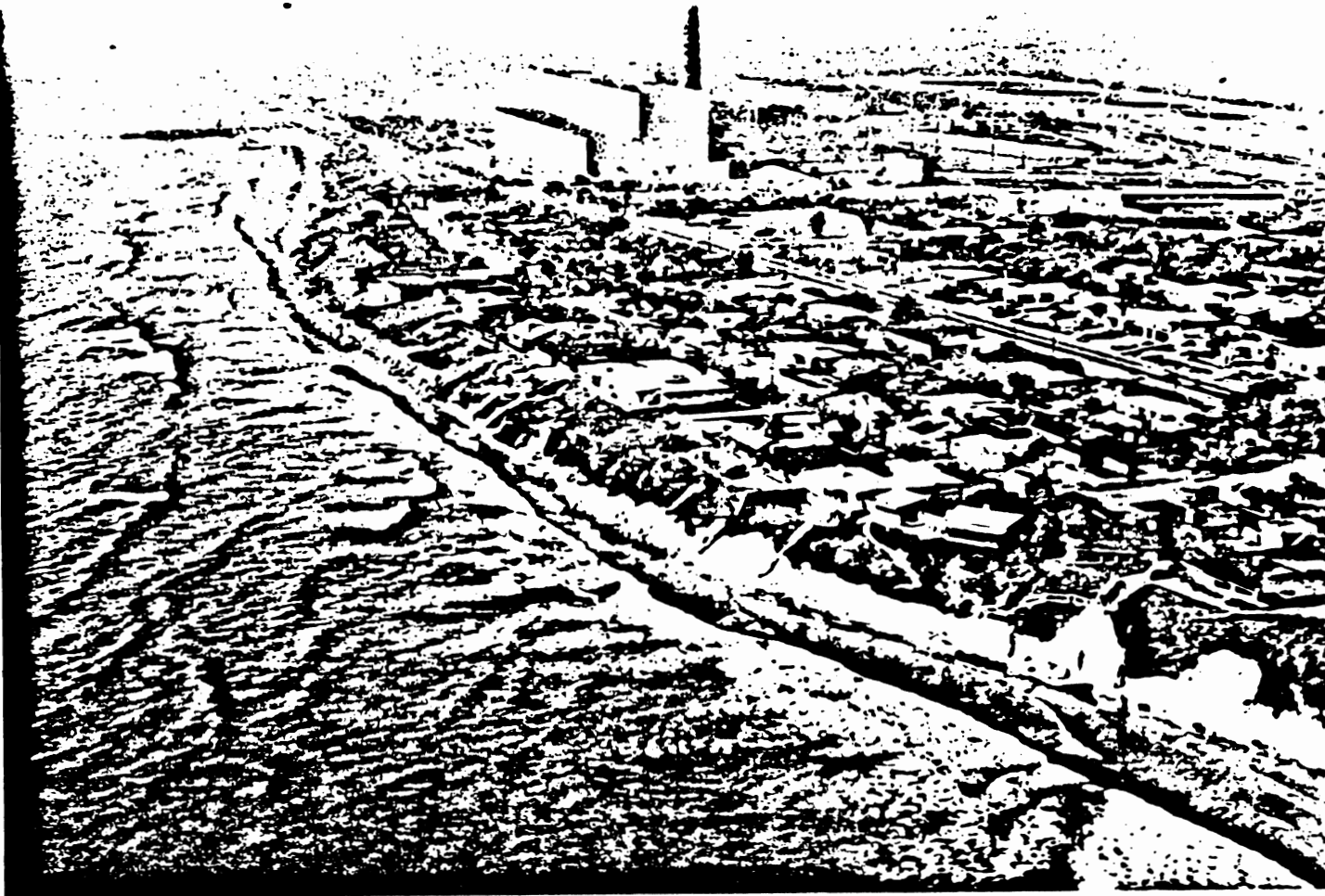


Figure 13. Protruding shoreline adjacent to Carlsbad Submarine Canyon; power station in background at south outlet of Agua Hedionda Lagoon; canyon affects 12,000 ft of shoreline.

possibly sediment carried alongshore in the littoral system, would have been deposited in the channel until it filled out to a present water depth of 120 ft and partially filled beyond that depth. This past 3000 to 5000-yr sequence of infilling by fine sediment appears to be continuing at a slow rate in water depths over 120 ft. The canyon walls are slowly prograding toward each other to form a fine-sediment-covered "V"-shaped profile in the canyon head.

IV. SEDIMENTATION IN SCRIPPS SUBMARINE CANYON

Since 1949 six shallow-water valleys that carry littoral sand into the main gorge of Scripps Canyon have been identified (Fig. 4). Sumner and South Branches are the most active. They intersect the main gorge near its updrift (north) end. Importantly, they also extend closest to shore. In Sumner and South Branches the cycle of canyon-head filling followed by its discharge to deep water occurs every few years or less. It occurs less frequently in North and Shepard Branches, and much less frequently in valleys downdrift of South Branch. In a survey of Scripps Canyon, Shepard (1951) found evidence of slump valleys and slump scars along much of the 4500-ft length of the main gorge southeast of South Branch (Fig. 4). The 100-ft contour along the landward side of the main gorge of Scripps Canyon is very irregular almost to its junction with La Jolla Canyon suggesting partly-filled valleys. Since the main gorge of Scripps Canyon extends southeast away from the coast at Sumner and South Branches, valleys to the south terminate further from shore (Fig. 4). These valleys fill slowly and infrequently discharge their sediment to the main gorge.

The field effort in Scripps Submarine Canyon focused on Sumner, South and North Branches. Shepard Branch was discovered in December 1984 and was subsequently included in the field measurement program. The two southernmost valleys discovered by Shepard (1951) in 1949 and Marshall (1978) in 1975 were not investigated in the field. Their effects are, however, included in the littoral sand loss estimates.

1. Previous Studies. Scripps Submarine Canyon has been studied since 1933 and in more detail than any other canyon in California. Sumner and South Branches have been investigated in comparatively great detail. Scripps is the only canyon in which volume infilling rates and discharge frequency data are available as a result of field measurements.

In 1951, Shepard described three-years of depth changes in Sumner and South Branches and noted his results were at that time ". . . the only thoroughly accurate and detailed information on canyon head changes." His information was based on comparisons of echo sounding records and wire line measurements. He found increases and decreases in the axial depth of the canyon heads, changes in the position of the valley axis where rock outcrops were absent in

the canyon heads, and the development of a new valley. In addition, Shepard (1951) noted: (1) deepenings occur contemporaneously along most of the axis of the same branch, (2) deepenings occur at slightly different times in South and Summer Branches, (3) cycles of cut and fill are variable in length and not related to the storm season, and (4) both cut and fill were progressive during a sequence of surveys.

Chamberlain (1960, 1964) later catalogued over 50 echo-sounding surveys of Scripps Canyon between 1948 and 1960 using Shepard's data, and data he and his colleagues collected diving in the heads of Sumner and South Branches between 1957 and 1960. He stated sand level fluctuations at one location in the head of South Branch were exact time-correlations with deepenings elsewhere in South Branch, but not in other canyon heads. In the 1948-1960 period he documented at least 11 significant deepenings in South Branch and estimated that canyon head discharge in South Branch occurred at an average rate of one per year. To estimate sand losses for the period 1948 through 1956 Chamberlain (1960) extrapolated volume changes based on South Branch deepenings using a volume-change relationship obtained from data he collected between 1957 and 1960. He concluded large shallow-water losses accompany large deepenings and estimated the mean sand loss in South and Summer Branches between 1948 and 1960 was $2.2 \times 10^5 \text{ yd}^3/\text{yr}$ with a range of $0.8 \times 10^5 \text{ yd}^3/\text{yr}$ to $3 \times 10^5 \text{ yd}^3/\text{yr}$. He considered about 10 percent of the volume to be organic material that did not originate in the littoral zone.

Shepard (1951) described a valley that opened south of South Branch between November 1949 and February 1950. He located the valley by comparing records of echo soundings taken at those times. The records showed the valley walls were steep, but not as high in the branches to the north. Slump scars and hummocks in the valley axis were an indication sediment had moved along its axis. Sediment on the floor of the valley had a high mud content and was very cohesive suggesting slower deposition rates than measured in Sumner and South Branches. Interwoven worm tubes penetrated the valley floor to a depth of at least two feet. Shepard (1951) estimated the sediment loss from the valley at $1.5 \times 10^5 \text{ yd}^3$. The valley had not discharged prior to 1960 when Chamberlain (1964) studied the area.

Marshall (1978) described a valley that opened during or just after a severe wave storm in late May 1975. Its head began about 400-ft northeast of the end

of Scripps Pier and somewhat south of the valley Shepard (1951) found. The valley, about 1300-ft long and up to 300-ft wide, formed when an estimated 1.3×10^5 yd³ of sediment slumped into the main gorge of Scripps Canyon. The newly-opened valley was broad and bowl-shaped, and at the landward end was outlined by a 6-ft high scarp at an angle of repose of about 30 degrees. The region had been a gently-sloping sandy shelf before the slump. The depression below the scarp was pock-marked. One to 2-cm diameter depressions were suggestive of pore-water escape conduits. The sediment was highly saturated and Marshall (1978) noted the deposit could be penetrated, with ease, to at least 3 ft by a diver's arm for at least 3-4 weeks following the slump. Above the scarp the sediment was solidly packed. It took 6 mos for the deposit below the scarp to become as well-packed as the deposit above it. The median size of sediments on the scarp face averaged 0.177 mm. The greatest volume displacement occurred near the steep slopes along the main gorge of Scripps Canyon. The depth of previous infilling was at least 150 ft where the valley joined the main gorge. Marshall (1978) attributed the slump to liquefaction and flow aided by gravitationally-induced failure.

2. Sediments. Sediments near and in the shallow heads of Scripps Submarine Canyon and at the North Reentrant of La Jolla Canyon were found to exhibit a well-developed zonation. The first zone in the canyon-head depressions (Fig. 4) was characterized by clean, fine to very fine quartz sand with lesser amounts of feldspar and heavy minerals. The composite size distribution of sediments in the depressions was very similar to the composite size distribution of sediments in the littoral zone of the southern Oceanside Littoral Cell. The littoral zone is herein defined as the region between the base of the shoreface and the normal upper limit of wave action as shown in Figure 4.

At the base of the depression, and especially in the upper limits of the gorge and in the upper parts of larger tributaries, the sediment was rich in mica and very-fine grains of quartz and feldspar. This mica zone was between depths of 55 and 80 feet in North Branch; very well developed along the low-gradient axis of Shepard Branch between depths of about 50 and 70 feet; typically in the depth range 50 to 70 feet in the upper gorges of Sumner and South Branches; and below a depth of 70 feet in the North Reentrant of La Jolla Canyon. It was not well developed above or below the rim at other locations in La Jolla Canyon. Mica often appeared to be moving in a net

downslope direction in response to wave-generated bottom oscillations. Platy mica grains were suspended during the onshore passage of a swell and moved downslope and settled on the seaward-flow leg of the oscillation.

The main component of the third sediment zone observed in Scripps Canyon was organic detritus torn loose from the bottom elsewhere in the littoral cell and deposited in layers in the gorge along with mica and inorganic sands and silts. This zone was also often rich in other debris with a low specific gravity. Cans, light bottles, lumber, rubber balls, golf balls, rubber dolls and swim fins were frequently seen on the surface and incorporated in the deposit. Shepard (1949), Limbaugh and Shepard (1957), Chamberlain (1960), and Dill (1964) describe the accumulation of plant and other material in the gorges of Scripps Canyon as a mat of fine sand and silt interbedded and mixed with pieces of sea grass, surf grass and kelp. The mat has the appearance and physical characteristics of a "dirty haystack" as noted by Dill (1964). When initially deposited the fresh grass and kelp was springy and interwoven giving the mat a high internal strength. When the organic portion decomposed, as illustrated in Figure 14, it formed gas which actively bubbled to the surface, often with a noticeable H₂S odor. With time the plant material shrunk, settled and pulled away from the canyon walls. Slow gravity-induced creep causes the mat to move downslope (Dill, 1964). As long as the plant material acted as a binder to the sediment because of the intertwining of the long kelp and shorter grass blades the mat remained quite cohesive.

Sediment/organic mats also formed in tributaries at the canyon heads. No mat was observed on the shelf surface or near and in the depressions, probably because with its low specific gravity kelp and sea grass was quickly carried downslope to the more quiescent gorge. Kelp was often observed moving continuously, but unsteadily, in a downslope path into the gorge. Observations from submersibles down to depths of 4000 ft have shown this material is carried downcanyon to the deep sea fan at the mouth of the La Jolla Canyon System.

The lower two sediment zones are not fixed in position. A vertical core taken through either the mica zone or the organic-material zone would likely penetrate lenses of sediments that are dominant in the zone above it. Dill (1964) notes internal bedding is typical within the lower portion of the mica zone and the upper part of the organic zone. This interfingering of different



Figure 14. Gas emission from organic debris mixed with quartz sand and mica at the apex of the Sumner Branch gorge in June 1986; depth is 57 ft.

material precludes consideration of these zones as dam-like in form. The position of a given zone on the surface varies depending on the (1) strength of the transporting mechanism that carries the three types of sediment toward and into the canyons, and (2) downslope movement of the material after it is deposited in the canyons.

Littoral sediment is defined that which can exist in dynamic equilibrium in the littoral zone and affect the position of the shoreline (Everts, 1985). Thus, when a volume of littoral sediment is added to a littoral cell the result is a net advance of the shoreline. A net loss of littoral sediment will correspondingly produce a net shoreline retreat when averaged for the length of the cell. In the Oceanside Cell littoral sediment is sand-sized and larger. Examples of sediments that will not affect the position of the shoreline, and are not littoral sediments, are inorganic particles too fine to remain in dynamic equilibrium in the littoral zone, mica, and low-specific-gravity organic material.

Long-term effects of sediment losses on shoreline behavior require that measured and estimated volumes of sediment transported to the canyon-head depressions, V_d , and gorges, V_g , be converted to the equivalent volume of littoral sediments, V_{ld} and V_{lg} , respectively transported into the depressions and gorges. V_d and V_g are obtained from the survey program. The task, then, is to separate the volume of littoral sediment, V_{ld} and V_{lg} , from the total volume of sediment deposited in the canyon heads.

Six sediment concentration values were obtained by sampling in the field: (1) P_{id} and P_{ig} , the portion of the total unknown inorganic sand volume, V_{id} and V_{ig} , excluding mica, that is trapped, respectively, in the depression and gorge and that has a size distribution that lies within the size distribution of littoral sediment, (2) P_{md} and P_{mg} , the portion of mica in the known total sediment volume, V_d or V_g , respectively, in the depression and gorge, and (3) P_{od} and P_{og} , the portion of organic material in the known total sediment volume in the depression and gorge. The volume of littoral sand deposited in the depression, V_{ld} , is

$$V_{ld} = P_{id} V_{id} \quad (1)$$

when

$$V_{id} = [1 - (P_{md} + P_{od})] V_d \quad (2)$$

or

$$V_{ld} = P_{id} (1 - P_{md} - P_{od}) V_d \quad (3)$$

and, similarly, the volume of littoral sand deposited in the gorge, V_{lg} , is

$$V_{lg} = P_{ig} (1 - P_{mg} - P_{og}) V_g \quad (4)$$

a. Littoral Zone Sediments. Littoral zone sediments are relatively homogenous. Sediment size distributions from samples collected on different littoral zone transects at the south end of the Oceanside Littoral Cell were found to be similar. Three sets of sediment samples were used to establish a composite size distribution, and to determine shore-normal and shore-parallel changes, if any, in the size distribution of littoral sediments. Sample Sets 1 and 2 were, respectively, taken across the littoral zone 2 miles north of South Branch and at South Branch (taken in October 1983, USACE-LAD, 1985). Composite size distributions as shown in Figure 15 indicate no apparent major alongshore differences. The size distribution for Sample Set 3 is a composite of 12 samples taken at the MSL contour along 3 miles of beach on 2 March 1985 for this study. The size distributions of all those samples were also similar and the composite size distribution for the MSL-elevation samples of Sample Set 3 was similar to the size distributions of the MSL-elevation samples included in the composites for Sample Sets 1 and 2. The composite distribution (solid line) in Figure 16 represents the best estimate for sediments in the littoral zone at the south end of the Oceanside Littoral Cell.

b. Depression Sediments. Sediments collected in the depression of Sumner Branch were found to be similar in size and composition to sediments collected in the depression of South Branch. The median sediment size, based on 12 randomly-selected samples, averaged about 0.16 mm and varied by less than 0.01 mm. Chamberlain (1960, p. 59) found the median size of samples he collected from those depressions to be 0.15 mm. The composite size distribution of the 12 depression sediment samples (Fig. 16) is also very similar to the composite distribution of littoral zone sediments. This

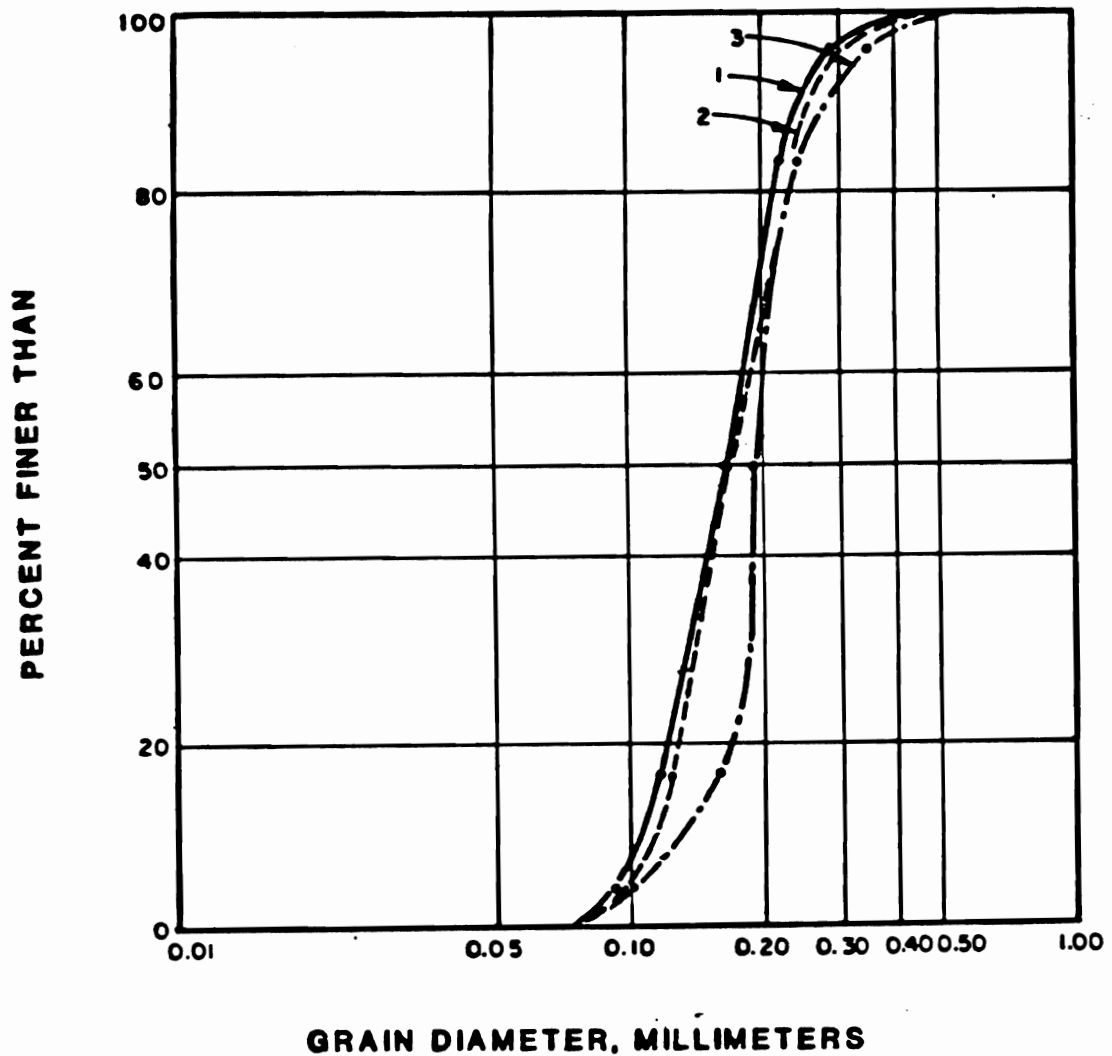


Figure 15. Sediment size distributions from the vicinity of Scripps Submarine Canyon; Distribution 1 is a composite of four distributions taken between -20 ft and +10 ft across the littoral zone 2-mi north of South Branch; Distribution 2 is a similar composite distribution across the littoral zone landward of South Branch; and Distribution 3 is a composite of 12 distributions taken at equally-spaced sample sites near MSL on the beach from 2-mi north of South Branch to 0.4-mi south of South Branch.

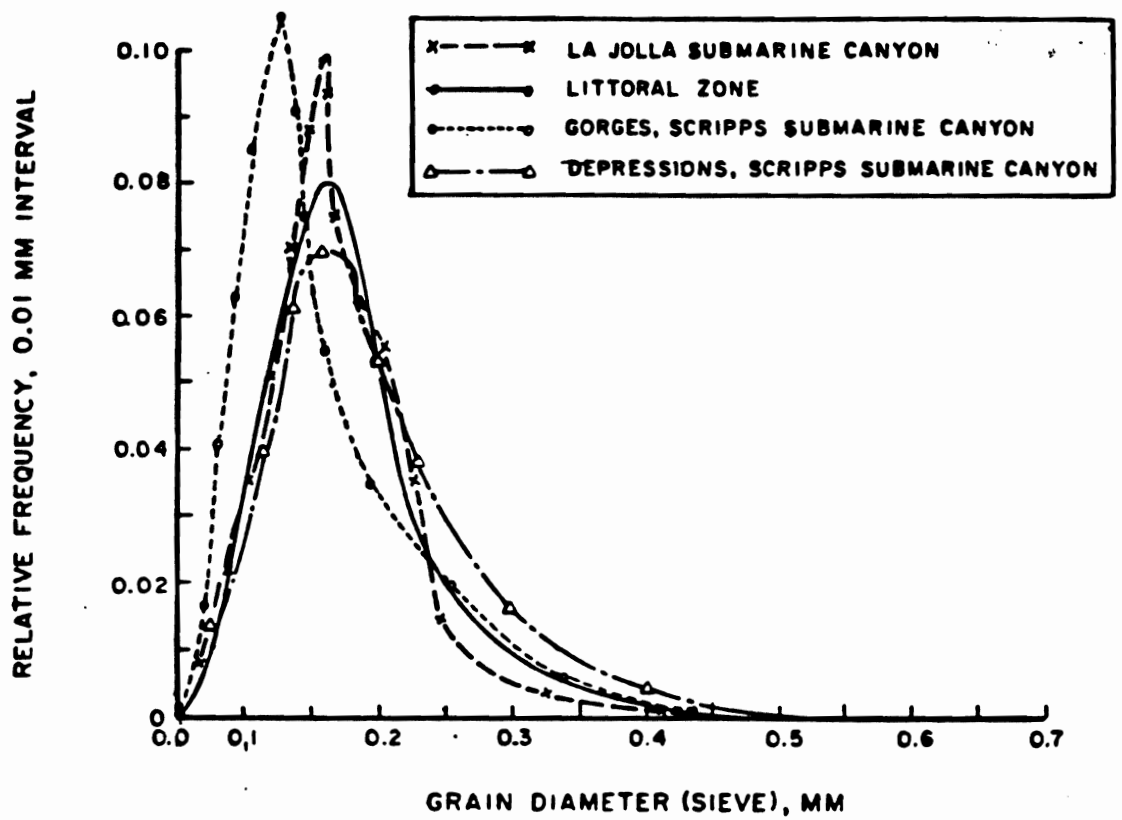


Figure 16. Relative frequency, inorganic sediments at the south end of Oceanside Littoral Cell, and in the depressions and gorges of the heads of Scripps and La Jolla Submarine Canyons.

suggests the canyon heads are sinks for all sizes of littoral zone sediment and the littoral zone-canyon head system is not a significant sorting filter whereby finer sizes are carried into the canyon depressions and coarser material stays in the littoral zone. No significant size difference was found related to depth in the depression. Sediment collected in traps fixed to the rim of the Sumner Branch gorge also had a composite size distribution similar to that found in the depression and in the littoral zone. The size distribution varied more in a single trap than the average size distribution varied between traps.

Sediment deposited in the depressions was almost all littoral sediment. Thus, $P_{id} = 1.0$, and $P_{md} = P_{od} = 0$. Organic material was not preferentially trapped in the depressions. The volume of mica trapped in the lower end of the depression was small and within the range of uncertainty in the total volume of material, V_d , deposited in the depression. In Scripps Canyon, therefore, $V_{ld} = V_d$ (from Equation 3) appears to be a reasonable approximation.

c. Gorge Sediments. Inorganic sediment in the shallow portions of the gorges of Sumner and South Branches was found to be somewhat finer than the sediment in the depressions or littoral zone. Size differences between sets of inorganic sediment samples collected in the two gorges were very small with a composite median diameter variation of less than 0.02 mm. South Branch had the finer material. In the depth zone sampled, size did not vary consistently with depth. Figure 16 shows the composite size distribution of 11 randomly-selected samples of sediment collected from a depth of 55 to 90 ft in the gorges of the two branches. The median grain size (0.125mm) is about 0.03mm smaller than it is in the littoral zone landward of the depressions or in the depressions. Shepard and Dill (1966) noted similar fine sizes below 55 feet in these gorges. The higher concentration of mica in the inorganic sand may account for the finer sizes in the gorge.

The portion of littoral-zone-sized inorganic sediment trapped in the gorge, P_{ig} , is 0.85 (when $P_{mg} = 0.10$) as shown in Figure 16. Figure 17 shows the estimated sand and mica volume (the rest is organic material) in the gorge of Sumner Branch about 6 months before it was discharged in March 1987. Approximately 70 percent of the material, by volume, was organic. This portion, $P_{og} = 0.7$, for the upper gorge is probably a reasonable average value to use in the other steep-walled gorges of Scripps Canyon as well. It is

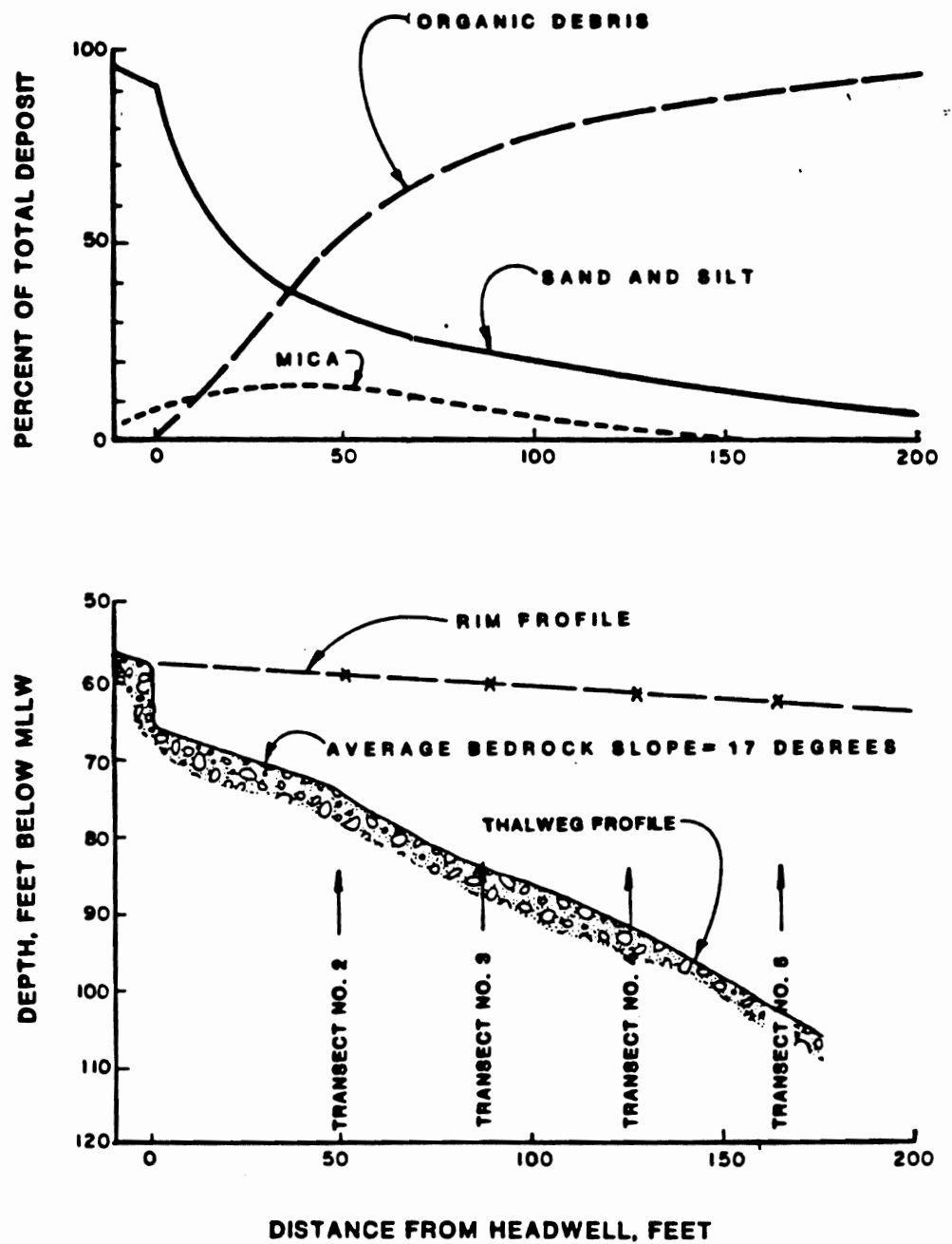


Figure 17. Bathymetric profile along bedrock axis of Sumner Branch and composition of sediment that accumulates in the gorge of Sumner Branch; organic debris is mostly kelp and surf grass.

based on visual observations of the surface sediment and frequent hand and arm penetrations of the gorge deposit when surveys were made. From Equation 4, $V_{1g} = 0.17 V_g$, therefore appears to be a reasonable estimate for the gorges of Scripps Canyon. The characteristics of sediments in the depressions and gorges of Scripps Canyon are given in Table 4.

TABLE 4. Sediment Characteristics, Scripps and La Jolla Submarine Canyons

Canyon Location	Sediment Characteristics ¹					
	P_{1d}	P_{md}	P_{od}	P_{ig}	P_{mg}	P_{og}
Scripps Canyon						
(1) North Branch	1.0	0	0	0.85	0.1	0.7
(2) Shepard Branch	1.0	0	0	0.85	0.1	0.7
(3) Sumner Branch	1.0	0	0	0.85	0.1	0.7
(4) South Branch	1.0	0	0	0.85	0.05	0.6
(5) New Valley	1.0	0	0	0.85	0.1	0.7
La Jolla Canyon						
(1) North Reentrant	1.0	0	0	1.0	0.05	0.05
(2) Remainder of Canyon Rim	1.0	0	0	1.0	0.05	0.05

¹see notation section for definitions

3. Measurements in Scripps Submarine Canyon. This part of the study had one purpose. It was to determine the rate at which the active canyons filled with sand from the littoral zone, and the rate at which that trapped littoral sand was discharged from the shallow canyon heads to deep water during the time field measurements were made. Due to budgetary constraints time in the field decreased over the life of the project. From December 1984 to November 1985 an average of approximately 32 diver-team measurement trips into the canyon heads were made each month. This dropped by half in the December 1985 to December 1986 period. From January 1987 to June 1987 a total of 20 diver-team measurement forays were made in the canyons. Measurements in the four most active valleys of Scripps Canyon are described below.

a. North Branch. This is the largest branch of Scripps Canyon. Located farthest from shore, it has a deep gorge orientation in a north-south

direction (Fig. 5). Between its headwall and its junction with Sumner and South Branches it is about 900-ft long. The average width of North Branch is approximately 250 feet as shown in Figure 18. Small tributaries and sand chutes enter its rock-walled gorge from both sides, but are most pronounced on the east side. An especially large tributary breaks the east rim about half-way between its junction with North and Shepard Branches and its apex (Fig. 18). This tributary is 40 feet wide and extends about 80 feet towards shore. On the east side of the gorge the upper part of the rock wall (sidewall) is rounded from the apex south to just beyond the large tributary. The rim, located near the crest of the sidewall, is a vertical scarp normally 1 to 3-ft high. South of the large tributary the gorge wall is steep with overhanging ledges. Dill (1964) reports the lower wall in the gorge is undercut and near its junction with Shepard Branch the wall may be as high as 250 ft. Shepard Branch enters North Branch as a hanging valley. Above its junction with Sumner and South Branches the average thalweg slope of North Branch is approximately 7 degrees (Table 2).

The rim was partially buried at the apex during this field investigation. Discontinuous outcrops of flat-lying, compacted, lithified sedimentary rock were observed between water depths of 60 to 66 ft on all dives into the head of North Branch. Outcropping rock constituted less than 30 percent of the south-facing perimeter of the apex at that depth, but the outcrops were spread relatively uniformly along that perimeter. The exposed rocks in the apex were heavily covered with living organisms indicating there had been no recent burial or mass movements over them.

From the rock rim of the headwall to the MLLW shoreline the distance is 1240 feet on a shore-normal bearing of 080 degrees, and 1860 feet on an upcoast bearing of 035 degrees (Figure 18). The depression leading down to the rock-walled gorge is bowl-shaped and slightly elongate to the north with an offset slightly to the east of an extension of the canyon axis. Figure 18 shows three profiles across the depression along transects away from a common point in the center of the gorge at a depth of 73 feet. The slope in the depression is steepest in a nearly shore-normal direction. Above a depth of 54 feet, which appears to have been the upper boundary of the depression on 12 June 1987, the slope is 3.5 degrees. The slope within the depression was about four times as great at 14 degrees. In the gorge below the rim the slope was about 11 degrees. Sediment in the upper gorge was a mixture of very fine

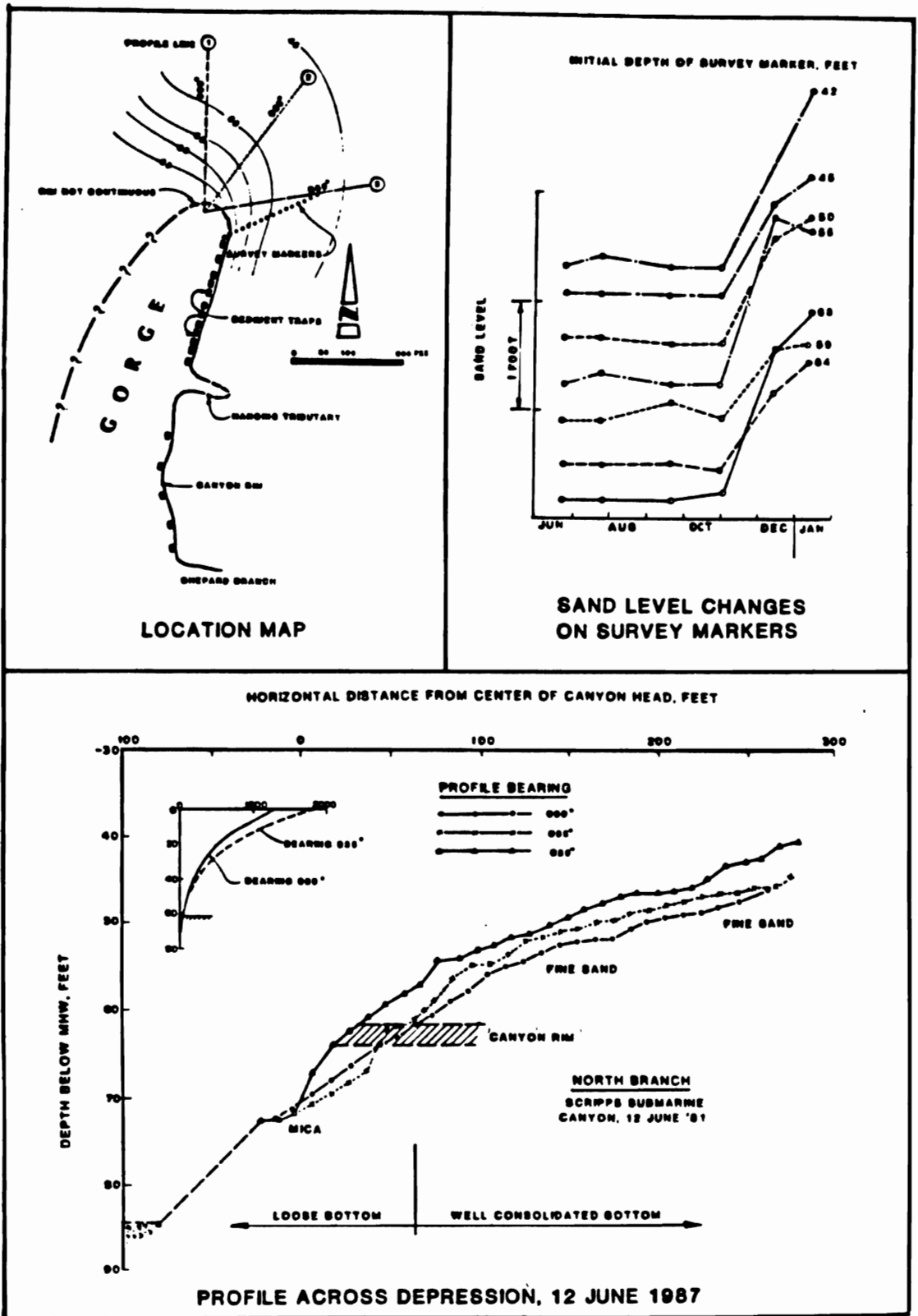


Figure 18. Location map, bathymetric profiles and sand level changes in the head of North Branch.

quartz sand, mica, and a high concentration of organic matter. Shallow, U-shaped slumps were commonly observed in the sandy sediments just below the canyon rim. The length of the outer perimeter of the depression was about 350 feet on 12 June 1987. From east to west directly across the partially sand-covered apex the rim length was about 100 feet (Fig. 18).

Nineteen survey markers placed along a line in the depression were monitored in 1985 and early 1986 (Fig. 18). There was no movement of sand into the depression during the summer months. In the autumn and early winter of 1985-86 the rise in sediment level averaged 1.6 ft, equal to about 1300 yd³ of littoral sand. The sand level increase was distributed evenly throughout the depression. In May 1986 sand level changes on the only rod that had not been knocked down by moving organic debris in the spring of 1986 indicated perhaps another 1 ft of infill (800 yd³) had entered in the first 4 months of 1986.

On three occasions a significant tilt was found on the survey markers. The first was in the summer of 1985 when the markers apparently were tipped by moving mats of kelp and surf grass. The upper gorge was filled with a mat of relatively fresh organic debris to at least 2-ft deep on the day the rod tilt was discovered and some kelp was found tangled on the rods. The large tributary on the east rim was also filled with kelp and grass, and organic debris was found in all the sediment traps. In December 1985 all rods were lying nearly flat and pointed slightly shoreward of the gorge axis at 150 degrees. Some rods were bent, which could not have happened as a result of slumping or downslope sand transport. Moving masses of seagrass and kelp are again a likely explanation. The third time the rods were also bent was in the spring of 1986, also probably as a result of moving organic debris.

A significant quantity of sediment is transported over the rim into North Branch as evidenced by the rounded, smooth, east sidewall of the gorge near the depression. Organic growth on the eastern sidewall is sparse or absent, and possibly prevented from developing by the abrasive action of sand as it passes over the rim. The rock sidewall has a slope averaging 45 to 55 degrees which is too steep to hold sand-sized sediment. Most of the material that reaches the eastern edge of the gorge is consequently carried over it by wave-induced bottom flow. At all times ripples in the sand lens at depths of 55 to 70 ft above the east rim were approximately parallel to shore. Ripples were

usually oriented parallel to shore in the depression as well. The net downslope movement of sand set in motion by waves is important in this branch.

A total of 19 sediment traps were fastened to the east rim between Shepard Branch and the depression in 1985. Most were at depths of 70 to 78 ft. Infilling rates were greatest along the eastern sidewall near the depression. The portion of littoral sand collected in the traps was greatest there as well. More grass and mica accumulated in traps further to the south. It appears the rate of cross-rim infilling decreased approximately linearly to the south with about three times the cross-rim infilling rate near the depression as near Shepard Branch. Sediment piracy by Shepard Branch is the probable cause. At the north end of the east rim the portion of organic material and mica that accumulated was 0.1 ($P_{lg} = 0.9$); at the south end of the rim these components of the cross-rim flux were such that $P_{lg} = 0.6$. All sand was of littoral size.

In the three month summer period from late June 1985 to late September 1985 a total of less than 3 yd³ of littoral sand crossed the east rim into the gorge. In the three autumn months, between 40 and 100 yd³ of littoral sand went into the gorge. An approximate, factor-of-three extrapolation of these rates for the first and second quarters of 1986, using wave data from the directional gage at Del Mar, suggests 80 to 200 yd³ probably entered in the first three months of 1986 and 200 to 500 yd³ of littoral sand probably entered in the spring quarter. The estimated totals of littoral sand that entered the gorge over the rim are given in Table 5. The estimated annual cross-rim littoral sand loss to the gorge of North Branch was 150 to 370 yd³/yr. Less than 200 yd³ of littoral sand entered the gorge between June 1985 and June 1986 through the apex.

A combination of the infilling rate of the depression, the cross-rim infill rate and the gorge infill rate at the apex indicates perhaps 2000 to 3000 yd³ of littoral sand were carried into the head of North Branch between June 1985 and June 1986. Dill (1964) describes a slow infill rate in the gorge in the early 1960's as well, basing his conclusions on the lack of meaningful movement or covering of distinctive man-made objects in the shallow part of the gorge just below the rim.

TABLE 5. Infilling in Gorge of North Branch by Cross-Rim Littoral Sand Transport

<u>Calendar Period</u>	<u>Infilling Volume, yd³</u>	<u>Source</u>
1 January 1985 to 21 June 1985	60-150	weighted estimate
21 June 1985 to 14 September 1985	3	measurement
14 September 1985 to 13 December 1985	40-100	measurement
13 December 1985 to 1 January 1986	10-25	weighted estimate
1 January 1986 to 1 January 1987	160-400	weighted estimate
1 January 1987 to <u>12 June 1987</u>	<u>100-250</u>	weighted estimate
Total (30 months)	370-925	

b. Shepard Branch. This newly-discovered branch was first identified in December 1984. A large storm had caused its sediment fill to flush into North Branch. This may have been the first exposure of its rock wall in the last 40 years or more. Shepard Branch was not observed empty of fill during Shepard's (1951) 1948 to 1951 acoustic surveys of the canyon, or dives made throughout the 1950's and early 1960's in the shallow heads of Scripps Canyon and the adjacent areas (Dill, 1964).

Shepard Branch is a shallow trough oriented downslope toward North Branch on a bearing of 240 degrees (Fig. 6). After the sand was discharged in Shepard Branch, probably on 13 December 1984 when Sumner and South Branches also lost their sand accumulations, low angle rocky sidewalls were exposed from its junction with North Branch upslope to a depth of 50 ft. The depth of the shallow trough is less than 8 feet below the gently-sloping rim at Transect Line No. 1, 120 ft from the apex (Fig. 19). The sidewalls steepen toward the junction with North Branch. When the main channel of the branch is empty of sediment, the depression of Shepard Branch appears to be shared with the Sumner Branch depression. However, the Sumner Branch gorge is closer to shore and intercepts most of the littoral sediment from the depression. Once

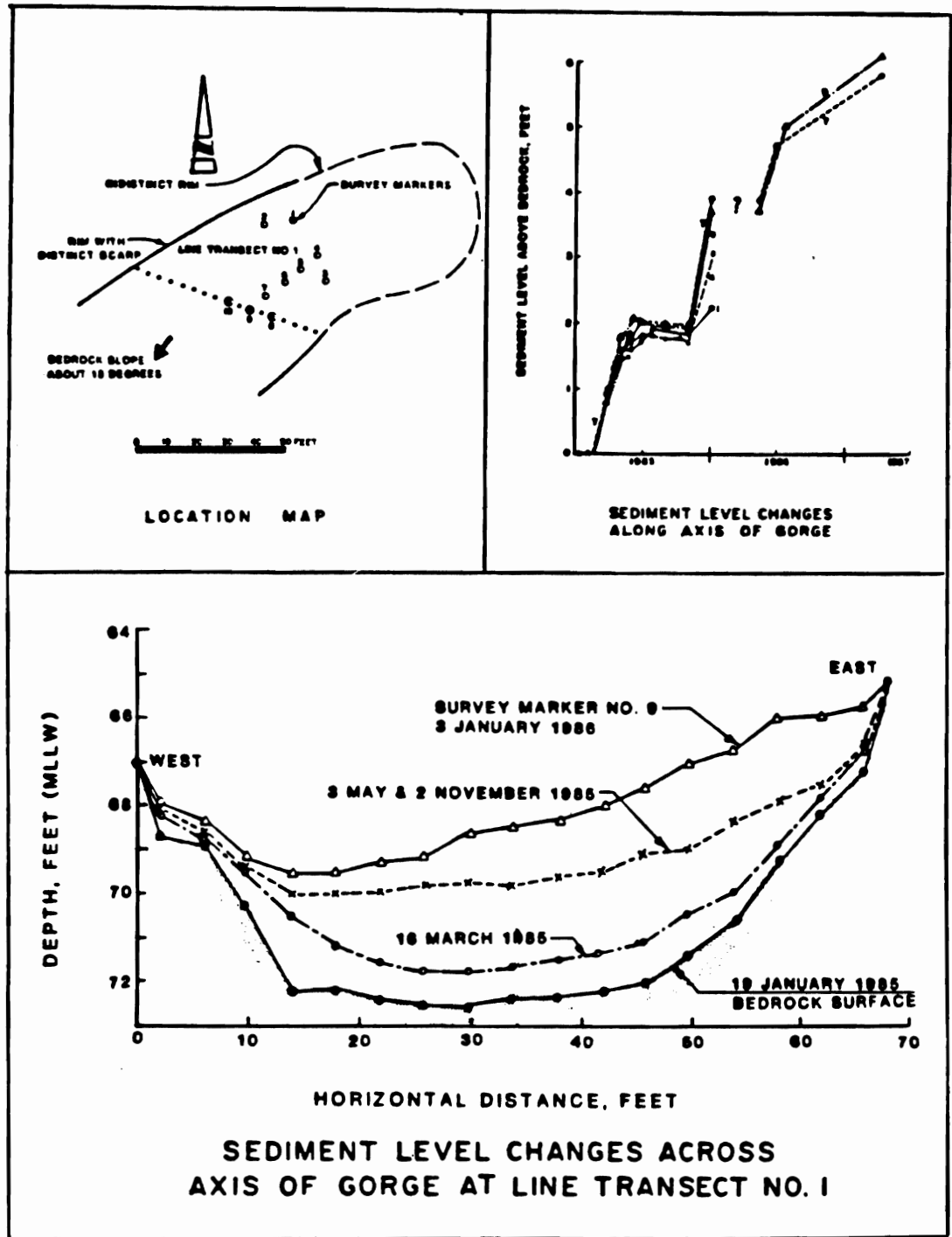


Figure 19. Location map and sand level changes parallel to and across the canyon axis in the head of Shepard Branch.

filled, the low gradient of the gorge of Shepard Branch appears to preclude frequent downslope losses of its sediment. Shepard Branch has few sand chutes or other breaks indicating it is much less active.

The reason Shepard Branch was not previously reported appears to be related to its bedrock geometry and orientation. Its trough-like and shallow gorge is distinctly different from the steep, deep gorges of North, Sumner and South Branches. Sidewalls of Shepard Branch have small (<1 ft) ledges near the top. The bedrock slope along its axis, about 13 degrees at a depth of 56 to 72 ft, is lower than other branches. Shepard Branch is about 350-ft long between its low headwall to where it enters North Branch as a hanging valley at a depth of about 135 ft. The upper end of the gorge was filled with sediment throughout the study, but probably continues landward as a gentle trough. Small outcrops of bedrock were observed in early 1985 at least 120 ft east of Line Transect No. 1 (Fig. 19) within the depression.

Observations by divers since 1950 have shown that sediment which gradually builds up in the canyon heads is discharged downcanyon when it becomes unstable. Stability is partially dependent on the surface slope of the sediment deposit, its internal strength, intergranular pore pressure, and the slope of the bedrock base on which it rests. In Shepard Branch the bedrock slope is relatively low. Before sediment in its gorge is discharged the deposit must prograde further into the gorge than it does in the neighboring gorge of Sumner Branch. Sumner Branch discharges its sediment load at a much greater frequency than Shepard Branch and thus captures much of the sand in the shared depression that would have caused the gorge deposit to prograde in Shepard Branch.

Organic material began accumulating in the gorge immediately following the December 1984 loss of material. At Line Transect No. 1 (Fig. 19), seagrass and kelp debris was the predominant constituent of the sediment deposit. This organic material, along with high concentrations of mica, covered the central 50 ft of the 70-ft wide gorge. Man-made debris, including shoes, wooden crates and beer cans, was also common. The surface of the gorge deposit sometimes looked like a landfill. Initially the organic material formed a thick, tangled, soft, spongy, dark-colored, hummocky mat. With time, the mat decomposed and settled producing a large volume of gas. Mica was deposited in a greater concentration and covered a larger surface area in the central 50

percent of the gorge (between depths of 55 to 75 feet) in this branch than anywhere else. Littoral sand was usually visible only on the upper edges of the channel suggesting it was transported over the low profile rim by wave surge. Away from the center of the gorge sediment constituents were often layered. It was not uncommon to find a 0.5-ft thick zone of decomposed organic material on top of a 0.5-ft thick finger of concentrated mica. Littoral sand was also found as laminae in the gorge deposit. Layers rich in a single constituent also contained the other materials.

As elsewhere in the Scripps-La Jolla Canyon system, sedimentation in Shepard Branch was seasonal. Figure 19 shows sediment level changes that occurred on Line Transect No. 1 in 1985 when the field effort to quantify sand infilling was most intense. The volume of littoral sand deposited in the gorge was comparatively low. Most sand deposited in the combined Shepard Branch - Sumner Branch depression east and northeast of the gorge was channelled into Sumner Branch when sediment in its gorge discharged to deep water in March 1987.

In the period between January and April 1985 about 2 ft of material uniformly accumulated in the central portion of the gorge as shown in Figure 19. This organic-rich sediment decomposed and settled in the summer of 1985 without any influx of new material. In late 1985 an additional 1 to 2 ft of sediment entered and was trapped in the gorge, primarily on the east and higher side (lower plot, Fig. 19). In early 1986 an estimated additional 1.5 to 2 ft of sediment, mostly organics, was deposited. Shoaling was more pronounced deeper in the gorge after the shallow part of the gorge filled to near its rounded rim.

Survey markers placed in the thalweg of the gorge were not displaced downslope, but they were frequently tilted as previously observed in other branches (Dill, 1964). Large volumes of organic debris moved through the shallow part of the gorge in 1986 and early 1987. In 1987 sediment prograded into progressively deeper, downslope areas of the gorge. At Line Transect No. 1 the deposit reached a maximum depth of about 8 ft. As sediment began to cover the rim, the portion of sand on the surface increased. By 1987 the upper part of Shepard Branch was almost filled in and was discernable only as a gentle swale.

Organic material preferentially accumulated on the steeper Sumner Branch side of the gorge in Shepard Branch suggesting transport was through the shared depression. Sediment accumulated in the shallow, gently-sloping gorge by filling to near the canyon rim, then by prograding west at a decreasing rate toward North Branch. The cross-sectional area of the gorge increases to the west since the slope of its north and south rims is between 2 and 3 degrees and the slope of the floor is about 13 degrees. Once the gorge becomes filled with sediment, it appears as a gentle trough without a visible rim. Sediment infilling is seasonal in Shepard Branch as it is elsewhere. The total volume of littoral sand that reached the gorge of Shepard Branch in 25 months was approximately 330 yd³ or 160 yd³/yr (Table 6).

TABLE 6. Sediment Infilling in the Gorge of Shepard Branch

<u>Period</u>	<u>Volume of Sediment Deposited, yd³</u>	<u>Volume of Littoral Sand Deposited, yd³</u>
19 January 1985- 22 February 1985	230	45
22 February 1985- 3 May 1985	280	60
3 May 1985- 2 November 1985	0	0
2 November 1985- 3 January 1986	250	50
3 January 1986- 11 April 1986	380 (est.)	80 (est.)
11 April 1986- 20 Jan 1986	220	45
20 June 1986 6 February 1987	230	45
<hr/> TOTAL	<hr/> 1600	<hr/> 330

c. Sumner Branch. This is the second-largest, deep-gorge branch and the most active littoral sand trap in Scripps Submarine Canyon. As shown in Figure 20, after its sand deposit slumped into the gorge in March 1987 the upper edge of

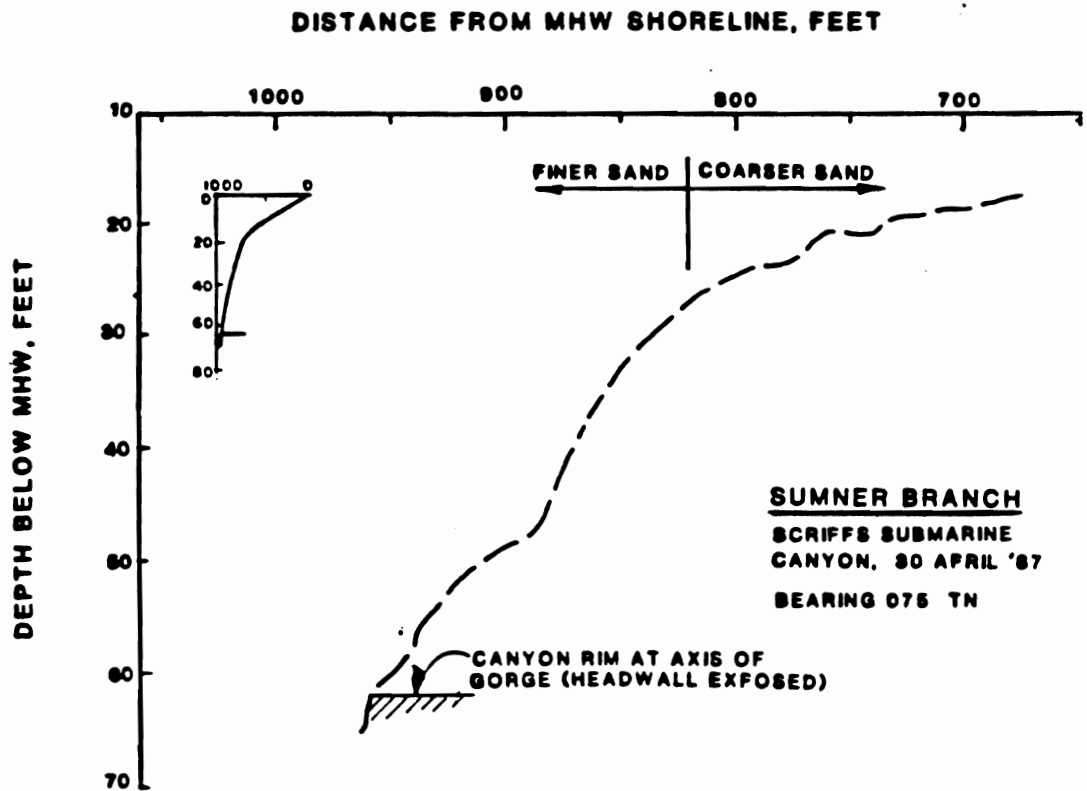


Figure 20. Profile across the depression of Sumner Branch after a large slump occurred in March 1987.

the sediment depression of this branch was about 820 feet from the MHW shoreline (600 feet from the MLLW shoreline and 920 feet from the seacliff). Sumner Branch joins North Branch as a hanging valley and has a length of about 700 feet. The axial trend of the upper reach of the rock gorge is nearly parallel to shore (Fig. 5), reflecting headcutting toward the source of sediment during the last 4,000 years of near stability in sea level.

Sumner Branch widens non-uniformly from about 8 feet at the apex of the North Tributary (Fig. 5), where the height of the canyon headwall is 8 feet, to about 130 feet where it is joined by South Branch. The gorge has steep rock walls (Fig. 21) that are typically undercut at the base. The estimated axial slope of Sumner Branch in the gorge is 17 degrees. All four tributaries enter Sumner Branch as hanging channels (Figs. 5 and 22). Two are at the apex, the North and South Tributaries, and two enter along the southeast rim. Intermediate Tributary is the largest. It enters from the east and trends upslope toward South Branch. Hanging valley is smaller and discharges into the main gorge near Transect Line No. 3.

The lower parts of the rock walls and tributaries to Sumner Branch are smooth and polished as the result of relatively vigorous submarine erosion by sand movement (Dill, 1964). All are narrow channels, V-shaped in planform and mostly U-shaped in section. Some of the tributary walls are undercut. Large slab-like blocks to 6-ft long that fell from the sidewalls were observed in the axis of the main gorge after sediment was removed on 13 December 1984. Bottom irregularities in the main gorge have a relief of up to 5 ft.

(1) Gorge. Variations in the amount of sediment above the bedrock bottom of the gorge were measured below four transect lines spaced about 40-ft apart (Fig. 22). A series of sediment traps placed above and fastened to the sidewalls of the gorge between the transect lines were used to determine the amount of sediment that spilled over the upper rim of the gorge. As shown in Figure 17, the sediment deposited in the gorge was predominantly organic debris except near the headwall.

Most sediment was transported to the gorge through the apex. Only a small quantity entered over the rim. Sediment levels increased at about the same rate throughout the landward 150 ft of the gorge (Fig. 23). Nearly uniform infilling occurred because the organic material that constituted the bulk of



Figure 21. East rim of Sumner Branch at a depth of 64 ft (November 1986); Line Transect No. 4 in background; note sparse covering of littoral sand above rim.

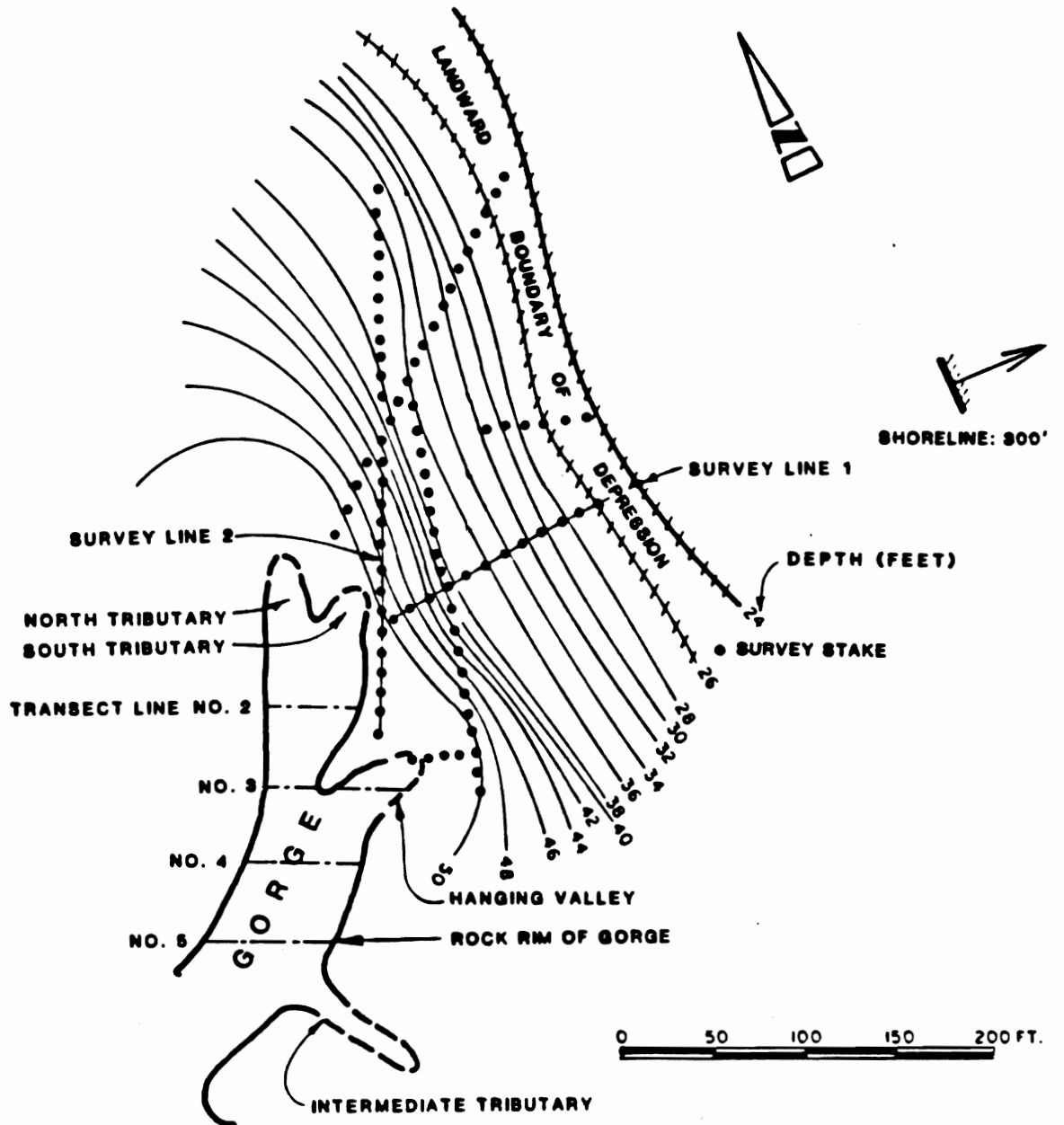


Figure 22. Location map, gorge and depression, Sumner Branch as it was in October 1986.

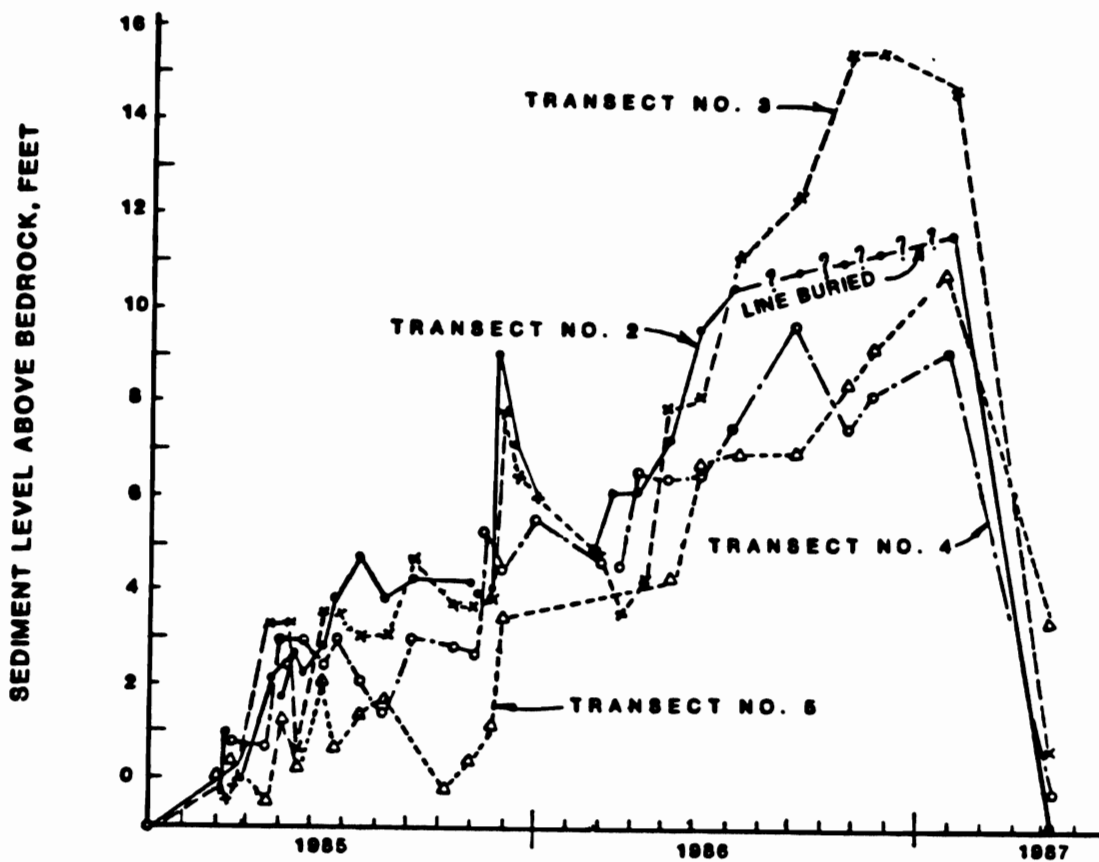


Figure 23. Change in sediment level at Transect Lines 2, 3, 4 and 5 (Fig. 22) showing an irregular increase until the sediment deposit in gorge slumped into deeper water in March 1987; note frequent lack of correspondence in sand level change at adjacent transect lines caused by downslope movements of tangled mats of organic debris.

the deposit had a specific gravity near that of seawater and moved freely downslope. An inspection of Figure 23 shows large deepenings and shoalings at each transect line. These vertical bottom fluctuations, not always in phase between transect lines, were caused by the relatively rapid downslope movement of interwoven fresh surfgrass and kelp. A measurement made at one location could not always be related to sediment level changes that occurred elsewhere.

As the gorge filled, its floor remained approximately horizontal as shown in Figure 24. Typically, there was a slight slope away from the east (landside) sidewall. Sediment that accumulated near the sidewall was composed mostly of organic material that had passed over the rim. Bottom fluctuations of over 12 ft between surveys were caused by sea grass and kelp that moved into the gorge at all times of the year, especially after large storms. Most of the plant debris passed through the upper part of the gorge in a period of weeks to months. However, some was trapped by inorganic sediment and formed an organic sand mat. Organics that remained were compressed between successive sand lenses and subsequently decomposed as shown in Figure 14. Methane and carbon dioxide gas byproducts bubbled to the surface, especially when bottom pressure was reduced at low tide. The bubbles provided an excellent means to delineate the canyon walls and the distribution of organic material in the gorge. Degassing was observed to a depth of about 150 ft.

Away from the apex, a relatively small volume of littoral sand was transported directly over the canyon rim into the gorge. Based on sediment trap measurements, the cross-rim transport rate for all of Sumner Branch averaged 1-2 yd³/month (Fig. 25). Times of enhanced cross-rim transport correlated well with high sediment transport rates into the gorge through the apex, and with times of high infilling in the depression. Some of the cross-rim transport was through small chutes, usually on the order of a few feet or less in width. Fed from minor depressions above the level of the landward rim, tributary transport and sand movement in these sand chutes conveyed most of the sand that reached the floor of the gorge away from the apex (Fig. 26). Over 75 percent of the sediment captured in sediment traps was littoral sand. The low cross-rim sand transport rate is thus substantiated by the fact that the gorge deposit is mostly organics carried in through the apex.

Well-rounded, grey, easily-abraded, elongate pebbles and cobbles to 3-in maximum length were often found in the sediment traps located on the sloping

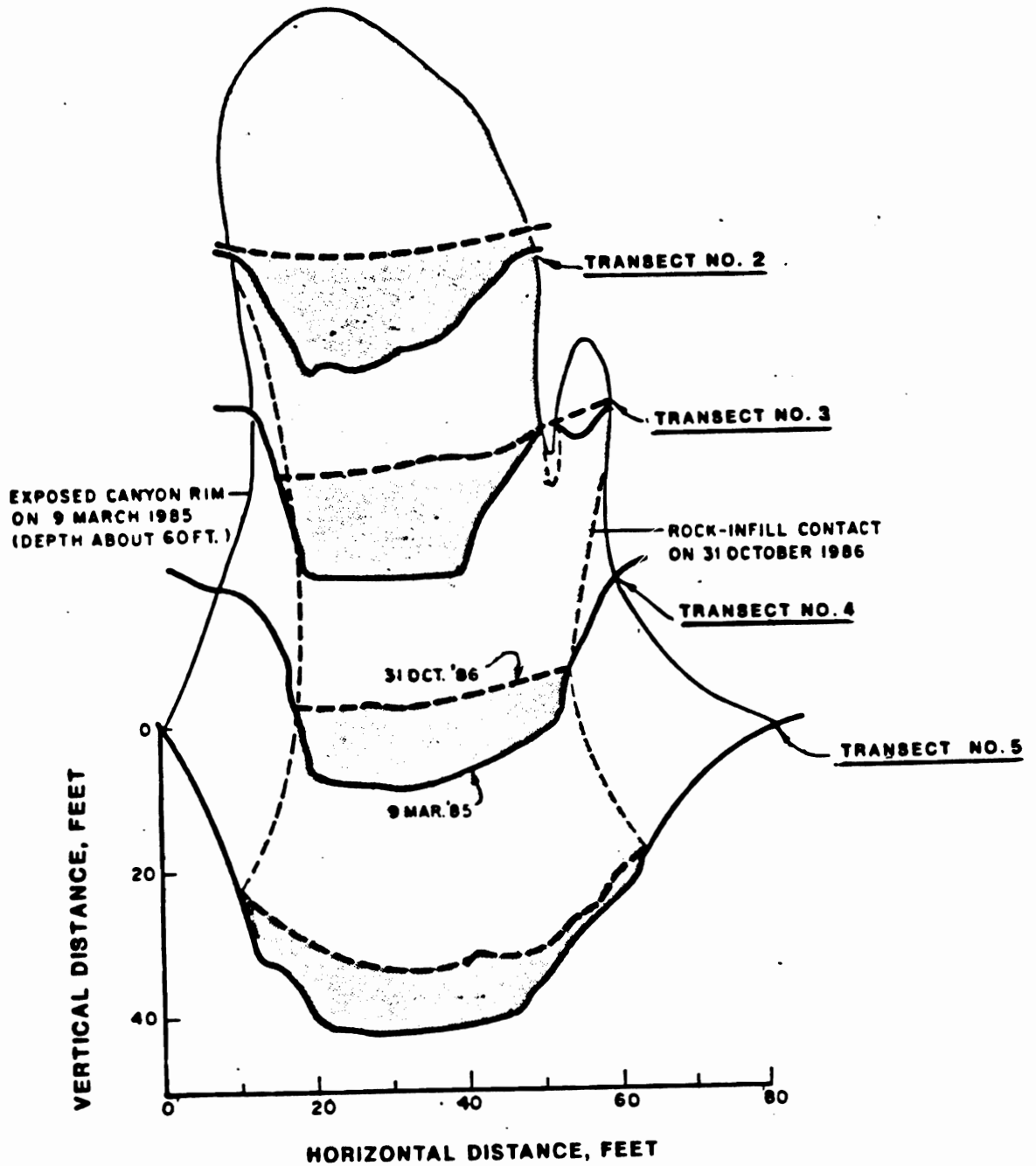


Figure 24. View upcanyon showing sediment infill in the gorge of Sumner Branch between 9 March 1985 and 31 October 1986 at transect lines identified in Figure 22; thin solid line is location of exposed canyon rim on 9 March 1985; dashed line is contact between sediment deposit and canyon sidewall on 31 October 1986; note infill forms a near-horizontal surface geometry except at Transect Line No. 5 where organic debris has created an undulating surface.

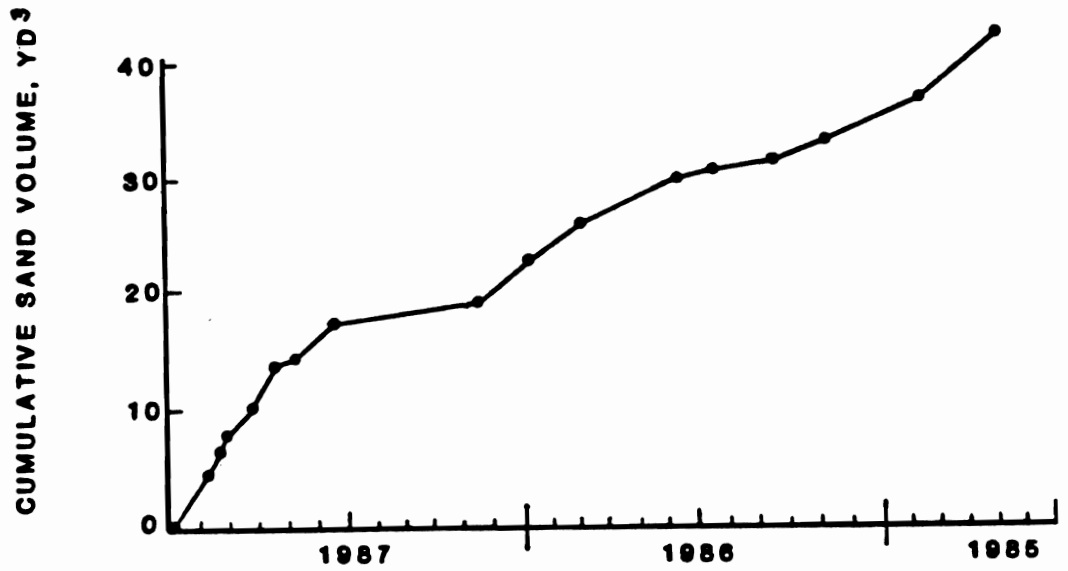


Figure 25. Cumulative volume of littoral sand transported over the sidewall of Sumner Branch into the gorge (1985-1987).



Figure 26. Small delta (2-ft diameter) at a depth of 92 ft in the gorge of Sumner Branch (November 1985) formed by transport through a 0.5-ft wide sand chute in the rock rim of the canyon.

east sidewall near Transect Lines 2 and 3. The pebbles and cobbles were probably of local origin, and possibly from the upper sidewalls. Nearby seacliffs and the walls of the submarine canyon to at least a depth of 200 ft are composed of massive grey siltstones and fine-grained sandstones with interbedded mudstones.

The total accumulation of sediment in the upper gorge is shown in Figure 27. Only about 20 percent of this volume was inorganic sand (Fig. 11), of which 0.85 (P_{ig}) or 17 percent was littoral sand (Table 4). Sediment infilling at Transect Lines 4 and 5 was almost all organic debris and the highest infilling rates were caused by the influx of organic debris. The largest influx of organic material took place in May and June 1986 (Fig. 27) following severe storms in February and March of that year. Gains and losses shown in Figure 27 are evidence of the passage of organic debris through the upper gorge between the times the gorge was cleared of sediment in December 1984 and later in March 1987. About 360 yd³ of littoral sand were trapped in the first 150 ft of gorge in that period, or an average 10-15 yd³/month. This is a very small quantity compared to the infilling rate for littoral sand in the depression.

(2) Depression. Immediately following the large slump of 13 December 1984 the depression began filling with littoral sand. Sand level changes, measured using survey markers along one or more of the survey lines shown on Figure 22, are given in Figure 28. Accretion was greatest just after the December 1984 slump. The sequence of sand level changes varied with time. Deposition was initially greatest in the shallowest depths, i.e., in the 20-25 ft region. There was a high initial infilling at 50 ft as well. The 50-ft region of the depression is just above the headwalls in the North and South Tributaries (Fig. 22). The sedimentation rate later became greatest between depths of 25 and 40 ft, evidence of progressive infilling toward deeper water. As shown by measurements along Survey Line 2 (Fig. 28), sedimentation was greatest north of a shore-normal line between the shoreline and the North Tributary. This suggests the importance of north-to-south longshore currents in moving sand to the canyon heads.

Littoral sand deposition in the depression between the major slumps of December 1984 and March 1987 is shown in Figure 29. Sediment infilling was greatest in the winter-spring seasons of 1985, 1986 and 1987. The volume

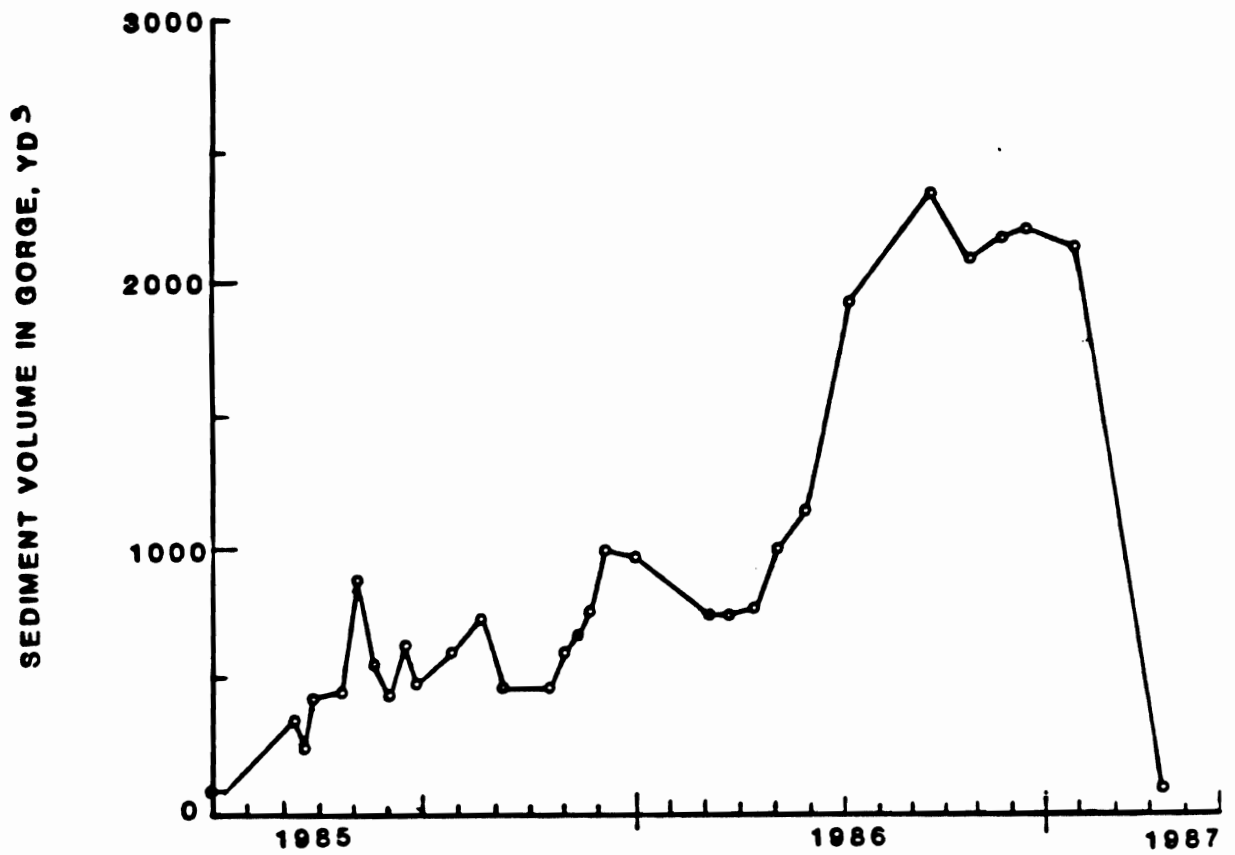
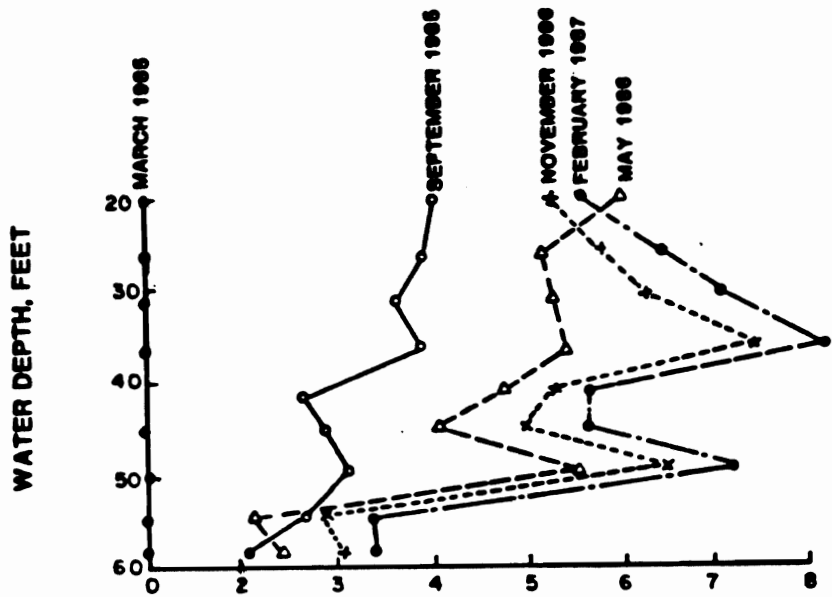
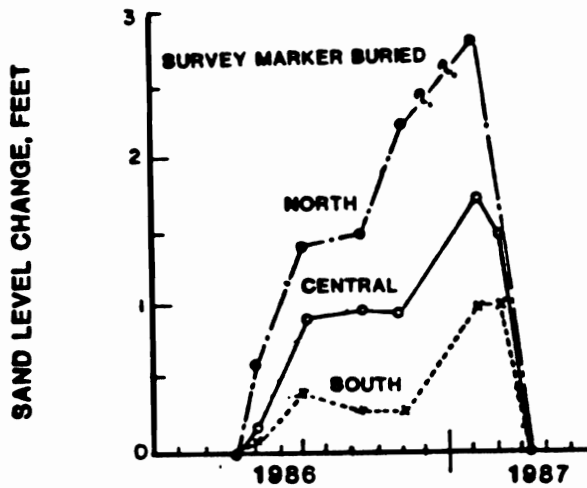


Figure 27. Cumulative change in sediment volume in the gorge of Sumner Branch above a bedrock depth of about 100 ft; rapid and relatively large changes in sediment volume were caused by movements of organic debris through the gorge.



SAND LEVEL CHANGES, SURVEY LINE 1



SAND LEVEL CHANGES, SURVEY LINE 2

Figure 28. Sand level changes normal to shore and parallel to shore in the depression of Summer Branch (see Figure 22 for locations); accretion was greatest in the depth interval 25-40 f. and north of a shore-normal line into the apex of the gorge.

losses in the autumn of 1986 and February 1987 were caused by minor slumps into the main gorge. The autumn 1986 slump occurred in Intermediate Tributary and was seaward of the reach of gorge that was monitored (Fig. 22). A February 1987 slump occurred in Hanging Valley. It moved sand into the gorge and caused a slight compression of the gorge deposit. The 52,000 yd³ of littoral sand deposited in the Sumner Branch depression between January 1985 and April 1987 exceeded the volume of sand deposited in all other areas of Scripps Canyon combined.

d. South Branch. South Branch is the smallest of the deep-gorge branches in Scripps Submarine Canyon. Extending slightly closer to shore than Sumner Branch (Fig. 5), it receives large quantities of littoral drift. South Branch is nearly straight the 250 foot length of its gorge. The gorge is oriented in an east-west direction and normal to the shoreline. Near its junction with the main channel of Scripps Canyon the gorge is less than 20-ft wide and the walls have an hourglass-shaped profile due to a higher erosion rate at their base and upper lip. The bowl-shaped headwall is 70-feet wide (Fig. 30). South Branch enters Scripps Canyon as a hanging valley at a depth of 135 ft. The rock-walled gorge is fluted with deep gouge marks; like Sumner Branch the walls overhang in places. At 25 degrees, the axis of the upper gorge is the second steepest of all the branches of Scripps Submarine Canyon (Table 1).

Following a sediment discharge event in April 1987 the upper boundary of the depression was at a water depth of 18 ft (MLLW). This is the shallowest measured depression boundary of any canyon head in San Diego County. The post-discharge slope of the depression averaged 16 degrees (Fig. 30). It was slightly steeper near its upper edge and slightly flatter near its base. The rock headwall of the upper canyon was exposed (Fig. 30) after sediment was discharged from the depression in 1984 and 1987. Large blocks were observed protruding through the sediment fill forming the floor of the lower rock-walled gorge following sediment removal in 1987. Bedrock was exposed on the floor of the gorge seaward of Transect 7 (Fig.5).

South Branch has no well-developed tributaries partially because tributaries expand along joint patterns that cross the gorge. South Branch and the joint pattern trend parallel to each other. The nearly shore-normal orientation of South Branch provides a sand transport path directly into its apex which also reduces the likelihood of tributary development.

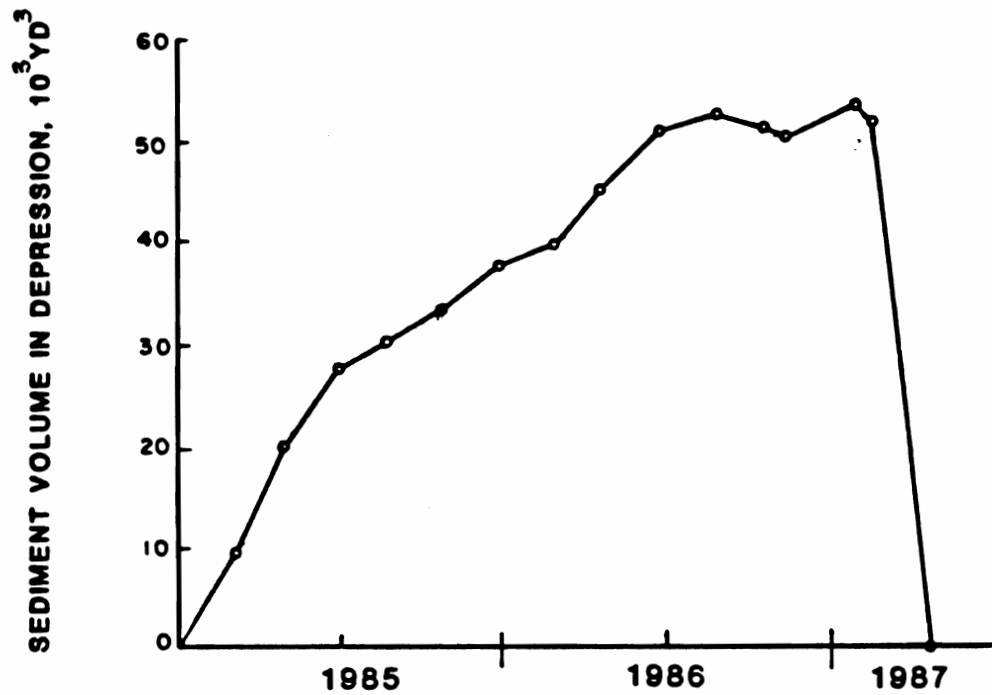
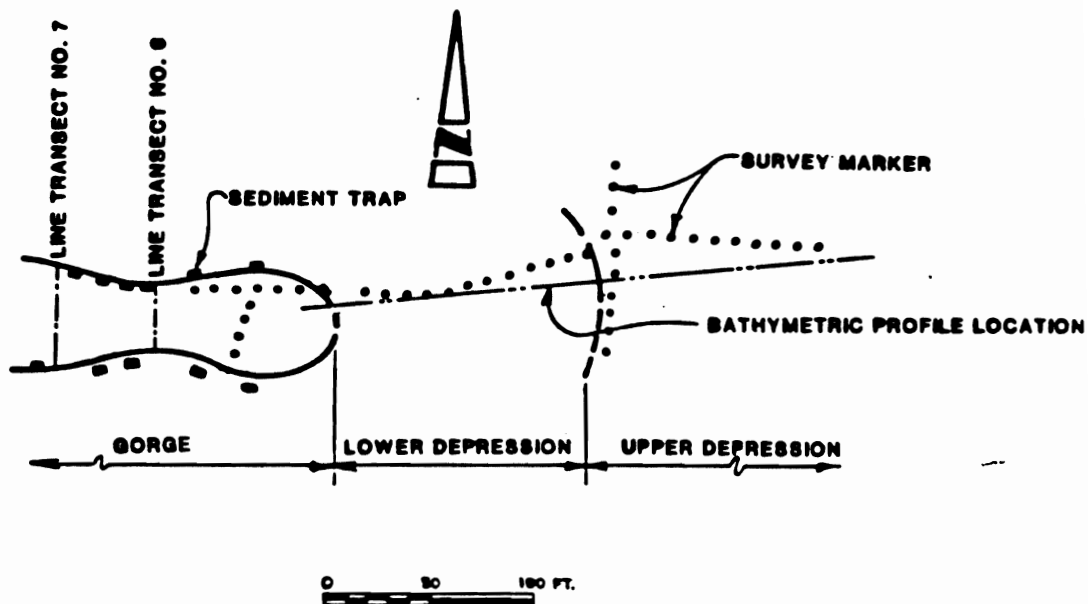
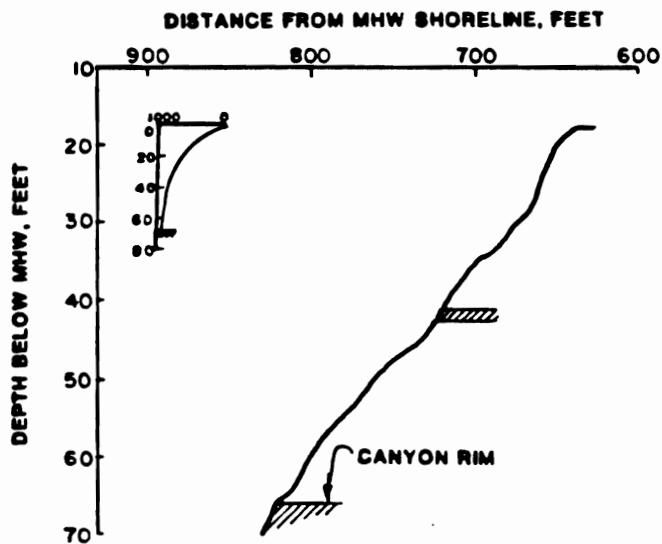


Figure 29. Sediment volume in the depression of Sumner Branch between January 1985 and April 1987.



LOCATION MAP



BATHYMETRIC PROFILE

Figure 30. Location map and bathymetric profile surveyed on 30 April 1987 across the depression of South Branch after it flushed in March 1987.

(1) Gorge. Sediment accumulation and discharge in the gorge was measured at Line Transects 6 and 7, along several lines of survey markers, and in sediment traps fixed to the sloping upper sidewall. Transect line, survey marker, and trap locations are shown in Figure 30. The bedrock thalweg slope, which is about 14 degrees at the upper part of the gorge, increases to over 30 degrees under Line Transect No. 6 then lessens to perhaps 20 degrees under Line Transect No. 7. The variable slope is a major control on sedimentation in the gorge.

Sediment that accumulated below Line Transects Nos. 6 and 7 was mostly organic debris. On 29 December 1984, only 16 days after the gorge emptied, two feet of organic sediment had accumulated at the base of the headwall (height = 7 ft). The volume of this deposit did not measurably change until April 1985. In April 1987 the gorge was again empty following a complete sediment discharge in March 1987.

Organic material moves through the upper gorge at all times of the year collecting beneath the transect lines as shown in Figure 31. The volume that accumulated in the steeper V-shaped section beneath Transect Line No. 6 was less than a quarter the accumulation that was measured on the lower-gradient slope beneath Transect Line No. 7.

About 80 percent of the fill under the transect lines was organic debris which often assumed steep slopes when it accumulated as a relatively fresh mat. The mat forms an organic "plug" in the narrow gorge. When released, headward erosion through slumping of the oversteepened slope drains the sand-filled depression. Sediment infill was approximately horizontal across the gorge although there were significant exceptions such as a 4-ft difference in late September 1986 when a large volume of new organic debris entered the gorge. The largest influxes of new organic material occurred in the August-November period in 1985 and 1986. Some was carried downcanyon out of the upper gorge in the winter of 1985-86.

The buildup of mostly organic sediment below a depth of 85 ft was usually not in phase with infilling elsewhere in the canyon. Major discharges of sediment that exposed the bedrock surface of the gorge, such as occurred in December 1984 and April 1987, however, were accompanied by large sand losses everywhere in the canyon head.

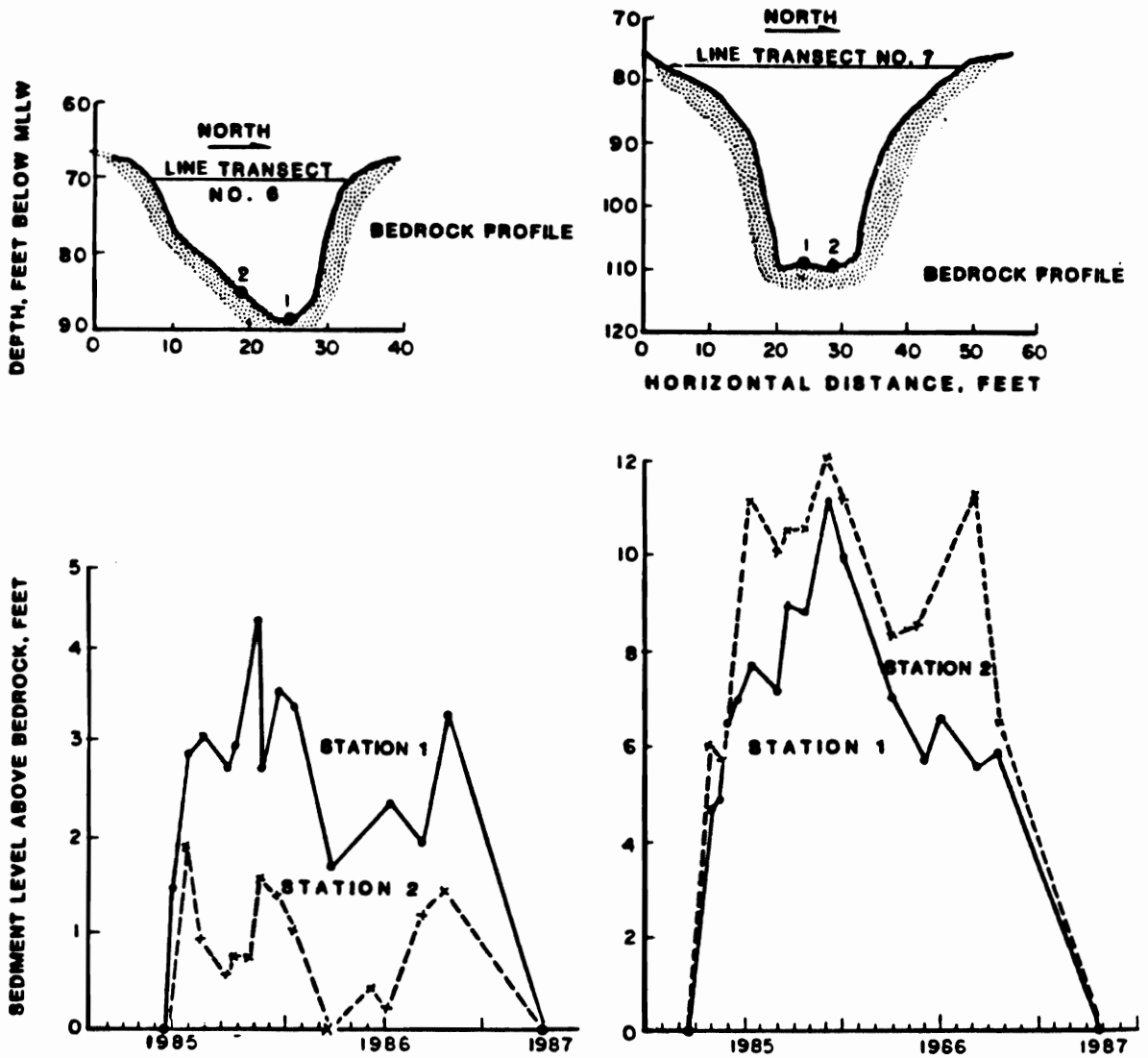


Figure 31. Sediment infilling beneath Line Transects 6 and 7 in South Branch between March 1985 and April 1987; transect locations are shown on Figure 30.

Traps were effective in quantifying the volume of sediment that entered the gorge over the rim. By volume, the ratio of inorganic sand (excluding mica) to mica to organic material that crossed the rim and accumulated in the traps was 70:10:20. The total volume of sediment that entered the gorge over the rim between May 1985 and April 1987 was about 30 yd³ (Fig. 32). This small volume, even though it was mostly littoral sand, thus had little effect on the infilling rate in the gorge.

Most sediments are funneled into the gorge through the depression shoreward of the upper rock rim (Fig. 30). Seaward of Transect Line 6 the total volume of canyon fill was 760 yd³ in late 1986, of which 230 yd³ was inorganic sand, excluding mica. Landward of Line Transect No. 6 the sediment level above bedrock in the gorge increased to an average depth of 5 ft by February 1987. The total volume of sediment in this upper gorge was about 500 yd³, of which 40 percent was inorganic sand (200 yd³) and the remainder organic debris and some mica. Survey markers were repeatedly lost when placed in sediment near the head of the branch. Slumping was active and an accurate time-history of infilling in the gorge is unavailable.

The combined volume of sediment that entered and was held in the gorge between January 1985 and February 1987 was 1250 yd³ ($V_g = 1250 \text{ yd}^3$) of which 450 yd³ was inorganic sand ($V_{ig} = 450 \text{ yd}^3$). Since $P_{ig} = 0.85$ the total volume of littoral sand, V_{lg} , that accumulated in the gorge was about 380 yd³ or an annual average infilling of 190 yd³/yr.

(2) Depression. The South Branch depression is physically two parts, the lower and upper segments shown in Figure 30. The boundary between the two is an outcrop of sedimentary rock at a depth of 46 ft. In early 1985 slumping exposed the outcrop as a 1.5-ft high scarp; in late-1986 and before April 1987 sediment prograding into the canyon had covered the rock; it was exposed again as a 1.5-ft high scarp in April 1987. Sand levels in the lower and upper segments of the depression were monitored using survey markers.

A relatively low volume of sediment accumulated in the lower depression during the study period. All sediment was lost there in December 1984 and it slowly filled thereafter. As shown in Figure 33, the accumulation occurred in two episodes. About 60 yd³ entered the lower depression during the summer and autumn of 1985 (mostly during a stormy period in November) and about 500 yd³

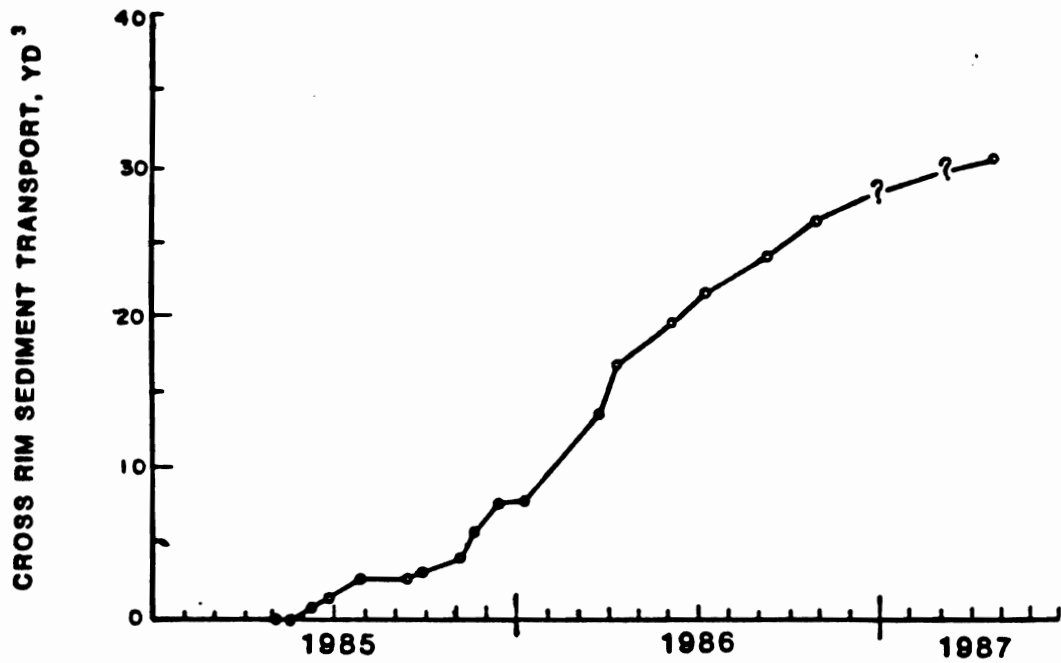


Figure 32. Cumulative volume of sediment that passed over the rim and entered the gorge of South Branch between May 1985 and April 1987.

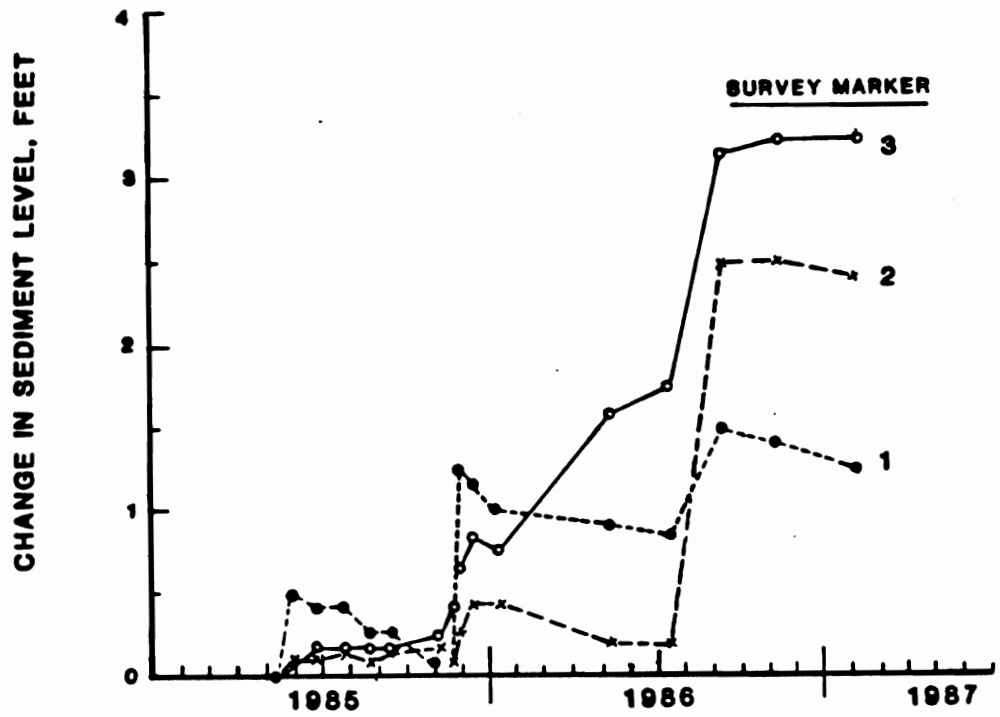


Figure 33. Sediment level changes in lower depression of South Branch; location of survey markers is given in Figure 30.

entered in the summer of 1986 (mostly in July-August). Shoaling decreased toward the gorge, indicating the transport path must have been downslope from the upper depression. The color of the sand also showed transport occurred as a prograding wedge. The deposit was discharged in April 1987, leaving the bedrock surface in the lower segment of the depression exposed. Sediment that accumulated in the lower depression was all inorganic sand with a $P_{id} = 0.85$ and $V_{id} = V_d$, so $V_{1d} = 0.85 V_d$ (Eq. 3).

Sediments accumulated at a faster rate at the shoreward edge of the upper depression. Figure 34 shows sand level changes that occurred at selected, about-equally-spaced survey markers. Sediment infilling was greatest between mid-January 1986 and late-March 1986 at all locations. In the summer of 1986 small surface slumps moved sand downslope from the shallowest locations. In late 1986 through early-February 1987 sediment accumulation at the upper part (above a 20 ft depth) and lower part (below a 35 ft depth) of the upper depression was minimal. From a depth of 25 to about 35 ft (MLLW) the sediment level increased several feet at the marked change in slope shown in Figure 35. Infilling occurred as a delta-like progradation over a horizontal distance of approximately 30 ft. The upper boundary of the depression was at Survey Marker 18, having moved seaward after late March 1986.

Most sediment entered the upper depression from its landward end, but a portion was also carried in over its north and south perimeters. Figure 36 shows the increase in sand level in the downslope part of the upper depression between 28 March 1986 and 6 February 1987. Most of the sediment that reached this end of the depression came in from the sides.

In April 1987 sediment was discharged from the lower and upper segments of the depression as a large scale slump or possibly as a series of slumps. Figure 30 shows the limit of the slump zone on 30 April 1987 perhaps a month or more after it occurred. The post-slump profile of the upper depression, taken as close as possible to the previous location of the survey markers, is shown in Figure 35. All survey markers were lost in that slump. About 4400 yd^3 of littoral material was lost from the depression as a result of the slump. This was 85 percent of the total 5200 yd^3 lost in a downcanyon direction.

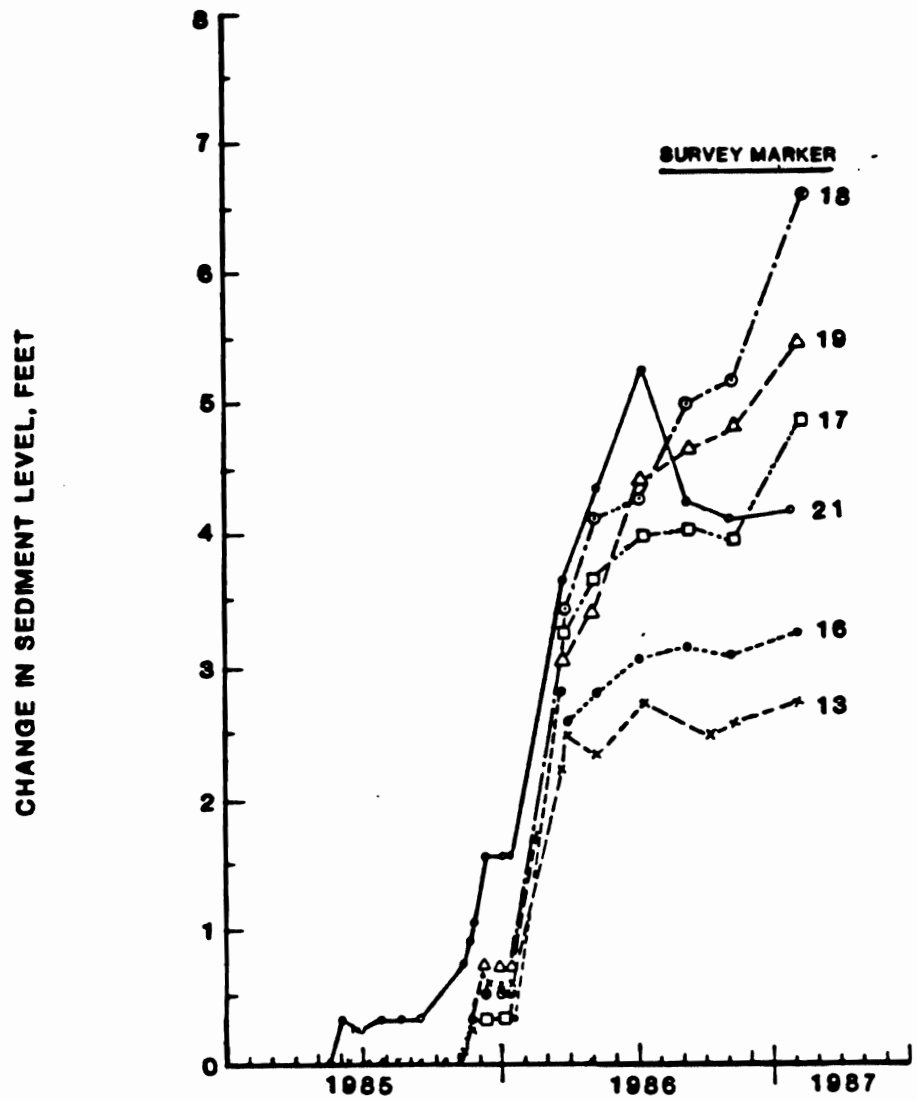


Figure 34. Sediment level changes in upper depression of South Branch; location of survey markers is given in Figure 30.

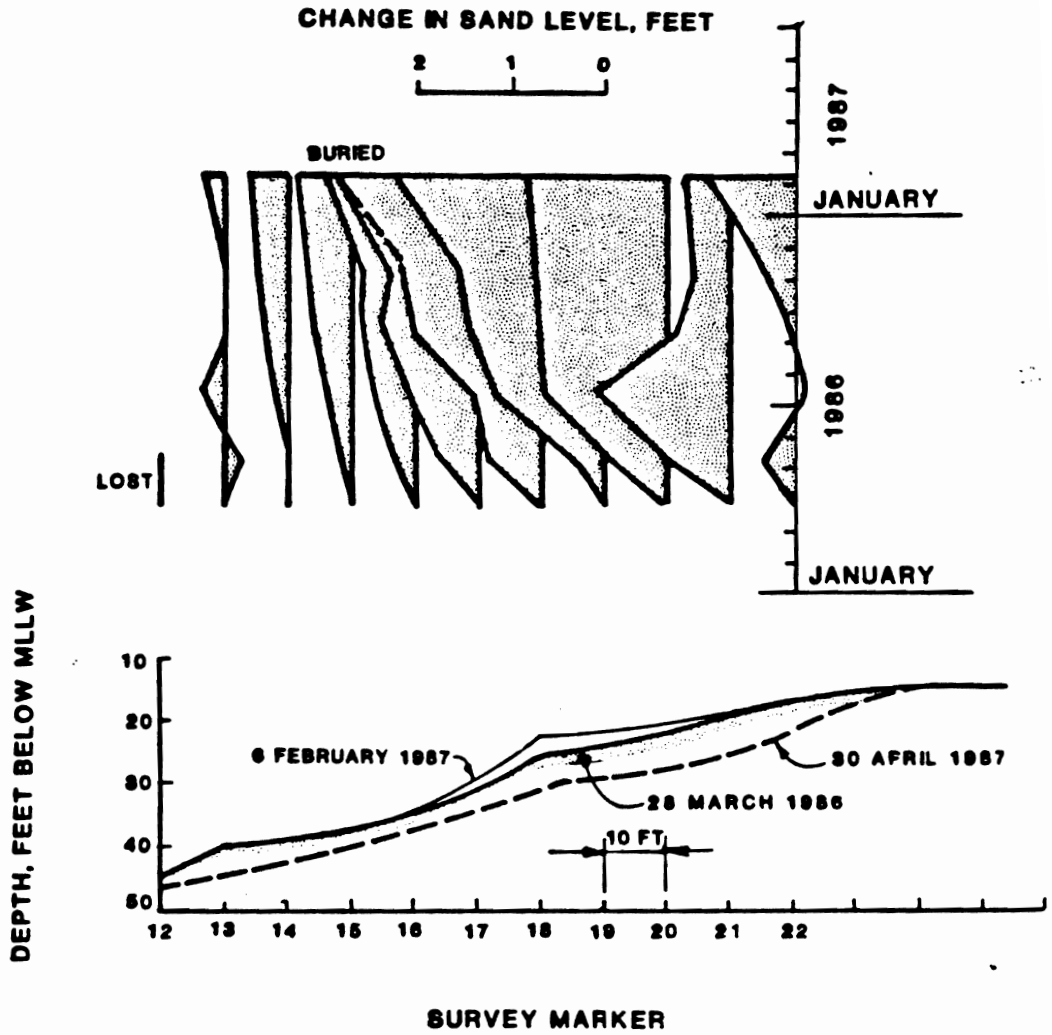


Figure 35. Progradational trend in sedimentation in the upper depression of South Branch between 28 March 1986 and 6 February 1987; accumulation was greatest between Survey Markers 19 and 20.

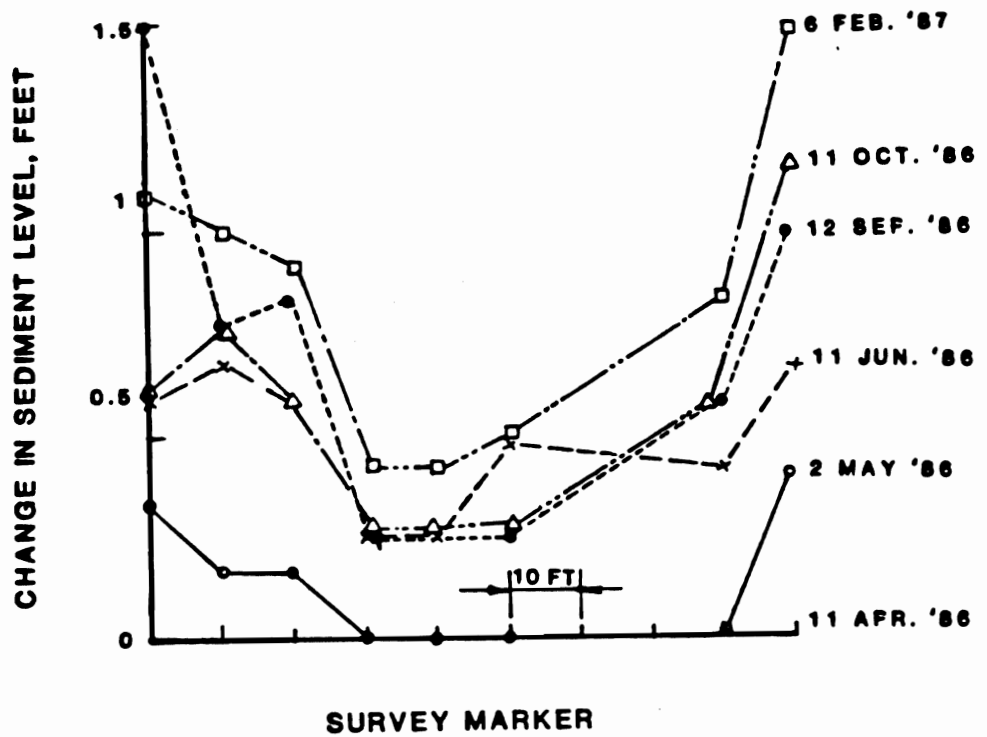


Figure 36. Sediment infilling along a profile normal to the axis of the upper depression of South Branch; transport is from north to south and south to north into the depression; location of survey markers is given in Figure 30.

From January 1985 to March 1987 approximately 3450 yd³ of littoral sand had accumulated (Fig. 37). Thus, about 130 percent of that volume or 4400 yd³ was discharged indicating the volume lost during discharge events is not always equal to the infill volume preceeding the discharge event.

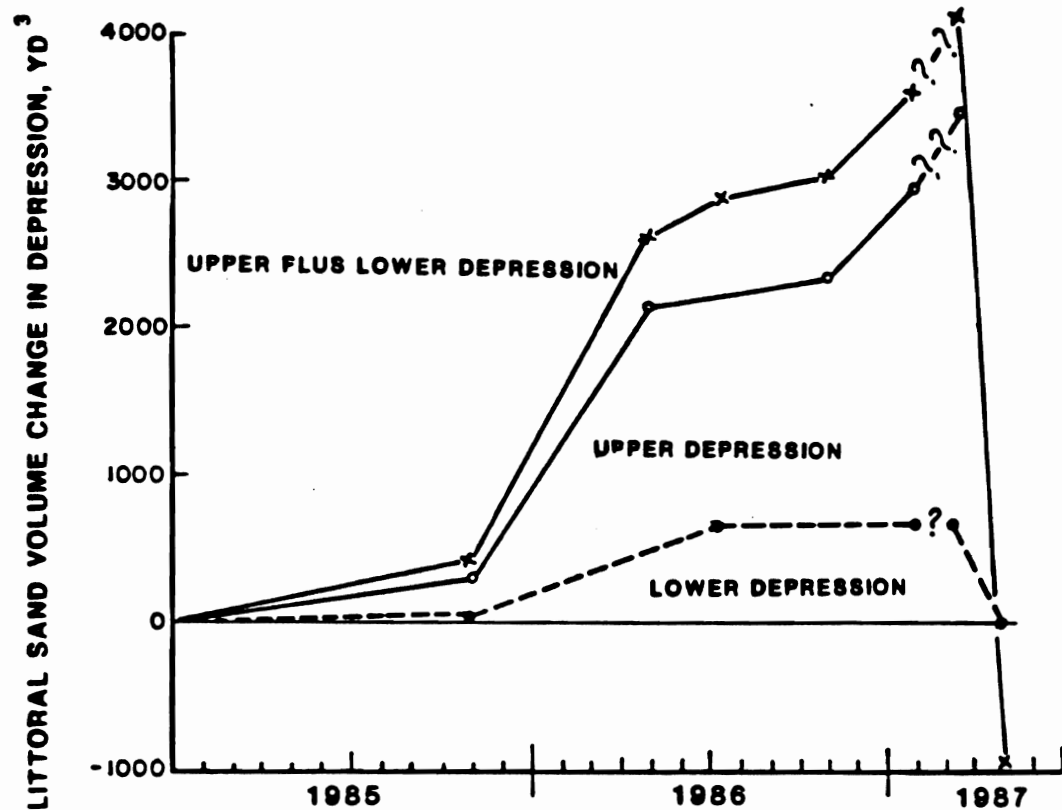


Figure 37. Littoral sand volume trapped in the depression of South Branch between January 1985 and March 1987, the sediment was lost in April 1987.

V. SEDIMENTATION IN LA JOLLA SUBMARINE CANYON

1. Previous Studies. Shepard (1951) made the first accurate and detailed surveys of the head of La Jolla Canyon in the late 1940's. In comparison to the changes in bottom elevation he recorded in Sumner and South Branches he concluded that changes in the head of La Jolla Canyon were "... much less significant ...". Shepard and Dill (1966) describe various geomorphic features of La Jolla Canyon in detail but do not quantify littoral sediment losses into it.

2. Sediments. The size distributions of sediments throughout the La Jolla Canyon region are similar. Samples taken from the depression at the North Reentrant, the depression at the central part of the canyon, and the depression at the south end of the canyon had similar median sizes, but the portion of sizes greater than 0.2mm increased to the south. Median sizes all ranged between 0.15 and 0.19mm. The average of 9 samples was 0.16mm. At the same location the size distribution varied through time by an insignificant amount. Over a 6 month period, for example, at a depth of 70 feet in the North Reentrant the median size of four samples collected at about equal intervals in time varied between 0.15 and 0.16mm. Not surprisingly, size distributions in the depression and in the gorge (below the rim) were similar because the sand in the gorge had been transported over the rim.

The composite size distribution of nine randomly selected depression and rim samples from all locations in La Jolla Canyon is shown in Figure 16. Sediment moving into and below the rim of La Jolla Canyon has the same size distribution as sediments in the littoral zone, therefore, $P_{id} = P_{ig} = 1.0$. In the depression $V_{id} = V_{ld} = V_d$. In the shallow regions of the gorge, $P_{og} + P_{mg}$ is approximately 0.9. Therefore, from Equation 4, $V_{lg} = 0.9 V_g$. The characteristics of sediment in the depressions and gorge of La Jolla Canyon are included in Table 4.

3. Measurements in La Jolla Submarine Canyon. Between January 1985 and June 1987 the measured sedimentation rate in the gorge of La Jolla canyon was low in comparison to sediment infilling in Scripps Canyon. Infilling in La Jolla Canyon decreased markedly from north to south and was highly seasonal.

a. North Reentrant. This broad, relatively low-gradient trough at the north end of the canyon head is a conduit to deepwater for much of the littoral sediment that passes the heads of Scripps Canyon to the north. Sediment was not discharged to deep water from the North Reentrant during the interval of this field investigation.

The headwall of the North Reentrant gorge is at a depth of 61 feet about 1690 feet from the MLLW shoreline (Fig. 6). It was mostly covered with sand during this study. The vertical face of the sidewall increased in height from zero at the apex to 20 ft about 500 feet southwest and away from the apex (Table 2). The upper edge of the depression on 2 June 1987 was at a depth of about 43 feet (MLLW) as shown in Figure 38. The sand body which is prograding into the depression has a downcanyon slope of 9 degrees, which is significantly less than it was through the sediment depressions at the heads of most of the active branches of Scripps Canyon.

Sand level changes were distinctly seasonal, just as they were in Scripps Canyon. Changes at selected survey markers are illustrated in Figure 39 with the location of the survey markers as shown in Figure 38. The sediment volume change that occurred at all survey markers during the investigation is also shown on Figure 39.

Based on reference rod studies over a 30-month period, about 1,000 yd³ of sand-sized material moved into the head of the North Reentrant (Fig. 39). At times the low-gradient gorge filled with kelp and grass but it was soon carried downslope and did not become incorporated in the fill. No active gas venting was observed in the canyon like it did in the active heads of Scripps Canyon. Sediment that accumulated in the upper gorge and lower depression was predominantly sand. Small pockets of mica were occasionally found in the central part of the depression at Survey Markers 4, 5, 6 and 9 (Fig. 38). The littoral sand infill volume is only slightly less than the total volume of sediment that accumulated in the apex of the North Reentrant, i.e., $V_{1g} = 0.9 V_g$ (Table 4).

Twenty sediment traps were fastened just below the crest of the canyon rim between stations 2 and 3 on Figure 6. Six traps were buried in sand in 1985 as the rim became covered between Survey Markers 15 and 1 (Fig. 38). Traps frequently filled between weekly to monthly survey visits because of the high

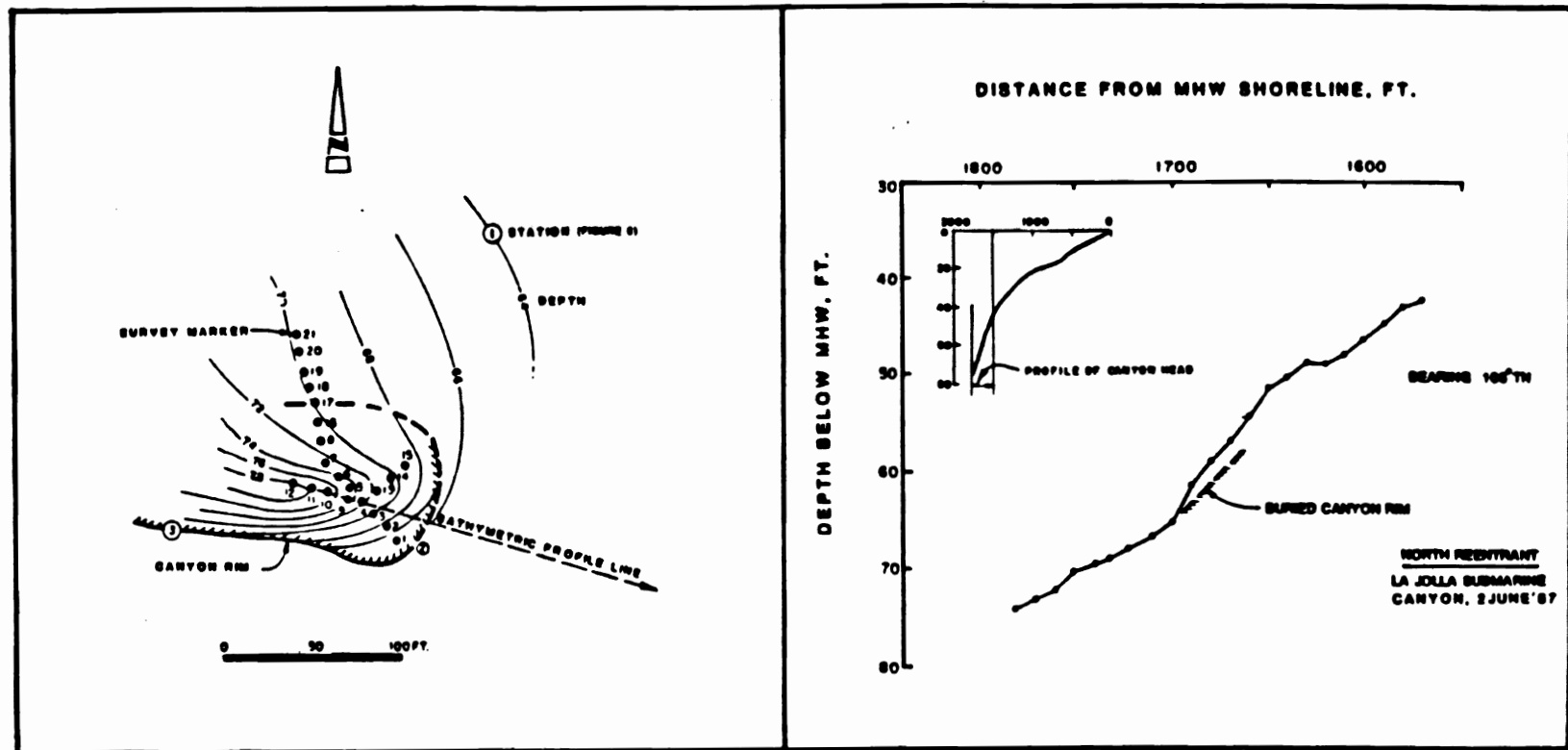


Figure 38. Location map and bathymetric profile showing conditions on 2 June 1987 in the North Reentrant, La Jolla Submarine Canyon.

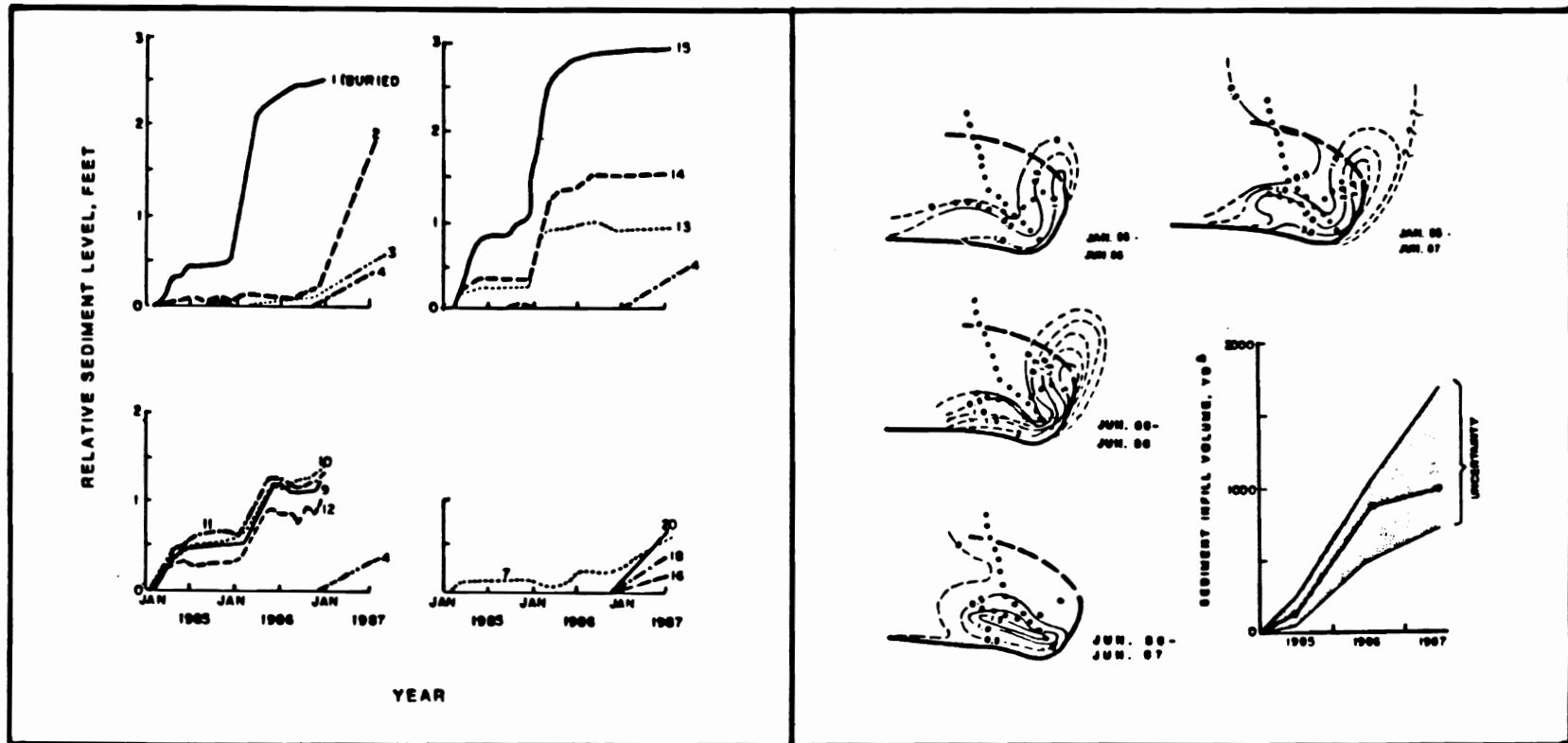


Figure 39. Changes in sediment level (left diagram) from January 1985 to June 1987 at survey markers located as shown in Figure 38, and contoured sediment level changes (right diagram) in the North Reentrant of La Jolla Submarine Canyon.

volume of sediment that entered at the apex. The "bedrock" comprising the sidewall is a semi-consolidated lagoonal clay and fluvial alluvium that was sometimes exposed above the rim and scoured by the sweeping action of sand as it was moved by wave surge. This erosion of the lagoonal sediments released fine-grained sediment that entered the traps. Traps located near Survey Marker 1 filled with almost 100 percent sand during the study; about 30 percent mud accumulated in traps near Station 3 (Fig. 6). The mud-sand ratio increased in an approximate linear fashion from east to west along the south rim of the North Reentrant.

Sand was captured in sediment traps at all times of the year. The greatest trap infilling periods, however, coincided with periods of measurable depression and gorge infilling coincident with storms. Mud-sized sediment that was eroded from the rim did not appear to collect in the trough of the gorge and probably was carried downcanyon. Observations made from submersibles indicate considerable mud and silt-sized particles are carried downcanyon by tidally-induced currents and during storms. Sediment infilling at Survey Markers 9-12 (Fig. 39) appeared to occur as the result of littoral sand carried north over the rim of the canyon. The slope of the "bedrock" surface above the rim is 10 to 17 degrees. Once sand reached the above-rim region it was rather quickly carried downslope into the gorge. From the base of the sidewall sand moved downslope in a series of shallow (< 0.5 ft) and small (< 8 ft²) slumps to the thalweg of the gorge.

The volume of sediment that moved over the rim was small compared to the volume that moved into the apex. In 30 months, about 90 percent of the 1,000 yd³ of littoral sand that accumulated in the North Reentrant moved offshore into the apex. The remaining 10 percent moved to and over the rim adjacent to the apex. The largest infill volumes were measured at the base of the rim near the apex. Over 7 ft of vertical accumulation, for example, was measured near Survey Marker 1 between December 1984 and January 1986.

Sediment infilling was clearly a winter and early spring phenomena. After 22 December 1984, almost 90 percent of the sediment accumulation occurred during three survey periods: 23 February 1985 to 27 March 1985, 20 December 1985 to 28 March 1986, and 31 October 1986 to 6 June 1987. The longer intervals in 1986 and 1987 were the result of a reduced level of survey effort and not necessarily a lengthened infilling period.

Between January 1985 and June 1986 material was transported to the apex of the gorge in an east-to-west direction, probably carried seaward to the canyonhead by downwelling or rip currents, and over the rim in a south-to-north direction as a result of downslope movement by wave-induced bottom surge. After June 1986 the volume of sediment in the east end of the gorge remained constant (Fig. 39), suggesting transport between June 1986 and June 1987 was from local sources and not from the coast. Sediment was carried into the gorge in the last year of the study in a northeast-to-southwest direction as well as over the rim from south-to-north.

Downslope movements of sediment deposited in the gorge was not apparent by tipped or displaced rods. Large mats of organic material, if they entered the North Reentrant, did not bend the survey markers or carry them away as they did in Scripps Canyon. This suggests the quantity of organic material reaching the gorge of the North Revetment was much less than it was in Scripps Canyon.

The North Reentrant is oriented upcoast at about 045 degrees (Fig. 38). The rate of infilling near and at the apex was about 400 yd³/yr. From a depth of 50 ft down to a depth of 200 ft the slope of the thalweg in the gorge was about 9 degrees. Along a bearing directly toward the shore (Fig. 38) the slope of the partially-filled depression (upper limit = 43 ft) was about 11 degrees. From the upper limit of the depression to shore the slope was about 1.6 degrees. These slopes were all less than comparable slopes in Scripps Canyon (Table 1).

b. Remainder of La Jolla Canyon. The central part of the canyon was not a particularly active area. Figure 40 shows a typical profile above and slightly below the canyon rim in the central reach of La Jolla Canyon (downcanyon from Location 15 on Figure 6). The rim in this area is a somewhat rounded scarp cut into compacted, semi-consolidated lagoonal muds and silts. Above the scarp the slope was about 17 degrees (Fig. 41). On 29 August 1986 the horizontal, shore-normal dimension of the depression was 115 feet. It extended upward from the canyon rim to a depth at its landward end of 31 feet (average slope = 11 degrees).

The south end of La Jolla Canyon is even less active than the middle reach. Sand movement into the canyon at the south end is very episodic and of low

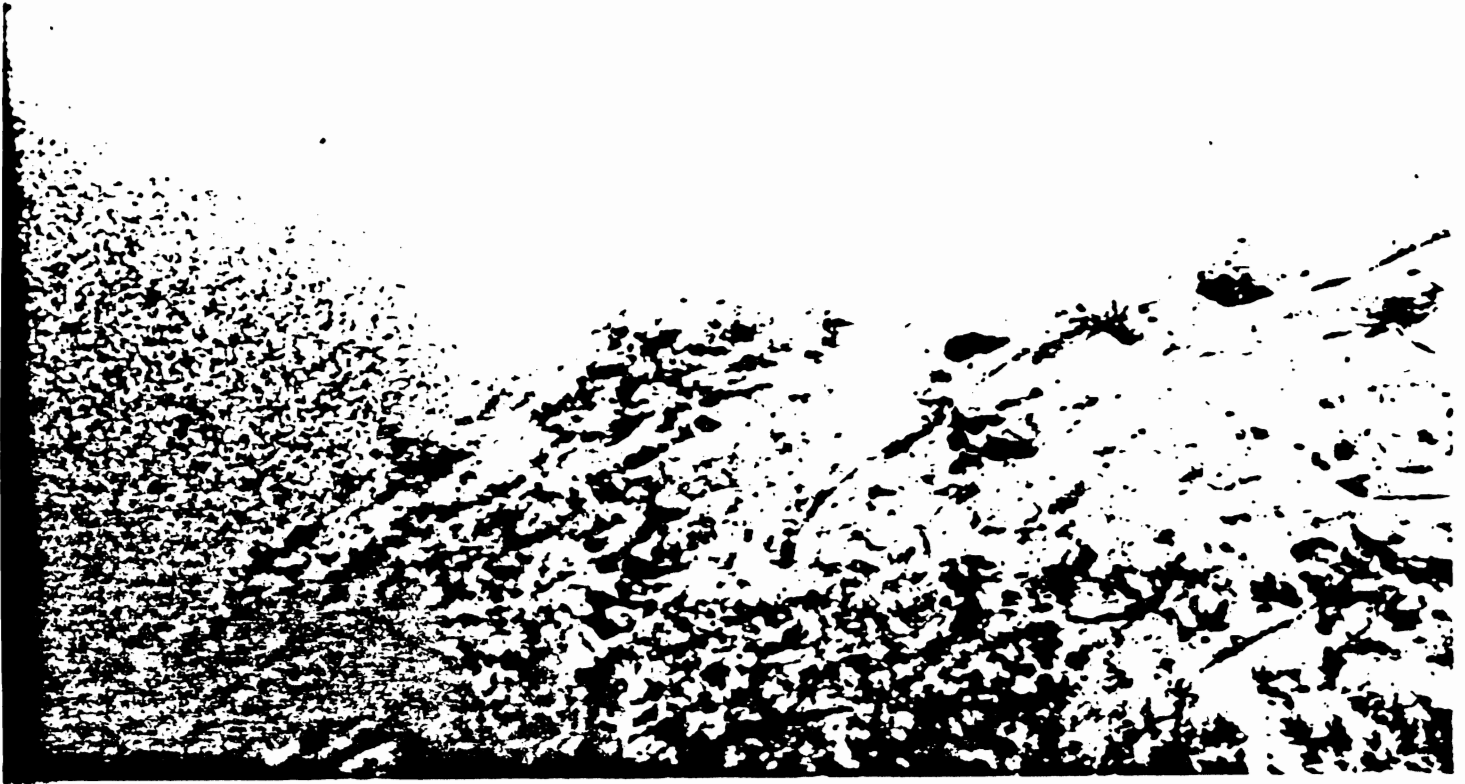


Figure 40. Typical view of the slope above the rim at south end of La Jolla Submarine Canyon; depth is 52 ft (October 1986); the thin, discontinuous layer of organic debris on the bottom above the rim indicates a lack of recent sand movement.

volume. The quantity of compacted mud chunks that have broken from the rim is larger than the quantity of littoral sand lost to the gorge. The profile at the south end of the canyon is similar to the profile near the center of the canyon. The rim elevation is 56 feet (MLLW), for example, at the profile shown in Figure 41. At that site the sidewall scarp is 8-ft high. The average slope within the depression was 12 degrees on 2 June 1987 to its upper edge at 20 feet (MLLW). This is the shallowest upper-depression boundary found in La Jolla Canyon.

Most of the sand enters the La Jolla Canyon gorge through a series of broad sediment chutes. In all areas some sand passes over the rim. Small fans of littoral sand are common along the base of the headwall.

In 1986, thirteen sediment traps were maintained in the mid-reach of the canyon along the rim between Stations 15 and 17 (Fig. 6). The depth of the rim along this 250-ft long measurement site was 50 to 58 ft (MLLW). A 50-ft wide sand chute separated the north and south parts of the site. Sediment captured in the sediment traps averaged 80 percent fine sand similar to that found in the littoral zone and 20 percent organics and mud. Traps fastened to shallower rim locations captured slightly more sand than traps that were placed where the rim was deeper. The infilling rate was 2 to 6 ft³/ft of rim per year (Table 7) with an average rate of 4 ft³/ft-yr. Twenty survey markers placed 10-ft apart in the sand chute showed no change in sand elevation between 2 May 1986 and 31 October 1986. At a depth of 28 ft the sand thickness above "bedrock" was 2.5 ft.

Another set of mid-canyon sediment traps was monitored along a 500-ft long perimeter of the rim about 500-ft further south in 1985 and 1986 (Stations 19 to 25, Fig. 7). The average rate of cross-rim transport there was also about 4 ft³/ft-yr. This average varied greatly, depending on season and year. Most transport occurred during the winter and spring storm periods. During 1986 a number of storms created swell and wave conditions that exceeded those of previous years and resulted in a higher annual sediment transport for that year.

TABLE 7. Sand Transport Rates Across Rim of La Jolla Submarine Canyon

Location ¹	No. of Sediment Traps ²	Period of Record	Transport Rate ³ , ft ³ /ft-yr		Portion Littoral Sand
			Range	Average	
15-17	13	25 April - 31 October 1986	2-6	4	0.8
19-25	10	22 March 1985 - 14 September 1985	1-2	1.5	0.6
19-25	9	14 September 1985 - 20 December 1986	6-8	7	0.6
37-40	13	10 April 1985 - 30 October 1986	1.5-2.5	2	0.5

¹Stations from Figure 6.

²This is number placed; traps were frequently lost as the gorge sidewall failed.

³Adjusted for seasonal variations.

Between Stations 37 to 40 (Fig. 6), at the south end of the canyon, a set of 13 sediment traps was monitored between 10 April 1985 and 3 October 1986. Erosion of the canyon headwall was rapid in this area and frequently large blocks of lagoonal material broke away and slid downcanyon from the base of the headwall. Since the traps were fastened in this material, it was difficult to maintain them long enough to get long-term values. The sand to silt plus mud ratio of sediment recovered from the traps was about 1:1.6. Some organic material also accumulated in the traps. As shown in Table 7, the average sediment transport rate across the south-central part of the rim was about 2 ft³/ft-yr. Survey markers placed above and below the rim and monitored between 16 February 1985 and 20 December 1985 showed no sand level changes occurred.

At the south end of La Jolla Canyon the water depth at the rim varies from 30 to 70 ft. Shallow rim depths are associated with the Rose Canyon Geologic Fault (Stations 40 and 41, Fig. 6). Material below the steep to overhanging headwall reflects the nature of the eroded headwall; below cobble beds abundant cobbles were found mixed with coarse sand and gravel.

The slope below the headwall is typically steep. For example, at the south end of the canyon, the below-rim slope is 35 degrees between a depth of 56 and 72 ft (Fig. 41). There is no indication that the region beneath the sidewall is experiencing a net sediment buildup. Sediment moves downslope from the headwall by slumping.

The headwall of La Jolla Canyon, and hence the position of the canyon rim, is noticeably retreating as evidenced by the ubiquitous eroded blocks of material at the base of the side wall. Retreat is highly variable from one location to another. Sidewall failure occurs by spalling. The mud and silt accumulation in sediment traps is indicative of rim and above-rim erosion of the compacted silt-mud canyon material by sand abrasion caused by wave-induced bottom surge. An average rim retreat rate of 0.25 to 1.5 ft/yr is probably reasonable for the 1985-1987 period of study in La Jolla Canyon. Shepard and Dill (1966) estimated a 10-yr average retreat rate of 2 ft/yr (1950-1960) for the headwall near the center of the canyon.

(4) Canyon Infilling Rate. The average infilling rate for La Jolla Canyon from January 1985 to June 1987 was obtained by adding the accumulation rate in

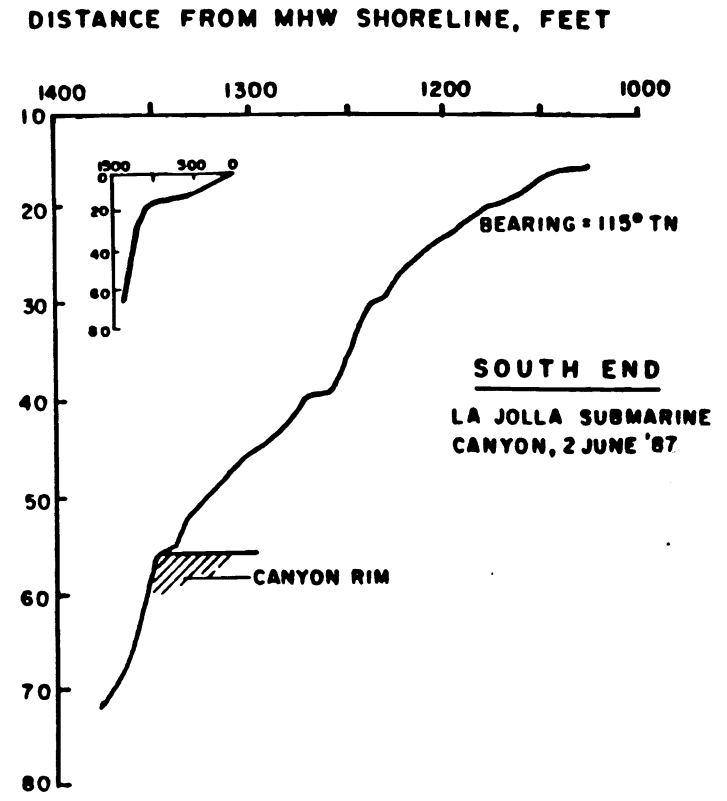
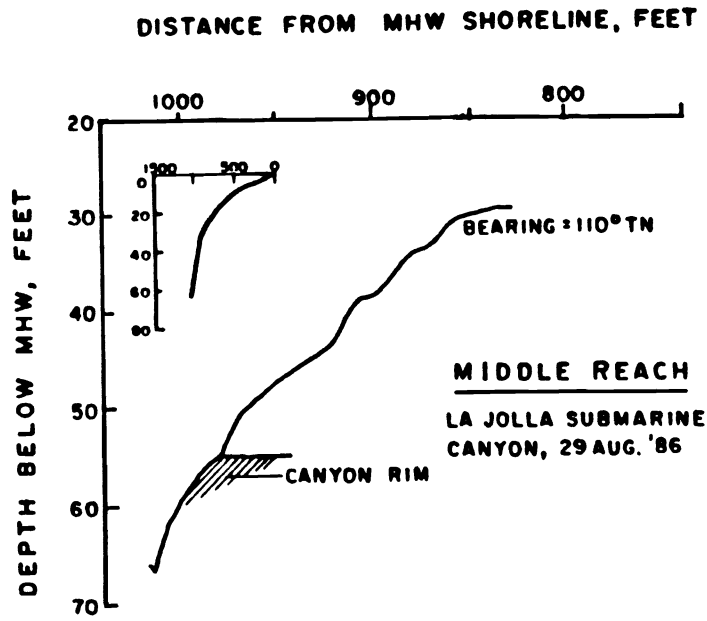


Figure 41. Profiles across the depression at the central and south reaches of La Jolla Submarine Canyon.

the North Reentrant and the integrated transport rate across the rim elsewhere in the canyon (Table 7). Figure 42 shows these rates separately and the combined rate for littoral sand.

Cross-rim transport rates vary directly as the rates into the North Reentrant depression vary. Simultaneous infilling was obvious in a comparison of sediment trap data and survey data at the north-facing rim of the North Reentrant. Cross-rim transport rates taken from specific periods were accordingly weighted with respect to the infilling rate of the North Reentrant. From January 1985 to June 1987, the average annual accumulation (littoral sand infilling) rate in La Jolla Submarine Canyon was 1140 yd³/yr.

TABLE 8. Summary of Littoral Sand Transport Across the Rim into La Jolla Submarine Canyon, January 1985-June 1987

<u>Location</u>	<u>Stations</u> ¹	<u>Rim Length, ft</u>	<u>Estimated, Cross-Rim Sand Transport Rates, yd³/yr²</u>		
			<u>Low</u>	<u>Average</u>	<u>High</u>
North Canyon	1-14	1700	285	380	500
Mid-Canyon	14-26	1750	135	180	240
South-Canyon	26-47	2100	60	80	100
TOTAL			480	640	840

¹from Figure 6.

²does not include cross-rim transport at North Reentrant

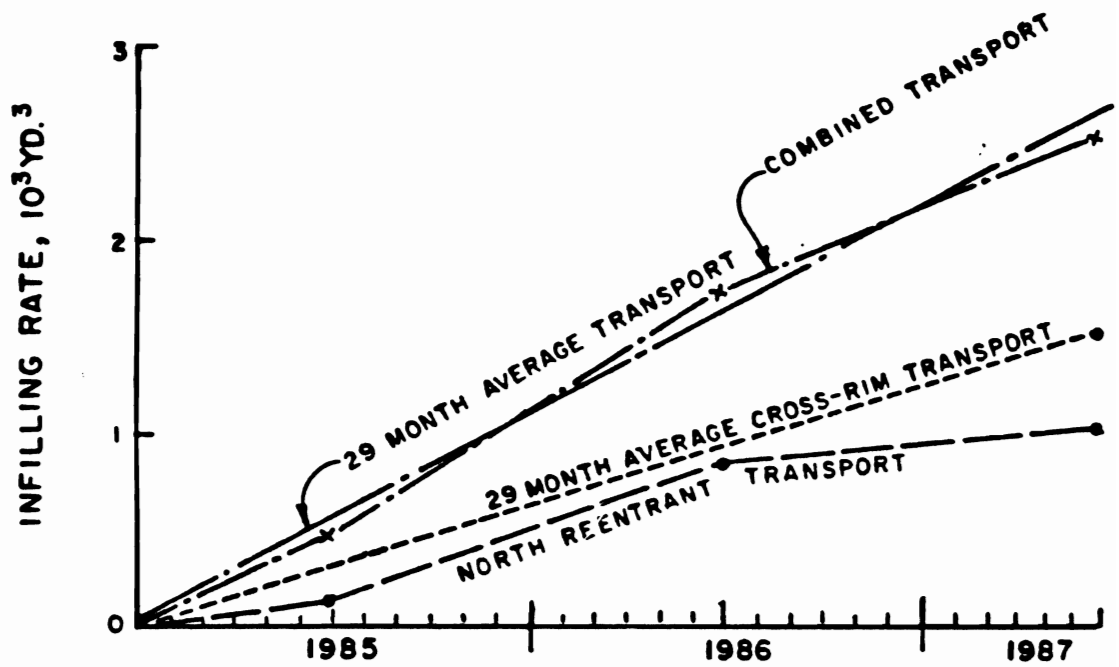


Figure 42. Littoral sand transport into La Jolla Submarine Canyon, January 1985 to June 1987.

VI. SEDIMENT INFILLING AND DISCHARGE RATES

The rates at which littoral sand is carried to and discharged downslope from the shallow heads of Scripps and La Jolla Submarine Canyons vary with time. Rates presented in this report are only applicable to the field measurement period from December 1984 to June 1987. The Scripps Canyon measurements were not made in valleys south of South Branch. Transport rates and discharge frequencies varied in the past and will no doubt vary in the future from those presented in this report. Indeed, even during the 30-month investigation the canyon head infilling rates changed from season to season and from year to year.

1. Infilling Rates. Most infilling occurred in the first quarter of each calendar year. The volume captured in the canyon heads in 1985, just after Summer and South Branches discharged in December 1984, was greater than the volume trapped in either 1986 or 1987. When averaged for the measurement period, the mean annual littoral sand infilling rate for Scripps and La Jolla Submarine Canyons was about 29,000 yd³/yr. Table 9 is a list of the mean annual infilling rates in the depressions and gorges, where applicable, of the three submarine canyons and their respective branches.

Table 9 shows the importance of deposition in the canyon depressions. In the four branches of Scripps Canyon where gorge infilling and depression infilling rates were measured, the volume trapped and held in the depression averaged over 20 times as much as that trapped in the gorge. Littoral sand was trapped in the depression while mostly organic debris and some mica accumulated in the gorge. When sediment in the depressions and gorges of Scripps Canyon discharged to deep water most of the material came from the depression and most was littoral sand. More than half of the sediment that was trapped in La Jolla Canyon entered over the rim.

Littoral sand losses were greatest in Scripps Canyon. Less than five percent of the sand lost to submarine canyons at the south end of the Oceanside Littoral Cell during the field investigation was trapped in La Jolla Canyon.

TABLE 9. Summary of Annual Littoral Sand Transport to the Heads of Submarine Canyons in San Diego County, California, December 1984 - June 1987

<u>Canyon Identification</u>	<u>Annual Sand Transport Rate, yd³/yr</u>		
	<u>into Depression</u>	<u>into Gorge</u>	<u>Total</u>
Carlsbad Canyon	0	0	0
Scripps Canyon			
(1) North Branch	2050	450	2500
(2) Shepard Branch	(a)	160	160
(3) Sumner Branch	22,300	150	22,450
(4) South Branch	1500	190	1700
(5) new valley (Shepard, 1951)	(b)	(b)	600
(6) new valley (Marshall, 1978)	(b)	(b)	400
La Jolla Canyon	(b)	(b)	1140
TOTALS	25,850 (c)	950 (c)	28,950 (c)

(a) included in value for depression of Sumner Branch

(b) only estimate of total infill rate available

(c) does not include possible infilling of valleys south of Marshall's (1978) new valley (infilling rate estimated to be 0 to 200 yd³/yr).

Sand entrainment rates were not the same in the six known branches of Scripps Canyon. Sumner Branch was, by far, the most active sink for littoral sand. South Branch has a much smaller depression into which littoral moved, although sand level changes in the depression of South Branch were nearly as great as they were in Sumner Branch. Sumner and South Branches extend closest to the shoreline. The water depth at which the upper boundaries of the depressions became obvious by abrupt steepening of the bottom slope, were, respectively, 23 ft and 15 ft in Sumner and South Branches.

2. Discharge Rates. Sediment was discharged from the sediment depression and rocky gorge of only three branches in Scripps Canyon during the field investigation. In December 1984 sediment flushed from Shepard, Sumner and South Branches during a large storm. In March 1987 sediment was again discharged from Sumner Branch and in April 1987 from South Branch. The volume of littoral sand discharged in the 1987 event in Sumner Branch was about 52,000 yd³, or nearly the volume that had accumulated since the canyon previously flushed in December 1984. In South Branch the volume of littoral sand flushed into deep water was 4,400 yd³. The volume deposited in the canyon head since the previous discharge was 3450 yd³, so about 125 percent of

the latest infill volume was discharged (some pre-December 1984 material was flushed).

The volume of sand that can be held in the depression and gorge of Sumner Branch is about 50,000 yd³ and the filled volume of South Branch is about 4,500 yd³. North, Sumner and South Branches never fill completely. The fill becomes unstable before it reaches rim elevation in the gorges. Shepard Branch and the two new valleys described by Shepard (1951) and Marshall (1978), however, apparently fill to rim elevation almost their entire length before they flush.

The discharge or flushing frequencies of the submarine canyon heads in San Diego County for the field study period are given in Table 10. Slumps in Sumner Branch and South Branch that removed the littoral sand deposit occurred 27 months apart.

TABLE 10. Discharge Frequencies of Submarine Canyon Heads in San Diego County, December 1984 - June 1987

<u>Canyon Identification</u>	<u>Discharge Frequency for Littoral Sand (times per year)</u>
Carlsbad	0
Scripps	
(1) North Branch	+0.025 ²
(2) Shepard Branch	+0.025 ²
(3) Sumner Branch	0.43
(4) South Branch	0.41
(5) new valley (Shepard, 1951)	+0.025 ²
(6) new valley (Marshall, 1978)	+0.025 ²
La Jolla ¹	<u>+0.025</u> ²

¹North Reentrant

²Estimate

VII. DISCUSSION

1. Comparison with Previous Estimates. Chamberlain (1960) described a 12-yr record of sand level changes in South and Sumner Branches based on over fifty consecutive fathometer surveys between 1948 and 1960, plus direct observations in the canyon heads from 1957 to 1960. He concluded canyon-head deepenings between 1948 and 1960 occurred about once per year and an annual average 250,000 yd³/yr of sediment (225,000 yd³/yr littoral sand) are lost to the canyon heads. He assumed North Branch was not an active littoral sand trap and Shepard's (1951) new valley trapped 15,000 yd³ of all kinds of sediment per year. Without the new valley loss which Chamberlain (1960) assumed would be repeated on a 10-yr cycle, his littoral sand loss rate would be about 210,000 yd³/yr. He also assumed 10 percent of the total loss was organic debris. He was not aware of the existence of Shepard Branch.

An annual infilling loss of 225,000 yd³/yr is almost eight times the loss measured during this investigation for all of the Scripps-La Jolla Canyon system. The difference between infilling estimates could result from: (1) long-term differences in wave conditions responsible for sand delivery to the vicinity of the canyons (sand availability factor), (2) long-term variability in waves and currents that move littoral sand from the beach and shoreface into the canyon heads (offshore sand transport factor), or (3) errors in one or more aspects of this work or of Chamberlain's (1960) work. It is beyond the scope of this study to address the first two possibilities. While the possibility of error cannot be definitively established, there are certain elements of each study that can be evaluated.

Infilling rates presented in this report were estimated using sediment level measurements made at specific locations at specific times. Inaccuracies result from this approach when significant changes occur between times when the measurements were made, and/or where significant changes occur between measurement stations or outside the region in which the measurements were made.

Consistent infilling trends were observed in all canyon heads. With one exception it is unlikely that large unrecorded changes in sediment volume occurred between surveys. The exception occurred in 1987 when an unmeasured volume of sediment was carried into Sumner and South Branches between a survey

made on 6 February and when sediment slumped from the depression and gorge of those canyon heads in March and April. Infill rates for that unmeasured period were estimated using first-quarter infilling rates from 1985 and 1986 in those branches, and relative 1985/1986/1987 infilling rates in canyon heads that did not discharge in 1987. Uncertainty in the annual average infill rates in Sumner and South Branches due to the temporal spacing of measurements probably does not exceed an estimated ± 10 percent.

Inaccuracies introduced because of spatial sampling problems could be more important. Measurement spacing in the gorges of all the shallow heads of Scripps Canyon except the new valleys (Shepard, 1951; Marshall, 1978) appear to have closely delineated the infilling region. The estimate of losses to valleys south of South Branch may be quite inaccurate since measurements were not made there. However, since these valleys are not particularly active, a possible inaccuracy of ± 200 percent would introduce an error of only a few percent in the total canyon infilling rate. Cross-rim sand transport may have varied by an estimated ± 50 percent, but again the magnitude of the littoral sand flux across the rims of both Scripps and La Jolla Canyons is so small that this inaccuracy has a negligible effect on the total infill estimate.

The largest potential inaccuracy caused by the spacing of measurement stations is in Sumner and South Branches. Survey markers were not established throughout each depression for all survey years. There was a physical limitation on the number of stations that could be monitored and the spatial limits of the depressions were poorly known when the investigation began. Nevertheless, over the 2.5-yr study, shore-normal and shore-parallel lines of survey markers appear to have well delineated the areal extent of infilling. Uncertainties introduced in the infilling rates of Sumner and South Branches by spatial-coverage limitations probably do not exceed an estimated ± 25 percent.

Considering inaccuracies introduced by both temporal and spatial factors, the average annual littoral sand infilling rate in Scripps and La Jolla Submarine Canyons between December 1984 and June 1987 was probably between 18,000 yd³/yr and 40,000 yd³/yr.

The 2.5-yr period of this investigation was too short to develop a useful year-to-year range of values. The measured infilling rate variation between years was probably controlled more by how much the canyon heads had filled the

previous year than by differences in wave conditions. Chamberlain (1960) stated yearly littoral sand losses between 1948 and 1960 varied from 55,000 yd³/yr (assuming Shepard's (1951) new valley loss is removed) to 260,000 yd³/yr. In 12 years of record, his yearly low estimate was still twice as great as our average for the 2.5-yr field measurement period.

Chamberlain's (1960) estimates of infilling and discharge losses were based on the assumption that shoalings and deepenings at specific locations in the canyon axis show exact time correlation with shoalings and deepenings elsewhere. Volume losses between 1948 and 1956 were estimated using sediment level changes obtained by fathometer along the axis of South Branch between depths of 30 and 110 ft. Chamberlain (1960) equated axial deepenings to sediment volume using simplified canyon cross-sections determined by surface and underwater surveys. Total sediment loss was computed assuming a ratio of sediment loss in Scripps Canyon to sediment loss in South Branch of 33:1.

Two of Chamberlain's (1960) assumptions are questionable based on the results of this investigation. He may have overestimated sediment losses by equating deepenings in the gorge of South Branch to unmeasured deepenings elsewhere. Frequently, one section of the canyon gorge experienced shoaling as a bundle of intertwined grass and kelp stopped there while another section deepened as shown in Figure 23. In addition, in this investigation deepenings that did not clear all or almost all the sediment out of the gorge were not accompanied by sand discharge from the depression. More than 90 percent of the sand lost from the littoral zone was deposited in the depressions of Scripps Canyon so depression flushing was very important. Littoral sand did not reside for any length of time in the upper gorge where most of Chamberlain's (1960) deepenings were recorded. When the sediment in the gorge slumped into deep water the sand in the depression also slumped and passed through the upper gorge. Quite possibly, a large quantity of organic debris alternately stopped awhile then passed Chamberlain's (1960) reference stations as it moved downcanyon. If there was an overestimation in Chamberlain's (1960) work for this reason it would require a major effort to resolve it. However, if his 1 flushing/yr based on level changes in the gorge of South Branch is reduced to the 0.4/yr measured in this investigation his estimated sand entrapment rate would become about 100,000 yd³/yr.

Chamberlain's (1960) estimates were all based on a few measurements in South Branch. He assumed sediment losses in Scripps Canyon are equal to 33 times the loss in South Branch or 30 times the loss in Sumner Branch. We found the infill loss ratio between South and Sumner Branch to be 1:13, or considerably less. Considering our loss ratio and the previous reduction in Chamberlain's (1960) average sand loss rate, his average rate could be as low as 40,000 yd³/yr.

2. Sediment Transport Paths and Processes. Sediment moves to the heads of Scripps and La Jolla Submarine Canyons along specific paths. Transport is highly seasonal and appears to be most dependent on the frequency, duration and severity of storms. Massive movements of littoral sand out of the canyon heads occur when the normal load exceeds the internal shear strength of the deposit. This discharge is controlled, in part, by infilling in the upper depression and the decomposition of organic debris in the gorge.

a. Transport Paths. Over 90 percent of the littoral sand transported to the heads of Scripps Submarine Canyon was initially trapped in the depressions shoreward of the rocky gorge. Sand was then periodically transported from the depressions into the gorges and then to deep water. Only small amounts of littoral sand were actually deposited in the upper gorges prior to a major downcanyon loss. The rocky gorges are therefore conduits and not depositories for littoral sand.

Most of the relatively small volume of littoral sand that was deposited in the gorges of Scripps Canyon passed over the headwalls. Only about 10 percent passed into the gorges over the sidewall rims. Most of the cross-rim transport was on the side of the gorge nearest shore. Owing to the broad head of La Jolla Canyon, a larger percentage of sand transported into its gorge passed over the rim. Still, the reentrants carried more sand into La Jolla Canyon via those sand chutes than passed over the rim.

Sediment is segregated by type after it moves into the canyon heads. Littoral sand moves into and is deposited the upper regions of the depression. The depression deposit progrades toward the gorge in a delta-like advance. Mica moves into and quite rapidly through the depression and is preferentially deposited in the narrow, uppermost region of the gorge where wave activity is greatly reduced as a result of protection provided by the rocky headwall and

the sidewalls. Weak currents move low-specific-gravity organic debris, typified by various kelp species and sea grasses, further seaward in the gorge. Some is caught and deposited there; some moves downslope through the upper gorge to deep water.

Littoral sand appears to enter most of the depressions from the north-northeast, or somewhat north of a shore-normal direction. This is clearly the situation in Sumner Branch and the North Reentrant of La Jolla Canyon and it appears to be the situation in North Branch as well. Transport to South Branch, the exception, is normal to shore and directed to the center of the upper depression.

Littoral sand transport across the rim of the canyons also exhibits a northeast to southwest approach direction. This tendency is particularly obvious along rims that parallel the shoreline. Cross-rim transport is much greater at the north end of the landward facing rim of North Branch, for example, than along the rim further south. The same is true for the landward-facing rim of Sumner Branch. From north to south along the 3500-ft long rim of La Jolla Canyon the sand transport flux into the gorge declines markedly. Considering the bigger picture, 25 times more littoral sand is trapped in the heads of Scripps Canyon than further south and downdrift in La Jolla Canyon.

b. Sediment Transport Relationships. Canyon head infilling was seasonal. Most littoral sand was transported from the littoral zone to the depression between November and April in all three years of the field investigation. The greatest transport was in the January-April period. As shown in Figure 43, infilling is greatest when longshore transport is in a net south direction or near zero. Large quantities of littoral sand are not transported into the canyon heads when the net transport direction is to the north. Infilling is also related to wave conditions as shown in Figure 44. Transport to the canyon heads is greatest during those periods when significant wave heights exceed 3 feet, i.e., stormier periods.

Rip currents were sometimes observed in the vicinity of some canyon heads, especially Sumner Branch, South Branch and north of North Branch during periods of high waves. They were not observed near the rim of La Jolla Canyon. The significance of rip currents as a primary transport mechanism is not well established. Shepard and Inman (1950) noted the presence of rip currents less

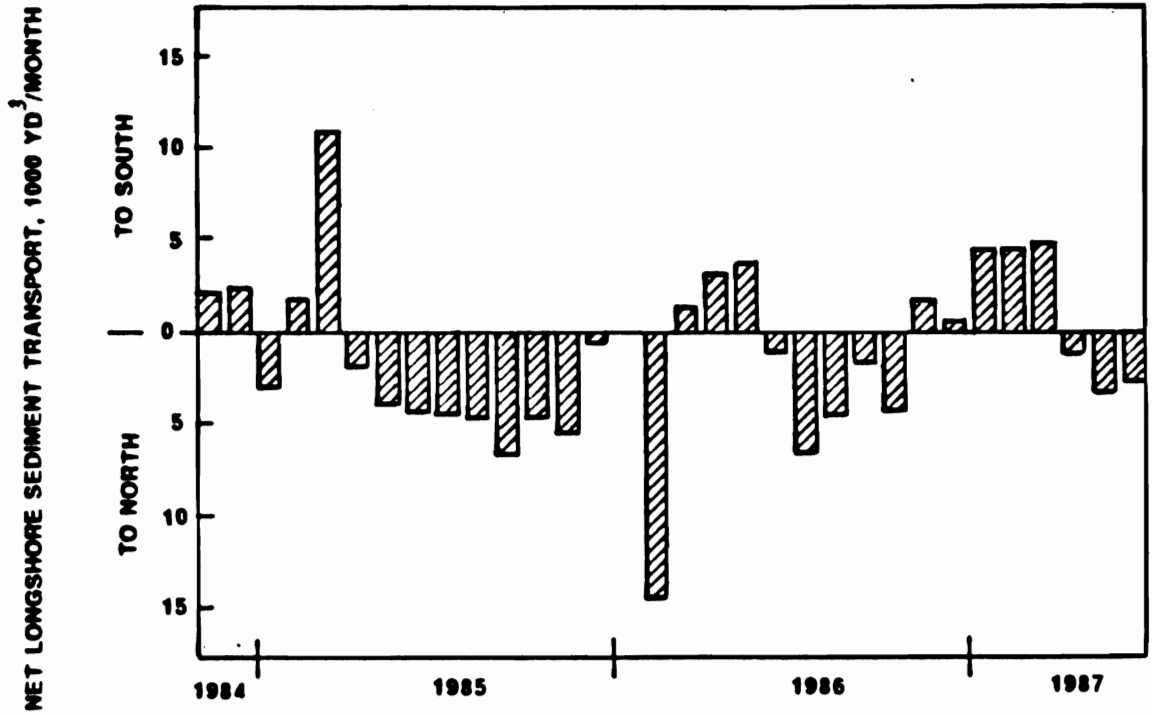


Figure 43. Net monthly longshore sediment transport rates obtained using the wave energy flux factor method with wave data from a directional gage located at Del Mar, California, about 3 miles north of Scripps Submarine Canyon.

SIGNIFICANT WAVE HEIGHT, DAILY AVERAGE

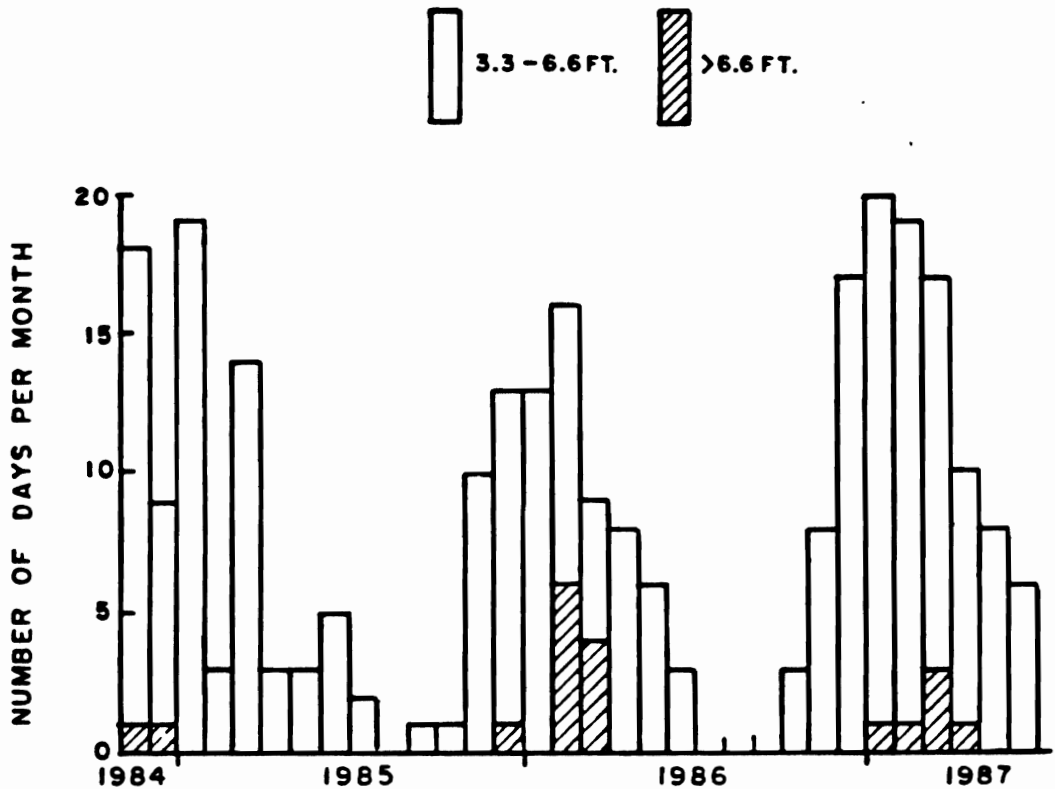


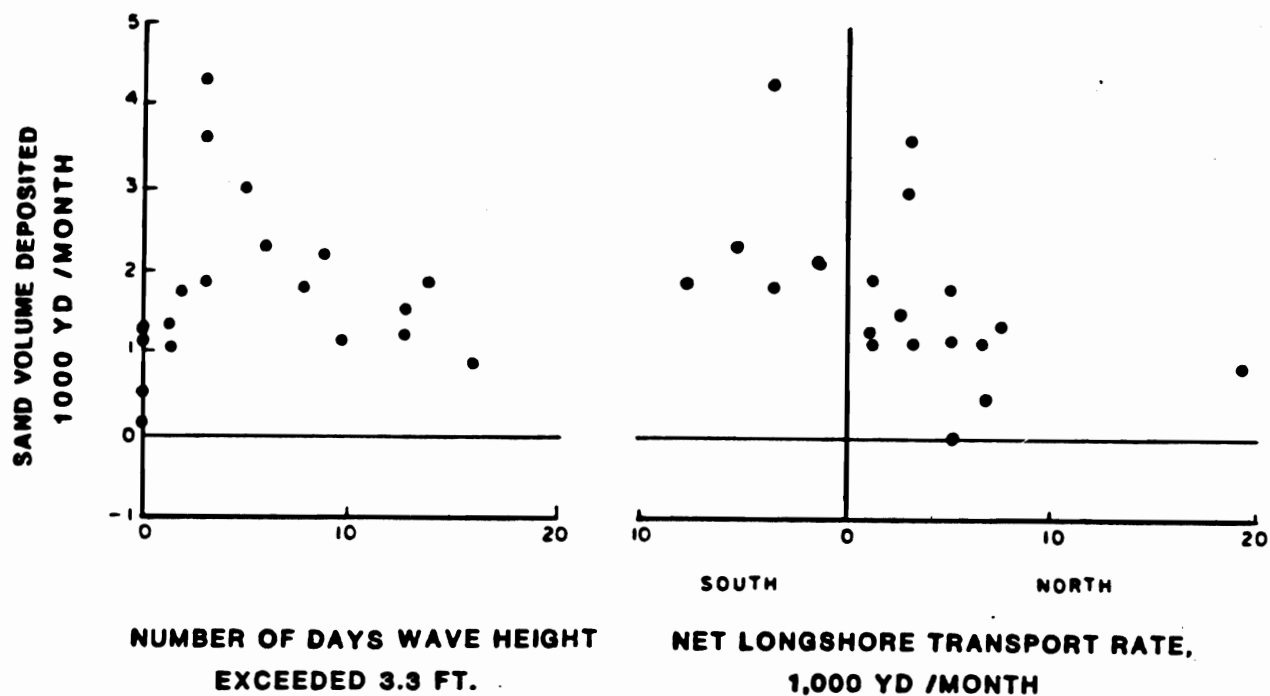
Figure 44. Number of days per month that the daily significant wave height exceeded 3.3 ft at a gage in Del Mar, California; waves over a height of 3.3 ft are a measure of wave "storminess" as it relates to sand transport into the shallow heads of Scripps and La Jolla Submarine Canyons.

than 20 percent of the time directly opposite the heads of Scripps Canyon, and observed the rip cells there were distinctly shorter than others away from the canyons. Rip currents are most likely to reach the depressions at the time of low water during spring tides accompanied by large swell. Non-localized shore-normal transport to the depressions (downwelling) also occurred during local storms when short-period waves were not greatly refracted. Downwelling may be a more important transport mechanism than rip currents.

The distance between the shoreline and the canyon head is a major control on the deposition rate. Net longshore transport direction and "storminess" alone do not explain sedimentation in the depressions. Figure 45 is a scattergram of monthly wave storminess and longshore sediment transport versus the monthly deposition rate for littoral sand in Sumner Branch. Clear cut relationships are not evident because another important factor is the volume of littoral sand that had been deposited in the depression since the last massive slump. Figure 46 illustrates the monthly infilling rate in Sumner Branch following the slump of December 1984. The largest monthly increases in sand volume occurred in the first winter-spring period following the 1984 slump. The volume transported into the depression declined even though south-directed transport (Fig. 43) and wave "storminess" (Fig. 44) increased in later years. The most likely explanation is that the location of the upper boundary of the depression moved progressively seaward as the depression filled. The distance littoral sand had to move to reach the depression thus increased with time.

Cross-rim sediment transport, while accounting for less than 10 percent of the material transported into the canyon heads, was greatest when sand transport into the depressions was greatest. Wave-induced bottom flow transported sand down the typically steep slopes above the rim and over the rim, especially during times of long-period swell from the west and northwest. In Scripps Canyon this process was most pronounced at the north end of North Branch where the refractive effect of the canyon was least. Bottom surge was a problem during almost all dives along the 60 to 75-ft deep rim of North Branch. In the other branches of Scripps Canyon bottom surge was rarely a problem, even though the rim in those branches is no deeper.

The transport of organic debris through the depressions into the gorges occurred at all times of year. The largest infilling of the gorge in South Branch, for example, occurred in the summer of 1985. The deposited material



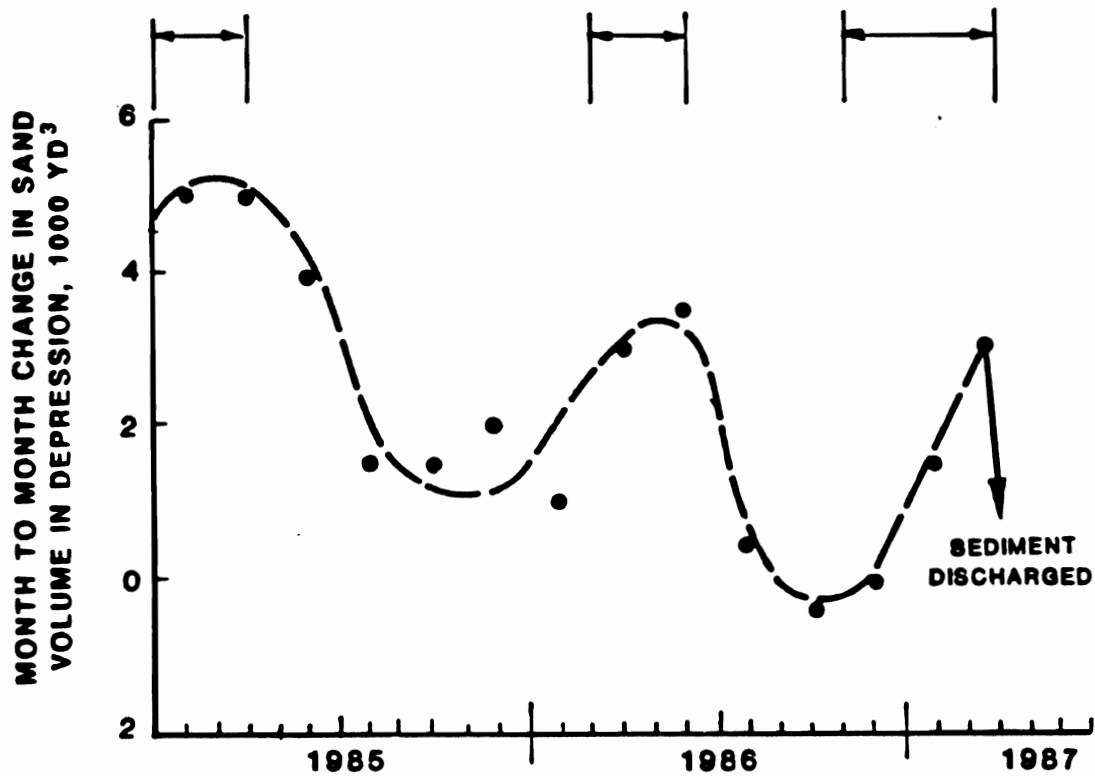


Figure 46. Monthly change in sand volume in the depression of Sumner Branch showing a decline in deposition with time since the previous massive slump flashed the canyon head in December 1984; periods of net longshore sediment transport to the south are shown between arrows at the top of the figure.

was almost all kelp and grass that moved into the gorge in bundles and lodged there.

3. Sediment Discharge. Large volumes of sediment were rapidly discharged from the shallow-water gorges and depressions of South, Sumner and Shepard Branches on 13 December 1984, from Sumner Branch in mid-March 1987, and from South Branch in early April 1987. At other times much smaller volumes of littoral sand moved slowly downslope along the surface of the depression, and from the depression to the gorge in these and the other branches of Scripps Canyon. Sand did not move downslope as a result of slope failures in the North Reentrant of La Jolla Canyon. The rate of downslope movement by slope failure in the shallow canyon heads, and the discharge rate from the canyon heads, appears to be controlled by the: (1) volume of sediment that passed into and accumulated in the depression and gorge, and (2) bedrock geometry of the depression and gorge, (3) geotechnical characteristics of sediment deposited in the depression and gorge and (4) a triggering mechanism to cause marginally-stable sediments to fail.

Sediment moves downslope in the canyons by at least five processes: (1) density currents composed of fine-grained sediment, (2) wave-induced bottom currents, (3) sand flows, (4) gravity-induced creep, and (5) slumps and slides. Slow, gravity-induced creep appears to be an important transport mechanism for moving the organic-rich sediment mat that builds up in the rocky gorges. Dill (1964, p. 158) observed gravity creep in the shallow, upper gorge of Sumner Branch by measuring the slow (average 1 ft/month near the apex) continuous downslope displacement and tipping of marker stakes. Three months was the longest he was ever able to maintain stakes in the gorge. At depths of 70 to 125 ft he measured the downslope movements of a car body and large concrete blocks and concluded the rate at this slightly deeper location, where the bedrock slope is greater, averaged about 3 ft/month. Based on the progressive downslope lean of the stakes Dill concluded the rate of surface creep exceeded the creep rate at depth. He attributed creep to a gradual decline in the internal strength of the deposit by the breakdown of its organic component as gravity caused the sediment deposit to adjust to an equilibrium slope. He also considered gas generation to have an effect on the internal strength of the deposit, especially along bedding planes, by increasing (slightly) its pore pressure. Dill (1964) found creep did not occur until the organic-rich gorge deposit reached an overburden thickness that exceeded 4 to 10 ft.

Slumps and slides are relatively rapid downslope movements of sediment that occur when external and internal stresses exceed the shear strength of the sediment deposit. Dill (1964, p. 185) differentiated between a slump and a slide by defining its shear plane. When the shear surface was within the sediment mass be considered it a slump. When the sediment mass moved on the rock bottom of the gorge he defined it as a slide. Slumps observed in this study ranged in size from small ($<10 \text{ ft}^2$), cusped, surface ($<0.5 \text{ ft}$ thick) displacements, as shown in Figure 47, to slumps that moved large volumes ($>10^4 \text{ yd}^3$) of sediment out of a depression and all the sediment out of a shallow gorge to a depth of at least 100 ft. Surface slumps were most pronounced after the upper boundary of the depression reached a value of 16 to 18 degrees (Figure 48).

A complete discharge of sediment by sliding only occurred once, on 13 December 1984, in the gorge of Sumner Branch. In his 1959-1964 investigation of that branch, Dill (1964) never observed a similar complete loss of sediment. He also did not find massive slumping to be restricted to a specific season although he found it occurred more frequently in the stormier winter season. Dill (1964) typically observed creep to occur after small slumps and suggested small-volume slumps in tributary gorges may, at times, be the agent that triggers major slumps in the branch gorges.

Each branch appears to have a critical sediment-holding capacity, V_c , or containment volume. It is equal to perhaps 50,000 to 60,000 yd^3 in Sumner Branch and 4,000 to 5,000 yd^3 in South Branch. When the critical capacity is approached or exceeded, circumstances become optimum for the downslope discharge of a large quantity of sediment by slumping or sliding. Because V_c is relatively small for tributaries away from the apex, such as those in Sumner Branch, and because the infilling rate for those tributaries may be relatively large, tributaries typically discharge into the branch gorge at a higher frequency than the discharge frequency of the gorge. Discharge volume depends primarily on the geotechnical character of the sediment in the depression, especially at the seaward, or toe, part the deposit in the gorge, and on the triggering mechanism. Discharge typically occurs along a plane of failure within the sediment when the internal strength of the deposit is exceeded by the normal load of sediment in the canyon head. As it decomposes, organic material which had initially increased the internal strength of the sediment mat, ceases to bind the grains of sand together. The decomposed

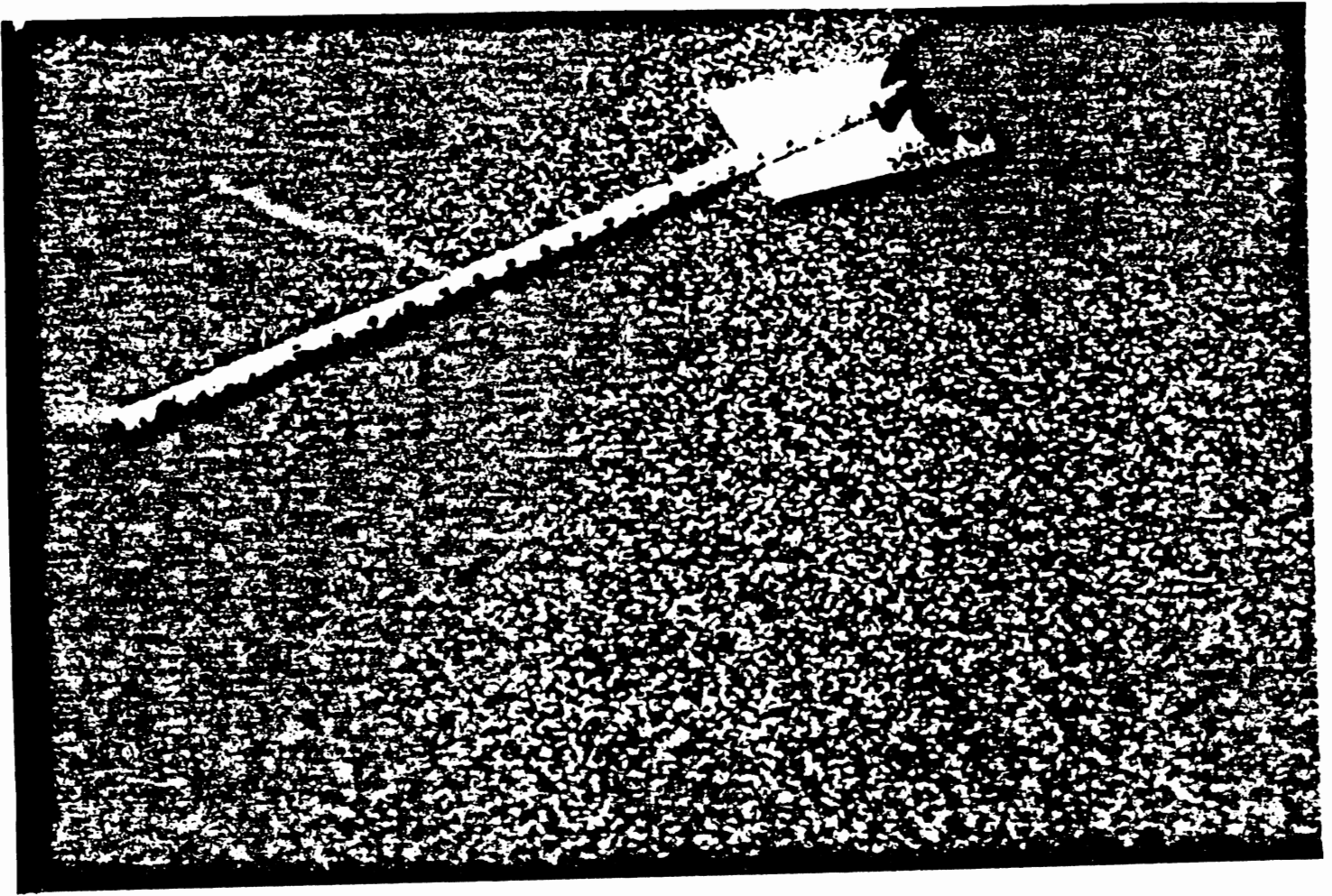


Figure 47. Typical small-scale surface slump on a slope of 18 degrees in the upper depression of Sumner Branch.

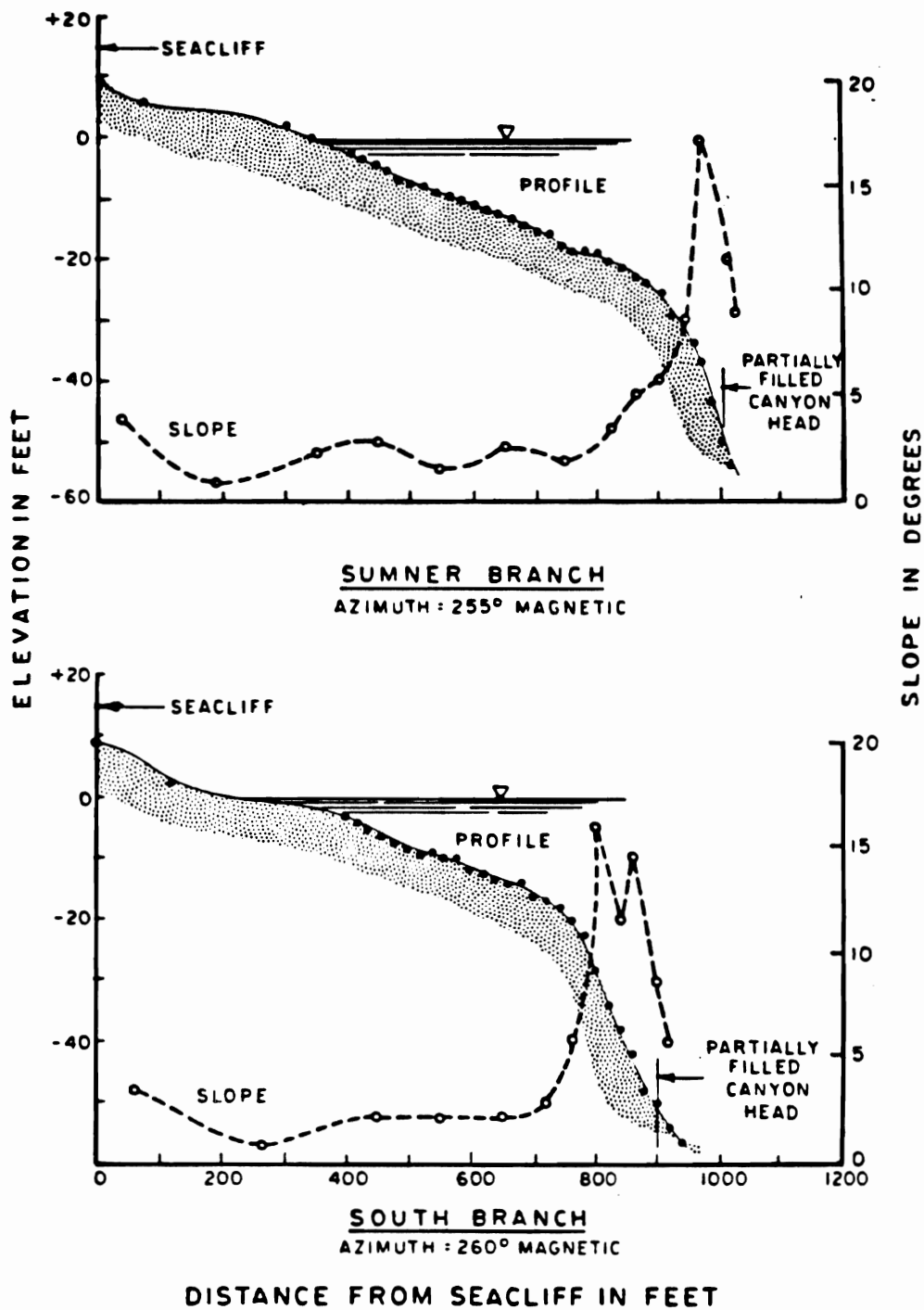


Figure 48. Profiles across the littoral zone through the depressions of Sumner and South Branches, November 1986; note the steepest slopes were created by a delta-like progradation of the deposit at the upper boundary of the depressions.

algal leaves are broken into a slick gelatinous goo that lubricates the zones of failure. After the large slump in Sumner Branch in March 1987, for example, the slip surface was observed to be a reduced, decomposed organic layer near the bedrock bottom. As the strength of the gorge deposit declined with time, sand carried from the littoral zone into the head of the depression increased the normal load. Typically large slumps and slides occur when the canyon head fills to near capacity during a storm. The relationship between sediment discharge and storms was cited by Chamberlain (1960), and Dill (1964). The five large canyon-head discharges during this investigation were all associated with storm-induced high wave conditions.

Beginning after a massive slump the next discharge cycle typically follows the sequence of events given below:

- (1) Sand is carried from the littoral zone into the newly deepened depression; mica and organic debris are carried into the gorge; fresh organic material forms a high-strength mat in the gorge.

- (2) The depression fills, the depth at its upper boundary increases and the distance of the upper boundary from shore increases. Littoral sediment must move farther from shore to reach the depression and the infilling rate declines.

- (3) The surface of the depression reaches a critical slope (about 18 degrees) and sand moves downslope in the depression as shallow slumps, typically closely spaced, but covering individual surface areas of less than 10 ft².

- (4) Sediment continues to accumulate in the gorge and buried organic material decomposes in a reducing environment emitting methane and carbon dioxide gas.

- (5) The internal strength of the lower canyon-head deposit is reduced as the organic material decomposes, often in layers separated by fingers of mica and fine-grained littoral sand.

- (6) The normal load on the marginally stable sediment deposit in the gorge is increased as the prograding sand body in the depression advances seaward into the gorge.

(7) Sediment enters the upper part of the depression, perhaps rapidly, during a storm when large quantities of littoral sand are carried seaward. This body of sediment thickens until the normal load exceeds the internal strength of the canyon-head deposit and a slump or slide occurs along a plane of weakness in the gorge. Sediment in the upper gorge and depression is carried downslope into a deeper part of the main canyon gorge or out of the canyon completely. The slump or slide moves downcanyon and overrides older sediments, overloading them and triggering a series of progressive slumps downcanyon.

The massive slump or slide need not occur during or just following a wave storm. A significant increase in the normal load is not a prerequisite for the discharge. It can occur with a fixed load when the internal strength of the deposit is reduced by the progressive decomposition of organic debris in the gorge.

Slumps and slides erode the sidewalls, headwall, and floor of the gorges. Evidence of this erosion is clear following a large slump. The sidewalls are striated and polished; pear-shaped pholad burrows in the upper sidewalls are truncated; the sidewall surface appears smoother toward the floor of the gorge where abrasion was greater; plucking scars are visible where rocks that had previously been a part of the sidewall were pulled loose; and blocks of bedrock are visible on the floor of the gorge.

4. Submarine Canyon Erosion. The sloping or vertical rock walls of the heads of Scripps and La Jolla Canyons appear to be eroding, although at different rates depending on the erodability of the rock and the capacity of the erosive agent to remove the rock. Future shoreline behavior will be partially dependent upon the rate of wall retreat because the location of the canyon-head depression is controlled by the location of the landward part of the gorge. In turn, the infilling rate of the depression is to a large extent directly controlled by its distance from the shoreline. The bedrock shape and slope of the depression and the thalweg slope of the gorge are important controls on the discharge rate.

All other factors being equal, if the headwall retreat rate of a submarine canyon exceeds the retreat rate of the adjacent shoreline the amount of

littoral sand deposited in the canyon will increase. The tendency of the adjacent shoreline to retreat at greater rate will also increase.

Rock type is shown in Table 11. The compacted muds and silts that crop out on the upper headwall of La Jolla Canyon are young. Shepard and Dill (1966) conclude they were formed during the last 0.6 to 1.5×10^4 years in a protected lagoonal environment. As sea level rose the lagoon retreated landward into the valley of Soledad Canyon. The head of La Jolla Canyon also retreated, and continues to retreat in an eastward direction. Dill (in Shepard and Dill, 1966) dated a root he found in the headwall at a depth of 75 ft at 8270 ± 500 yr BP. Noting the root was found at a location when the headwall was 780 ft seaward of the most landward present position of the headwall, Dill concluded the nearcoast headwall must have retreated at least 780 ft in the last 9×10^3 yr (about an average 0.1 ft/yr), and probably more.

TABLE 11. Character of Rock Walls in Scripps and La Jolla Submarine Canyons¹

<u>Submarine Canyon</u>	<u>Wall</u>	<u>Depth, feet</u>	<u>Rock Type</u>	<u>Type of Erosion</u>
1. La Jolla	headwall	40 to 130	compacted lagoonal muds and silts, some sand lenses, basal fanglomerate	block falls, abrasion by moving sand, burrowing organisms
2. Scripps Sumner Br.	headwall, upper sidewalls upper floor	70	silty shale	scour mainly by slow downslope movement of in-filled sediment mass
	lower sidewalls lower floor	120	conglomerate	
South Br.	headwall, sidewalls floor	40 to 130	mudstone	scour mainly by downslope movement of in-filled sediment mass

¹from Shepard and Dill, 1966

Headwall retreat in La Jolla Canyon was observed, during this study, to occur mostly as a result of blocks of compacted mud breaking away from the near-vertical cliff. Typical blocks were 0.5 to 1.0-ft thick by 1 to 5-ft long by 1 to 10-ft high (down the headwall). Near-vertical cracks in the headwall rock apparently formed by cyclic loading by waves. Block erosion mostly

occurred during wave storms when differential bottom pressures were greatest. The reflection of internal waves from the headwall and the weathering effects of burrowing organisms also may have played an erosional role. During the 30-month field study the top of the headwall in La Jolla Canyon retreated an estimated 0.5 ft when averaged along its entire length. Retreat was highly episodic and site-specific. The 0.2 ft/yr value is mostly based on observations of sediment traps lost because of blockfalls. Direct measurements of headwall retreat were not made. Erosion also occurred at a slow rate when sand passing over the crest of the headwall scoured the weak mud-silt rock.

Shepard and Dill (1966) cite an average headwall retreat rate of over 2 ft/yr in La Jolla Canyon between 1950 and 1960. Shapiro (1988, pers. communication) noted the severe wave storm of January 1988 caused mud blocks to spall from most of the length of the canyon rim. Wave periods were short (10 sec) during the storm. Consequently the effects of refraction were less than during most other storms and wave heights were relatively large over the canyon rim.

Headwall and sidewall erosion rates in Scripps Submarine Canyon are unknown but appear to be lower than they are in La Jolla Canyon. Blocks occasionally fall from the sidewalls of Scripps Canyon and remain for a while on the shallow gorge floor. Shale clasts and pebbles from the rock bottom above the rim were often found in sediment traps. Some, but surely not all, may have come from the littoral zone and local seacliffs.

VIII. SUMMARY AND CONCLUSIONS

In 1984 a 30-month long field investigation was begun in San Diego County, California: (1) to determine which of the three submarine canyons that approach or pierce the littoral zone of the Oceanside Littoral Cell are active sand traps, and (2) to quantify the rate at which littoral sand was lost to and discharged downslope from the shallow heads of the active canyons. A reconnaissance field survey made in December 1984 showed Carlsbad Submarine Canyon is not presently diverting littoral sands into deep water and is not an active sink for littoral sand. A review of the literature and unpublished data also supported this conclusion.

Detailed underwater observations and measurements were made in Scripps and La Jolla Submarine Canyons between December 1984 and June 1987 to quantify canyon-head sedimentation rates. Three methods were used to quantify sediment volume changes. Marked traverse lines strung across the rocky canyon rims were used to monitor the levels of sediment filling and to establish deepenings and shoalings in the narrow rock gorges. Sediment traps fastened to or below the rock rims were used to measure the cross-rim movement of littoral sand. In the broad shallow sediment depressions landward of the steep, rock-walled gorges, sand level changes were referenced to vertical survey rods emplaced in the sand to determine sand level changes.

Littoral sand was trapped at an average annual rate of about 29,000 yd³/yr in the depressions and gorges of the shallow, narrow heads of Scripps Canyon, and in the broad, wide gorge of La Jolla Canyon. Uncertainties, introduced by the frequency at which measurements were made and by the extent and density of the measurement grid, suggest the sand entrapment rate was between 18,000 yd³/yr and 40,000 yd³/yr.

Littoral sand is transported seaward from the littoral zone and preferentially trapped in the deeper, quieter waters of the sediment depressions. As the depression fills, the deposit progrades seaward in a delta-like manner. Kelp and seagrass debris and lesser quantities of mica, because of their low settling velocities, move further out and accumulate in the deeper gorges along with minor amounts of littoral sand. Sand deposited in the depression has the same size distribution as sand in the littoral zone.

The gorges and depressions fill toward what appears to be a critical volume. When eventually the critical volume is reached, the normal load of sediment exceeds the internal strength of the deposit and the sediment mass becomes unstable. Storms can cause rapid filling of the depression with sediment which, in turn, triggers the mass downslope movement. During storms in December 1984, and again in March and April 1987, for example, massive slumps carried the accumulated sediment in Sumner and South Branches into deep water beyond diver observation depths. The flushing frequency for those branches was about 0.4/yr during the field measurement period. Sediments in the low gradient, shallow gorges of Shepard Branch and valleys south of South Branch are discharged at a much lower frequency, perhaps 0.025/yr. The discharge frequency for North Branch may be similarly low. North Branch is probably a relic head of Scripps Canyon formed when sea level was rising and transgressing the Continental Shelf following the last ice age. It is large, its infilling rate is low, and it takes a long time to reach an infill capacity such that its deposit becomes unstable. In the younger, higher-gradient, steep gorges and shallow-water depressions of Sumner and South Branches, which pirate sediment that would have entered North Branch, the discharge frequency is much higher. The release rate for sediment deposited below the rim of La Jolla Canyon is unknown.

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X. NOTATION

- V_d = total volume of sediment transported to and deposited in the depression of a submarine canyon (L^3)
- V_g = total volume of sediment transported to and deposited in the gorge of a submarine canyon (L^3)
- V_{1d} = volume of littoral sediment transported to and deposited in the depression of a submarine canyon (L^3)
- V_{1g} = volume of littoral sediment transported to and deposited in the gorge of a submarine canyon (L^3)
- P_{id} = portion of total inorganic sand volume (excluding mica) of littoral sediment size that is trapped in the depression (dimensionless)
- P_{ig} = portion of total inorganic sand volume (excluding mica) of littoral sediment size that is trapped in the gorge (dimensionless)
- V_{id} = volume of inorganic sediment, excluding mica, transported to and deposited in the depression (L^3)
- V_{ig} = volume of inorganic sediment, excluding mica, transported to and deposited in the gorge (L^3)
- P_{md} = portion of mica in the total sediment volume in the depression (dimensionless)
- P_{mg} = portion of mica in the total sediment volume of the gorge (dimensionless)
- P_{od} = portion of organic material in the total sediment volume in the depression (dimensionless)

P_{og} =

portion of organic material in the total sediment volume in the gorge (dimensionless)