AGGRADATION AND DEGRADATION OF ALLUVIAL SAND DEPOSITS, 1965 TO 1986, COLORADO RIVER, GRAND CANYON NATIONAL PARK, ARIZONA—EXECUTIVE SUMMARY

By John C. Schmidt and Julia B. Graf

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DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information write to:

District Chief
U.S. Geological Survey
Box FB-44
Federal Building
300 West Congress Street
Tucson, Arizona 85701-1393

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CONVERSION FACTORS

For readers who prefer to use metric units (International System), conversion factors for the inch-pound units in this report are listed below:

Multiply inch-pound unit	By	To obtain metric unit
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

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ABSTRACT

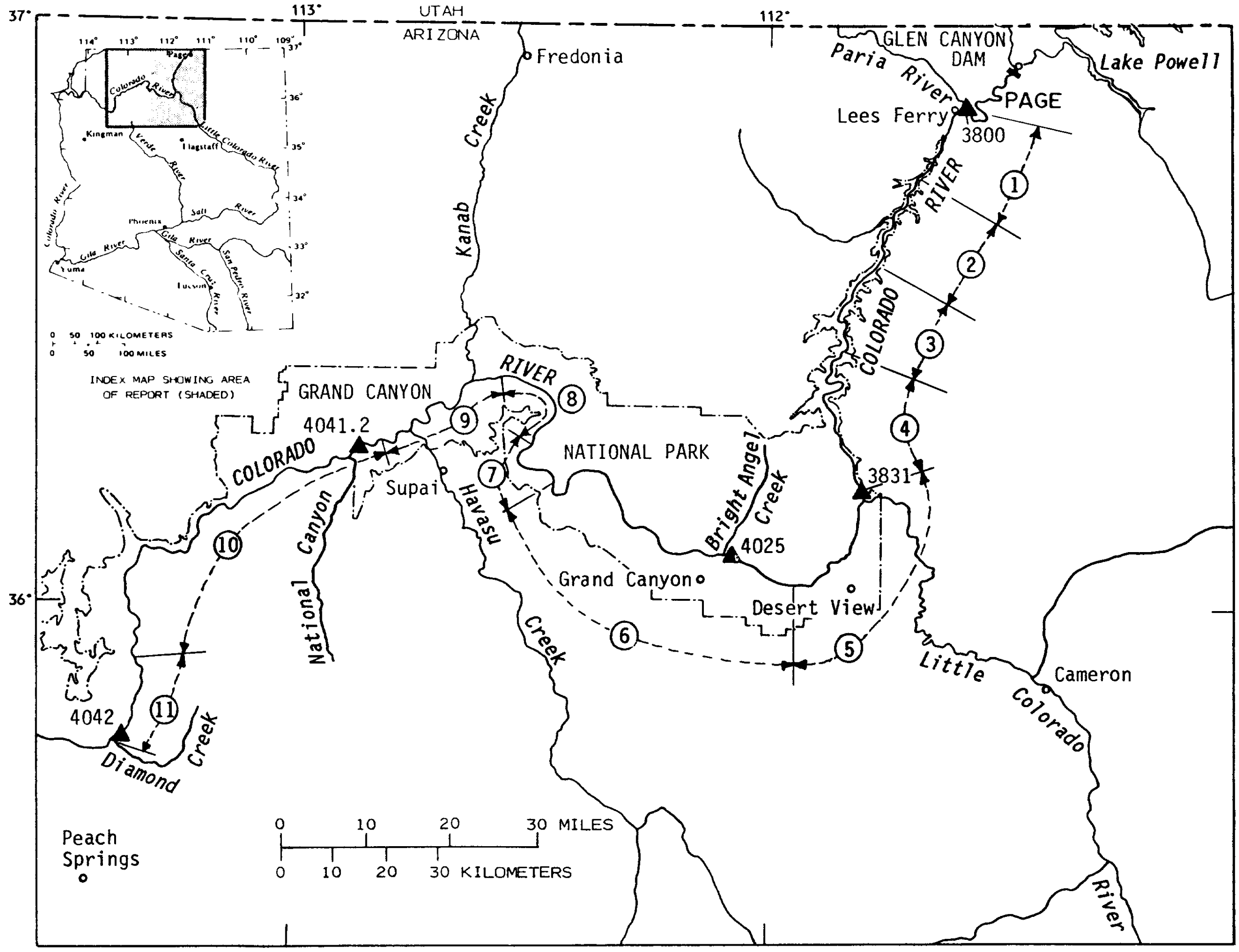
High discharges that occurred in 1983-85 resulted in redistribution of sand stored in zones of recirculating current in the Colorado River in Grand Canyon National Park. Redistribution resulted in net loss in the number of reattachment deposits in narrow reaches and aggradation of some separation deposits. Separation deposits were more stable than other types of deposits. Alluvial sand deposits that are large enough and of sufficient areal extent for use as campsites were more stable than smaller lower-elevation deposits. Fluctuating flows between October 1985 and January 1986 caused erosion throughout the Grand Canyon and caused erosion of some deposits created by the high flows of 1983-85.

INTRODUCTION

Alluvial sand deposits along the Colorado River in Grand Canyon National Park are used as campsites and are substrate for riparian vegetation (fig. 1). The purposes of this report are to (1) present a classification of alluvial sand deposits in the Colorado River, (2) describe major characteristics of the deposits, and (3) describe changes in these deposits that have occurred since 1965, especially changes that occurred from 1973 through January 1986.

Previous studies on the effects of operations of Glen Canyon Dam, completed in 1963, on alluvial sand deposits along the Colorado River yielded conflicting results. Howard and Dolan (1981) found that alluvial sand deposits along the Colorado River throughout the Grand Canyon had achieved stable profiles by the late 1970's. Brian and Thomas (1984) concluded that high discharges in 1983 had caused degradation in sand deposits used as campsites within 173 river miles downstream from Lees Ferry. Beus and others (1985) concluded that the high discharges of 1983 resulted in aggradation of the same type of sand deposits studied by Brian and Thomas (1984). Beus and others (1985) based their conclusions on repeated surveys of 19 alluvial sand deposits, and Brian and Thomas (1984) based their conclusions on comparison of inventories of all sand deposits used as campsites.

For most of its course through Grand Canyon National Park, the width of the Colorado River is constrained by bedrock and large talus blocks. Debris fans at the mouths of steep ephemeral tributaries



EXPLANATION

① PERMIAN SECTION

② SUPAI GORGE

③ REDWALL GORGE

④ LOWER MARBLE CANYON

⑤ FURNACE FLATS

⑥ UPPER GRANITE GORGE

⑦ AISLES

⑧ MIDDLE GRANITE GORGE

⑨ MUAV GORGE

⑩ LOWER CANYON

⑪ LOWER GRANITE GORGE

Figure 1.--Grand Canyon National Park, Arizona, and reaches within the study area.

partially block the river's course and form riffles or rapids. Notable geomorphic features of the channel in the vicinity of debris fans are (1) the channel constriction, which is a shallow and narrow channel near the apex of the debris fan; (2) a scour hole immediately downstream from the channel constriction; and (3) an expansion in channel width downstream from the scour hole (fig. 2). At a broad range of discharges, large zones of recirculating current exist in the channel expansion. The largest and most numerous alluvial sand deposits along the Colorado River are associated with these zones of recirculating current.

Downstream from most constrictions, recirculation zones exist at discharges that range from at least 4,000 to 45,000 ft^3/s. At most sites, recirculation zones increase in length with increasing discharges up to at least 45,000 ft^3/s. Lengthening of recirculation zones usually occurs by upstream migration of the separation point, which is the point at which downstream-directed flow becomes detached from the channel banks. Lengthening also occurs by downstream migration of the reattachment point, which is the point where downstream-directed flow is reattached to the channel banks (fig. 3).

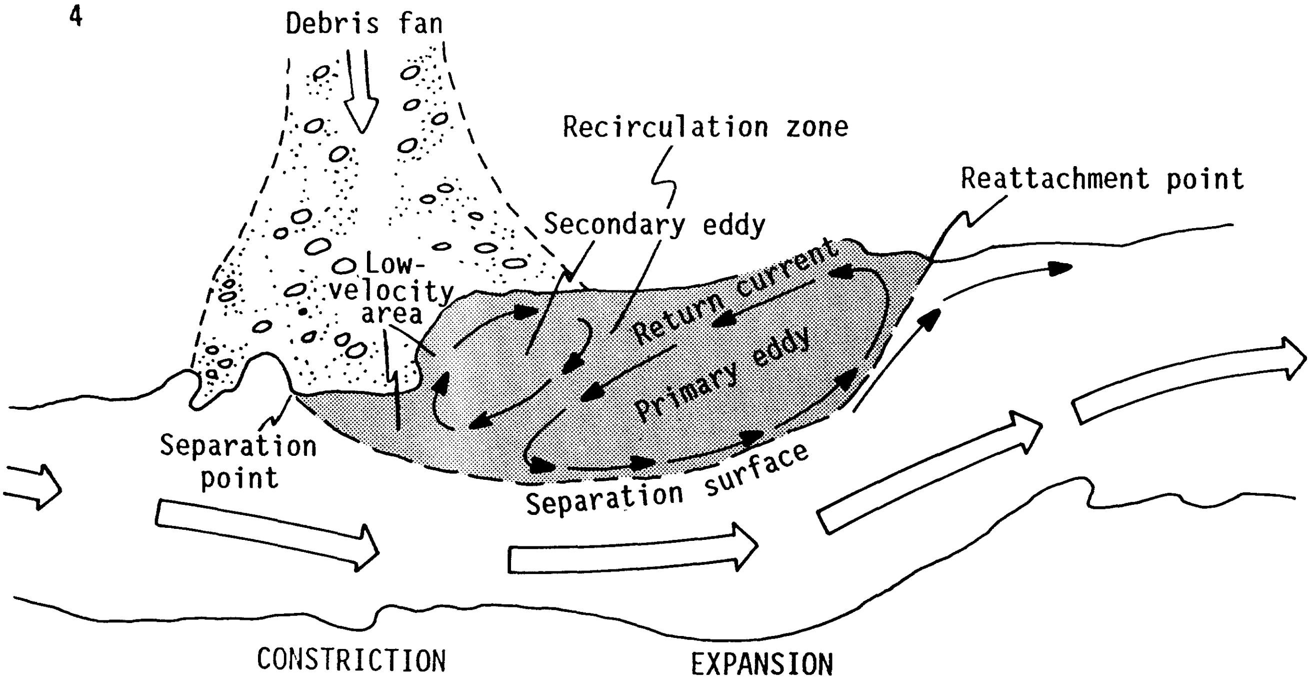
Flow patterns are similar in recirculation zones throughout the Grand Canyon, and specific parts of recirculation zones can be distinguished. Recirculation zones are composed of one or more eddies. All recirculation zones have a primary eddy and may have a secondary eddy located upstream from the primary eddy (fig. 2A). That part of the primary eddy where direction of flow is opposite the main downstream current is referred to as the primary-eddy return current. Other parts of recirculation zones are not organized into a rotation and are referred to as low-velocity areas.

Because channel characteristics of the Colorado River vary with the types of bedrock that are exposed at river level, reaches of the river were defined on the basis of average channel top width, average channel shape, reach slope, and relation to major tributaries. Eleven reaches of the Colorado River were defined (table 1). The narrowest reaches are Upper Granite Gorge, Supai Gorge, and Muav Gorge. The widest reaches are Lower Marble Canyon, Furnace Flats, and the Lower Canyon (fig. 1).

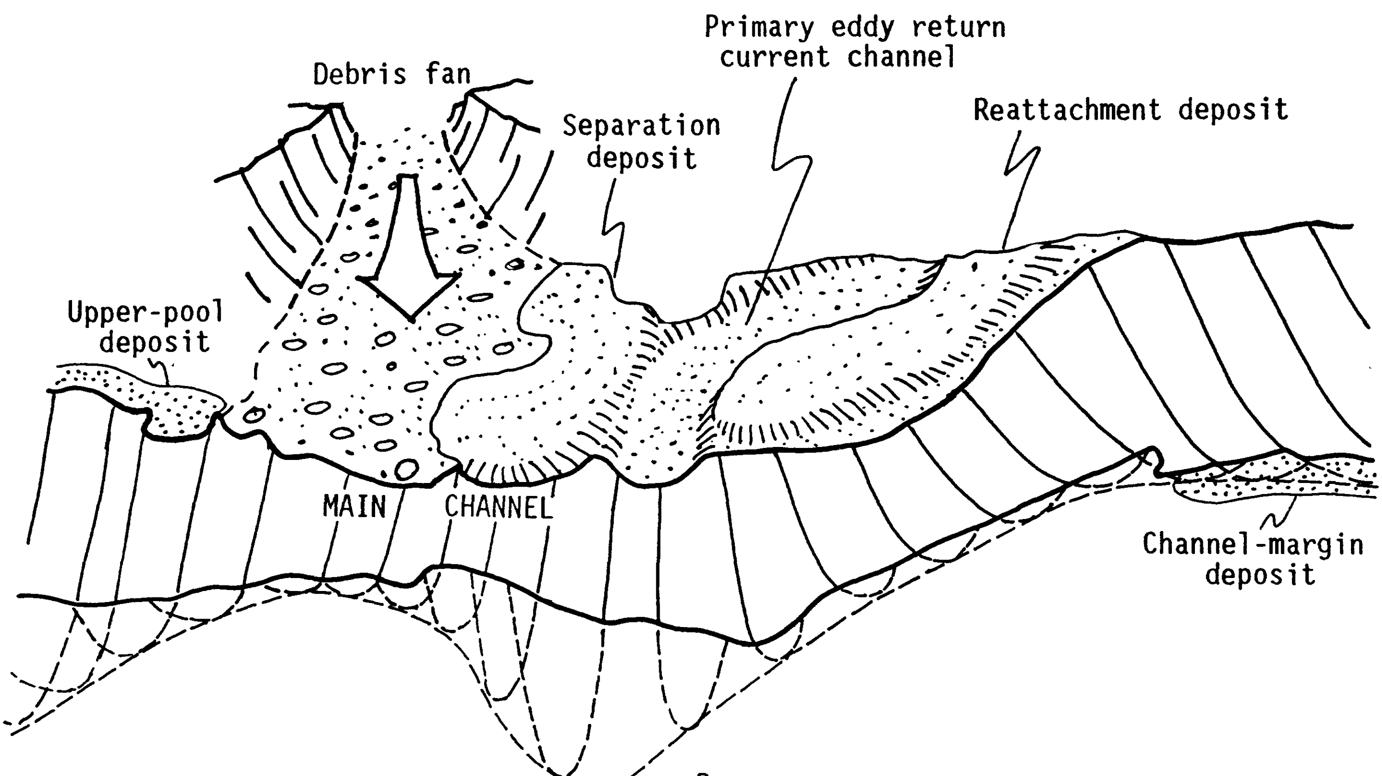
METHODS OF STUDY

Data collected for this study included measurements of flow velocity, scour-and-fill of sand deposits, topographic and bathymetric surveys, mapping of surface-flow patterns, water-surface slope surveys, sedimentological analysis, and replication of photographs. Forty-one study sites representative of different types of alluvial sand deposits used as campsites in most major reaches of the Colorado River were selected. A classification system of alluvial sand deposits was developed on the basis of morphometric characteristics and the location of these deposits in relation to parts of recirculation zones. Earlier data such as aerial photography and topographic surveys also were studied.

Two types of analysis of historical changes between 1973-84 were done: (1) analysis of change in alluvial deposits in all



A.



B.

Figure 2.--Flow patterns and configuration of bed deposits in a typical recirculation zone. A, Flow patterns. B, Configuration of bed deposits.

recirculation zones and (2) analysis of change in those recirculation zones where designated campsites are located. The first analysis was done for 399 recirculation zones between Lees Ferry and river mile 117.8. The second analysis was done for recirculation zones between Lees Ferry and river mile 35.9 and between river miles 122 and 160. The second analysis was done in about 45 percent of the total number of recirculation zones. The first analysis was an inventory of each recirculation zone in which the presence or absence of deposits was noted. Areas were not measured because in some reaches, stage differed significantly in the 1973 and 1984 photographs. The changes in number of deposits reflect significant sediment storage changes in all recirculation zones. The second analysis involved planimetering exposed areas of sand in reaches where stages were similar in 1973 and 1984. The results of the second analysis reflect changes in area of sand exposed at low discharge of those recirculation zones of most concern to whitewater boaters—those zones with designated campsites as identified by Brian and Thomas (1984). Topographic changes between 1965-73 at 17 alluvial deposits also were done on the basis of aerial photograph comparisons.

RESULTS

Characteristics and Classification of Alluvial Sand Deposits

Sand is stored primarily in main-channel pools and in recirculation zones. Sand stored in recirculation zones generally is very well sorted and fine to very fine grained in size, whereas sand stored in channel pools generally is medium in grain size.

The pattern of sand deposition in recirculation zones is remarkably consistent throughout the Grand Canyon. Two types of sand deposits within recirculation zones—separation deposits and reattachment deposits—are highest in elevation and are used most by whitewater boaters as campsites (fig. 2B). Separation deposits mantle the downstream part of tributary debris fans and are near the separation point. Reattachment deposits are located at the downstream end of recirculation zones, project upstream into the center of the zones, and are near the reattachment point.

Alluvial sand deposits also may be immediately upstream from constrictions. This type of deposit is referred to as an upper-pool deposit. Deposits whose origin could not be determined on the basis of planimetric shape or location are referred to as channel-margin deposits. Separation and reattachment deposits are not located in every recirculation zone. Where they do occur, however, the location and form in relation to debris fans is consistent from site to site.

Separation deposits form in low-velocity areas and in secondary eddies upstream from the primary-eddy return-current. The formation of a bar within a secondary eddy and the upstream migration of this bar onto

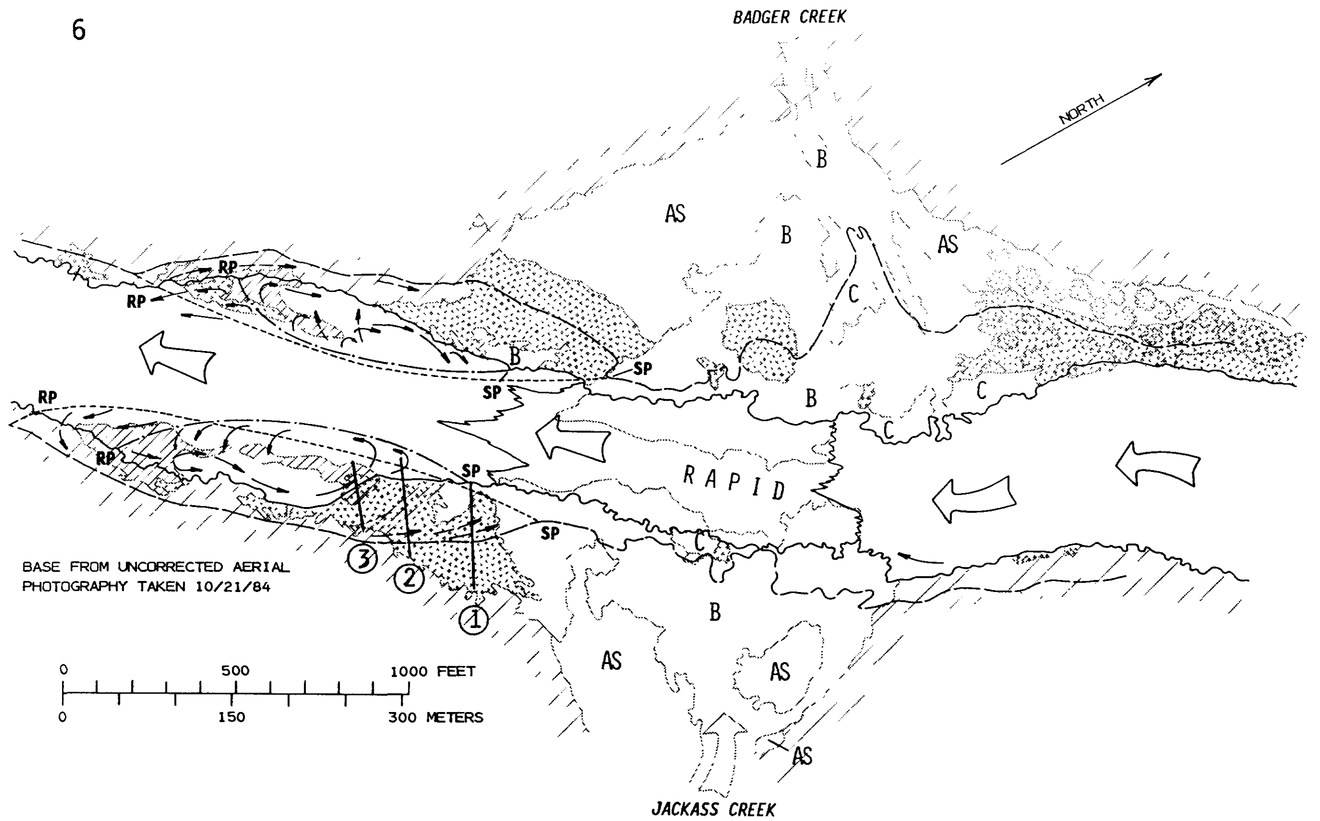


Figure 3.--An example of migration of separation and reattachment points with changing discharge, Badger Creek Rapid.

EXPLANATION

Symbol	Explanation
	RIVER-DEPOSITED OR REWORKED VERY FINE TO MEDIUM SAND (October 21, 1984)
AS	AEOLIAN SAND OR TERRACE DEPOSITS—Silt and fine sand, well sorted
B	TRIBUTARY DEBRIS FAN—Boulders, cobbles, gravel, sand, poorly sorted; boulders cover more than 50 percent of surface area except in tributary streambed
C	COBBLES AND GRAVEL
	TALUS AND BEDROCK
	ADDITIONAL RIVER-DEPOSITED SAND (1973)
	EDGE OF WATER
	Low flow, October 5, 1985, 5,600 cubic feet per second
	High flow, May 20, 1985, 44,000 cubic feet per second
	SEPARATION SURFACE
	Low flow
	High flow
	GENERALIZED SURFACE-FLOW DIRECTION IN RECIRCULATION ZONES
	Low flow
	High flow
	Surface-flow direction of main current
RAPID	LIMIT OF BREAKING WAVES (WHITE WATER) AT LOW FLOW—At high flow, breaking waves in main current extend downstream to a point opposite center of recirculation zones
	DENSE STANDS OF TAMARISK
SP	SEPARATION POINT
RP	REATTACHMENT POINT

Figure 3.

Table 1.--Characteristics of the reaches within the study area

Reach, in miles[1]	Reach name and number	Average ratio of top width to mean depth[2]	Average channel width, in feet[2]	Width character	Channel slope[3]	Average unit of stream power, in pounds per foot[4]	Percentage of bed composed of bedrock and boulders
0-11.3	Permian Section (1)	11.7	280	Wide	0.00099	5.3	42
11.3-22.6	Supai Gorge (2)	7.7	210	Narrow	.0014	10.2	81
22.6-35.9	Redwall Gorge (3)	9.0	220	Narrow	.0015	10.2	72
35.9-61.5	Lower Marble Canyon (4)	19.1	350	Wide	.0010	4.3	36
61.5-77.4	Furnace Flats (5)	26.6	390	Wide	.0021	8.0	30
77.4-117.8	Upper Granite Gorge (6)	7	190	Narrow	.0023	17.6	62
117.8-125.5	Aisles (7)	11	230	Narrow	.0017	10.9	48
125.6-139.9	Middle Granite Gorge (8)	8.2	210	Narrow	.0020	14.2	68
140-159.9	Muav Gorge (9)	7.9	180	Narrow	.0012	9.9	78
160-213.8	Lower Canyon (10)	16.1	310	Wide	.0013	6.2	32
213.9-225	Lower Granite Gorge (11)	8.1	240	Narrow	.0016	10.2	58

[1]See figure 1.

[2]Average of cross-section data at about 1-mile intervals at 24,000 cubic feet per second (Randle and Pemberton, 1987).

[3]Based on predicted water-surface elevations at 24,000 cubic feet per second (Randle and Pemberton, 1987).

[4]Unit stream power is calculated as equal to: (Specific weight of water)(24,000 cubic feet per second) (slope of reach)/(average channel width).

[5]From channel-bed material maps (Wilson, 1987).

the debris fan was documented at some sites during high flows in May and June 1985. This process may be responsible for the formation of many separation deposits. Large parts of many separation deposits form at discharges in excess of 30,000 ft^3/s.

Reattachment deposits occur at the downstream end of many recirculation zones and project upstream as spits. A slipface typically exists along the bank side of the spit. Sand is transported across the top of the bar, cascades down the slipface, and is swept upstream by the primary-eddy return-current. Sand transported upstream by the return-current may be delivered to the main current or be recycled within the recirculation zone. Reattachment deposits fill recirculation zones to a varying extent. Substantial reworking of reattachment deposits may occur at high discharges. Reworking of reattachment deposits probably occurs at lower discharges than for separation deposits.

Distribution of Deposits

Alluvial deposits large enough for use as campsites are most numerous in Lower Marble Canyon, Furnace Flats, Aisles, Middle Granite Gorge, and Lower Canyon (table 2). The channel in most of these reaches is wide, and the size of alluvial sand deposits is greatest in wide reaches. The number of campsites in narrow reaches is limited and in some reaches is less than one campsite per mile. For example, at a discharge of 5,600 ft^3/s in October 1984, average campsite size was 60,000 ft^2 in Lower Marble Canyon but was only 8,200 ft^2 in the narrower Muav Gorge. The increase in number and size of campsites in wide reaches is related to increase in number and size of reattachment and channel-margin deposits. At a discharge of 5,600 ft^3/s in October 1984, channel-margin deposits had an average size of 73,000 ft^2 in Lower Marble Canyon but had an average size of only 7,500 ft^2 in Muav Gorge. Reattachment deposits large enough to be used as campsites are numerous only in parts of Lower Marble Canyon, Aisles, and Lower Canyon. The size of separation deposits is greatest in wide reaches; the number of deposits, however, does not vary with width. Local topography of debris fans is the most important determinant in the occurrence of separation deposits.

Changes in Alluvial Deposits, 1973-84

Between June 1973 and May 1983, discharge typically fluctuated on a daily basis in response to hydroelectric generation requirements at Glen Canyon Dam. In contrast, discharge was much higher and steadier between June 1983 and October 1984. Peak discharge at Lees Ferry reached 97,300 ft^3/s in June 1983 and 58,200 ft^3/s in August 1984. Discharge did not vary in relation to hydroelectric-power production. Between October 21 and 23, 1984, flow decreased to about 5,600 ft^3/s, and aerial photographs of the river corridor were taken.

Changes in the area of exposed sand deposits between 1973-84 were measured in order to evaluate the effects of high discharges in 1983 and 1984. It was assumed that changes that occurred between 1973-84 were

Table 2.--Characteristics of recirculation-zone deposits in selected reaches

Reach number[1]	Campsites per mile[2]	Primary type of deposit used as campsite[3]	Number of recirculation zones per mile	Average area of deposits, in square feet			Total area of major deposits, in square feet[4] [5]
				All types	Separation	Reattachment	
1	0.4	Separation	3.2	51,000	57,000	31,000	410,000
2	0.9	Separation	3.6	23,000	30,000	16,000	510,000
3	0.9	Separation	4.5	25,000	21,000	47,000	540,000
4	2.6	Separation and reattachment	4.5	60,000	49,000	87,000	4,700,000
5	2.5	Channel margin	2.3	([6])	([6])	([6])	([6])
6	0.6	Separation and channel margin	2.7	([6])	([6])	([6])	([6])
7	3.2	Reattachment, separation, and channel margin	([6])	25,000	26,000	35,000	920,000
8	2.3	Channel margin	([6])	22,000	17,000	34,000	900,000
9	1.1	Channel margin	([6])	8,200	14,500	2,300	240,000
10	2.4	([6])	([6])	([6])	([6])	([6])	([6])
11	2.3	([6])	([6])	([6])	([6])	([6])	([6])

[1]See figure 1.
[2]Inventoried by Brian and Thomas (1987).
[3]Listed in order of importance.
[4]Measured area is that exposed at about 5,600 cubic feet per second in October 1984.
[5]Major deposits are those alluvial sand deposits inventoried as campsites in 1973 or 1984 as well as other deposits in the same recirculation zones. Major deposits are in about 45 percent of all recirculation zones.
[6]Not evaluated.

due primarily to high discharges in 1983 and 1984 because (1) peak discharges were much higher and of longer duration than during any other part of the 1973-84 period, (2) Beus and others (1985) showed that alluvial sand deposits did not change significantly between 1975-80, and (3) Beus and others (1985) showed that alluvial deposits changed significantly because of the high flows of 1983 and 1984. In 1980, discharge at Lees Ferry exceeded 30,000 ft^3/s for 9 days and the effect of these flows is uncertain. In 1983 and 1984, discharge exceeded 30,000 ft^3/s for 149 days and exceeded 40,000 ft^3/s for 120 days.

On the basis of the inventory of separation and reattachment deposits in all recirculation zones between Lees Ferry and river mile 118, sand was eroded from recirculation zones in narrow reaches, regardless of distance downstream from Glen Canyon Dam (table 3). The greatest decrease took place in Upper Granite Gorge, the narrowest and steepest reach evaluated (table 1). The number of recirculation zones with separation or reattachment deposits in wide reaches increased between 1973-84, indicating that the volume of sand stored in recirculation zones in wide reaches may have increased.

Measurements of change in area of major alluvial sand deposits in reaches where discharges in 1973 and 1984 were similar indicate that the largest and highest alluvial sand deposits are less susceptible to change than are other alluvial deposits. Summation by reaches of all increases and decreases in area indicates that no significant change in total area of major alluvial sand deposits occurred in any reach, except between Lees Ferry and mile 11.3. All change measured in that reach was due to erosion of one point-bar deposit. Summation of net-area change of separation and reattachment deposits by reach indicates that significant decreases occurred in separation deposits in Muav Gorge and in reattachment deposits in Supai Gorge.

The general susceptibility to change of separation and reattachment deposits was also evaluated. Summation of the number of major separation and reattachment deposits that increased or decreased in area showed that in most reaches reattachment deposits are more susceptible to change than are separation deposits. Of the total number of separation deposits evaluated, about 40 percent did not change in area. Of the total number of reattachment deposits evaluated, about 20 percent did not change in area (table 4). The inventory of alluvial sand deposits in all recirculation zones also indicated that reattachment deposits had more changes than separation deposits. In all but one reach, the number of reattachment deposits that increased or decreased in occurrence exceeded the number of separation deposits that increased or decreased in occurrence (table 3). These results confirmed an analysis of change in size of all alluvial deposits between Lees Ferry and river mile 20 (Schmidt, 1986), which showed that separation deposits are more stable than reattachment deposits. Comparison of the area of sand exposed at about 25,000 ft^3/s in 1973 and 1984 indicates that vertical aggradation of separation and channel-margin deposits occurred at many sites and is consistent with that determined by Beus and others (1985).

Table 3.--Number of separation and reattachment deposits in recirculation zones

Reach number	Total number of recirculation zones surveyed	Relation of 1984 stage to 1973 stage[1]	Deposit type: Reattachment 1973	Reattachment 1984	Separation 1973	Separation 1984
1	36	Higher	31	28	18.5	19.5
2	40	Higher	27	20.5	26	26
3	60	Higher	37.5	34	38.5	29.5
4	115	Lower	96.5	100.5	49.5	50
5	37	Lower	28	32	23.5	25
6	111	Lower	78.5	68.5	28.5	27.5
Total	399		298.5	283.5	184.5	187.5

[1]Based on comparison of observed stage in aerial photographs.

Table 4.--Number of deposits that experienced changes in selected reach segments, 1973-84

Reach number	Separation			Reattachment			Channel margin			Upper pool		
	Gain	Loss	No change	Gain	Loss	No change	Gain	Loss	No change	Gain	Loss	No change
1	1	0	3	2	2	1	0	0	0	0	0	0
2	4	3	6	0	6	1	0	0	0	0	2	1
3	2	6	6	1	1	2	0	0	0	0	1	2
7[1]	1	1	0	2	0	1	7	2	0	1	0	1
8	6	3	5	2	2	0	7	9	4	0	1	2
9	0	4	3	1	0	0	10	4	3	0	1	0
Total	14	17	23	8	11	5	24	15	7	1	5	6

Types of deposits

[1]Includes miles 122-125.5 only.

Changes in Alluvial Deposits Resulting from High Flows in 1985

Limited data are available concerning changes. At each of four separation deposits that were surveyed, aggradation occurred in small areas associated with low-velocity areas upstream from the primary-eddy return current. Measurements at Eighteen Mile Wash indicate that scour may precede the period of fill. Each of three reattachment deposits surveyed degraded because of these high flows.

Changes in Alluvial Deposits Resulting from Fluctuating Flow, October 1985 to January 1986

Although parts of some alluvial deposits aggraded, all deposits experienced net degradation. Of 41 profile lines at 13 separation-deposit study sites, about one-fourth of the profiles showed aggradation and about three-fourths of the profiles showed degradation (fig. 4). The mean net change of separation deposits was -0.65 ft. Erosion in excess of 1 ft was measured at profiles at six sites—five of which are located in narrow reaches. At the end of the period of fluctuating flow, cutbanks existed at many sites, which indicated that profiles were not yet stable.

Comparison of topographic changes with local water slope and near-bank velocity indicate that neither steep water slope nor high near-bank velocity necessarily causes the greatest erosion. The fact that five of six sites with greatest erosion are located in the narrowest reaches indicates that the range of stage change is the most important factor in determining locations of degradation.

Sites where erosion was significant during fluctuating flow were also sites where aggradation was significant following high flows in 1983 and 1984. The only sites where this pattern was not obvious were in narrow reaches where high separation deposits were armored from further erosion by exposure of underlying debris fan deposits near the edge of the water. Fluctuating flows, therefore, significantly eroded those sites where aggradation from high discharges had occurred.

The upper surface of most surveyed reattachment deposits degraded during fluctuating flow. Bathymetric surveys of one site indicate that fluctuating flows tend to smooth out the distinctive topography of reattachment deposits. For example, sand removed from the crest of reattachment deposits may be deposited on the slope extending from the crest of the deposit to the channel thalweg.

Bathymetric surveys at three sites show that net volume changes can occur in recirculation zones at a broad range of discharges. At each of these sites, data indicate that large volumes of sand may be exchanged between recirculation zones and the main channel even at moderate or fluctuating discharges.

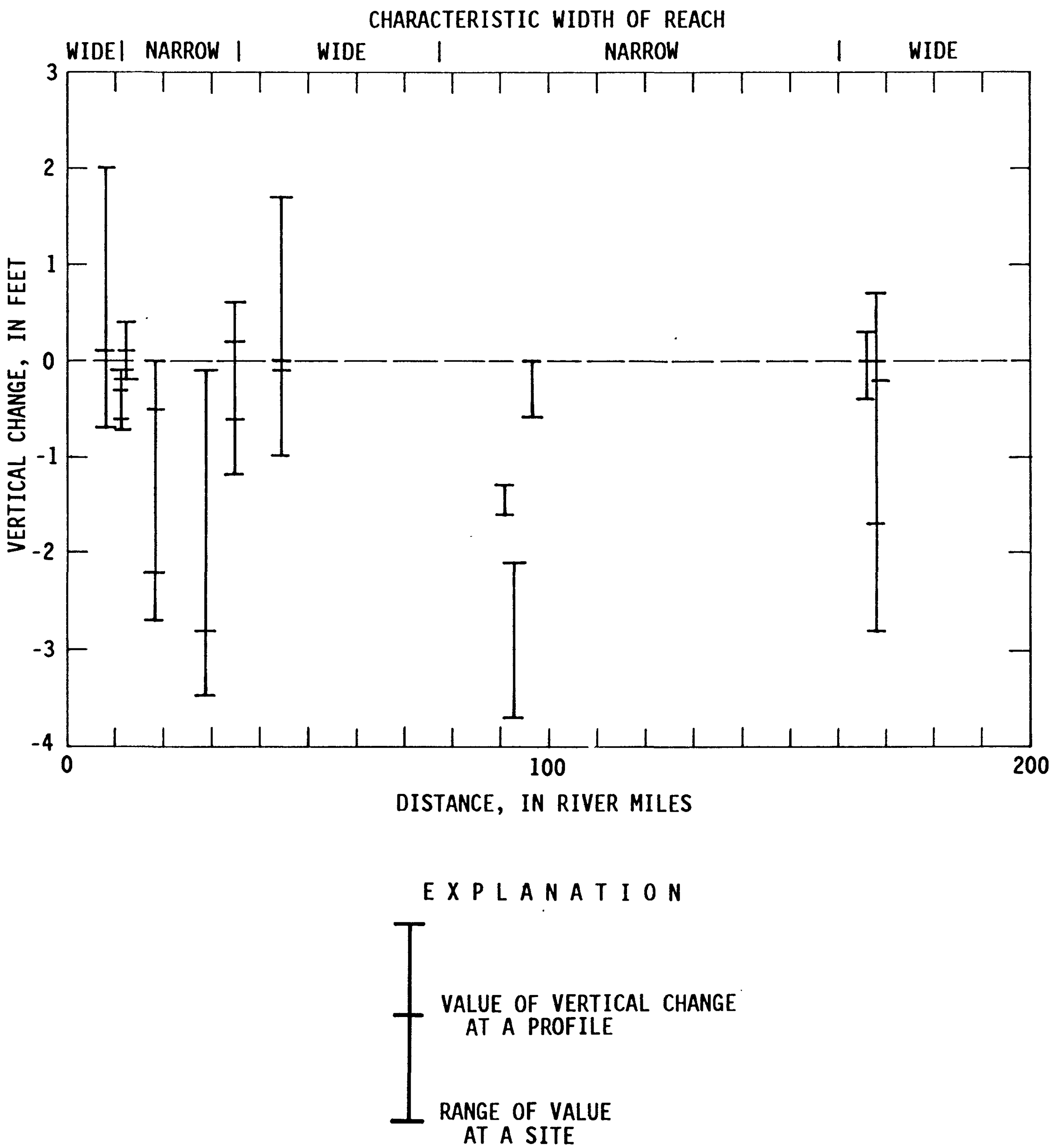


Figure 4.--Vertical change along profile lines at 13 separation deposits between October 1985 and January 1986.

DISCUSSION

Separation deposits are more stable than reattachment deposits. The greater stability of separation deposits can be related to the different environments of deposition of separation and reattachment deposits. Separation deposits form in lower-velocity areas of recirculation zones. At sufficiently high discharge, both types of deposits may be reworked; however, the threshold for such reworking is probably higher for separation deposits.

Fluctuating flows during the period October 1985 to January 1986 caused significant erosion throughout the Colorado River in Grand Canyon. Such erosion indicates that alluvial sand deposits formed or reworked by steady high flows such as occurred between June 1983 and September 1985 are unstable when initially exposed to fluctuating flows. Although erosion was significant throughout the Grand Canyon with the onset of fluctuating flows, results of topographic surveys in the late 1970's indicate that equilibrium profiles may develop after a number of years of fluctuating flows.

Generally high rates of degradation in alluvial sand deposits in narrow reaches indicates that campsites in these reaches may decrease over time. The number of campsites in these reaches are already limited. If loss of sand deposits continues, the disparity in campsite availability between narrow and wide reaches may be accentuated over time.

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