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Aggradation and Degradation of Alluvial Sand Deposits, 1965 to 1986, Colorado River, Grand Canyon National Park, Arizona

By JOHN C. SCHMIDT *and* JULIA B. GRAF

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CONVERSION FACTORS

For readers who wish to convert measurements from the inch-pound system of units to the metric system of units, the conversion factors are listed below:

Multiply inch-pound unit	By	To obtain metric unit
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square foot (ft^2)	0.0929	square meter (m^2)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
ton (short)	0.9072	megagram (Mg)

SEA LEVEL

In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Sea Level Datum of 1929."

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

By JOHN C. SCHMIDT and JULIA B. GRAF

ABSTRACT

Alluvial sand deposits along the Colorado River in Grand Canyon National Park are used as campsites and are substrate for vegetation. The largest and most numerous of these deposits are formed in zones of recirculating current that are created downstream from where the channel is constricted by debris fans at tributary mouths. Alluvial sand deposits are classified by location and form. Separation and reattachment deposits are downstream from constrictions within recirculation zones. Separation deposits are near the point of flow separation and typically mantle large debris fans. Reattachment deposits are near the point of flow reattachment and project upstream beneath much of the zone of recirculating current. Upper-pool deposits are upstream from a constriction and are associated with backwaters. Channel-margin deposits line the channel and have the form of terraces. Some are created in small recirculation zones.

Reattachment and channel-margin deposits are largest and most numerous in wide reaches, although small channel-margin deposits are used as campsites in the narrow Muav Gorge. Separation deposits are more uniformly distributed throughout Grand Canyon National Park than are other types of deposits. In some narrow reaches where the number of alluvial sand deposits used as campsites is small, separation deposits are a high percentage of the total.

During high flows, both separation and reattachment deposits are initially scoured but are subsequently redeposited during flow recession. Sand is also exchanged between the main channel and recirculation zones. The rate of recession of high flows can affect the elevation of alluvial deposits that are left exposed after a flood has passed. Fluctuating flows that follow a period of steady discharge cause initial erosion of separation and reattachment deposits. A part of this eroded sand is transported to the main channel. Therefore, sand is exchanged between the main channel and recirculation zones and redistributed within recirculation zones over a broad range of discharges.

Comparison of aerial photographs and reinterpretation of published data concerning changes of alluvial sand deposits following recession of high flows in 1983 and 1984 indicate that sand was eroded from recirculation zones in narrow reaches. In wide reaches, however, aggradation in recirculation zones may have occurred. In narrow reaches, the decrease of reattachment deposits was greater than that of separation deposits. In all reaches, the percentage of separation deposits that maintained a constant area was greater than for other deposits. Separation deposits, therefore, appear to be the most stable of the deposit types.

Fluctuating flows between October 1985 and January 1986, which followed the higher and steadier flows of 1983 to 1985, caused erosion throughout the park. For separation deposits, erosion was greatest at those sites where deposition from the 1983 high flows had been greatest. The existing pattern of low campsite availability in narrow reaches and high campsite availability in wide reaches was thus accentuated by the sequence of flows between 1983 and 1985.

INTRODUCTION

BACKGROUND

Alluvial sand deposits are used as campsites by backpackers and by about 15,000 persons who float the Colorado River in boats or rafts through Grand Canyon National Park each year. Sand deposits also are substrate for riparian vegetation. Flow in the Colorado River through Grand Canyon National Park has been regulated by Glen Canyon Dam since its completion in 1963 (fig. 1). From 1963 to 1982, regulation greatly decreased the range of discharges that occurred in any given year but greatly increased the range that occurred in a given day.

The mean annual peak discharge of the Colorado River before flow regulation (1921–62) was 93,400 ft^3/s (cubic feet per second); this decreased to about 29,200 ft^3/s after regulation (1963–82). For most of 1965 through 1982, flow was regulated in direct response to electrical power demand. During a typical 24-hour period, the discharge range was large because power demand is high during daylight hours and low at night (fig. 2). Although flow through the powerplant at the dam could range from 1,000 to 31,500 ft^3/s, discharge rarely varied over this entire range in a given day. A daily discharge range of 10,000 to 20,000 ft^3/s was typical of the period. Unusually large releases of water that bypass the powerplant using river outlet works or both outlet works and spillways occurred in 1983, 1984, and 1985. In 1983, peak discharge at Lees Ferry (station 09380000, Colorado River at Lees Ferry, fig. 1) was 97,300 ft^3/s. In 1984 and 1985, peak discharges at Lees Ferry were 58,200 and 47,900 ft^3/s, respectively.

Before construction of Glen Canyon Dam, the Colorado River carried a large suspended-sediment load through Grand Canyon National Park. All the sediment from the drainage area above the dam is now trapped in Lake Powell formed behind Glen Canyon Dam. Suspended-sediment samples collected at the gaging station at Lees Ferry between 1928 and 1959 commonly had concentrations that exceeded 10,000 ppm (parts per million). In contrast, samples collected since dam construction typically have concentrations less than 200 ppm.

Concern was first raised in the mid-1970's that the combination of large daily discharge ranges typical of regulated flow and the loss of sediment supplied from areas upstream from the dam would cause a decrease in the size and number of alluvial sand deposits within the park. Laursen and others (1976) estimated both the capacity of the regulated river to transport sand and the amount of sediment supplied by tributaries below the dam. They predicted that sand deposits would eventually be depleted because transport capacity exceeded supply under regulated flow. Although Dolan and others (1974) suggested that widespread degradation of sand deposits might result from operations of the dam, Howard and Dolan (1981) found that sand deposits had "suffered only a very slight erosion." Howard and Dolan (1981) estimated that alluvial sand deposits had reached equilibrium by the late 1970's, and they predicted little net change in the future. They stated, however, that erosion might occur if the characteristic pattern of dam releases of the 1970's were changed.

On the basis of an inventory made after the high releases in 1983, Brian and Thomas (1984) concluded that a net loss of sand deposits large enough for use as campsites had taken place in the first 173 mi below Lees Ferry. They also concluded that a net increase in the same type of sand deposits had taken place farther downstream. Beus and others (1985) evaluated the history of change of 20 major sand deposits between 1974 and 1984 by repeating topographic surveys first begun by Howard (1975). Beus and others (1985) concluded, "a substantial net gain of sand [due to high flows in 1983] * * * more than compensated for the previous 8-year loss."

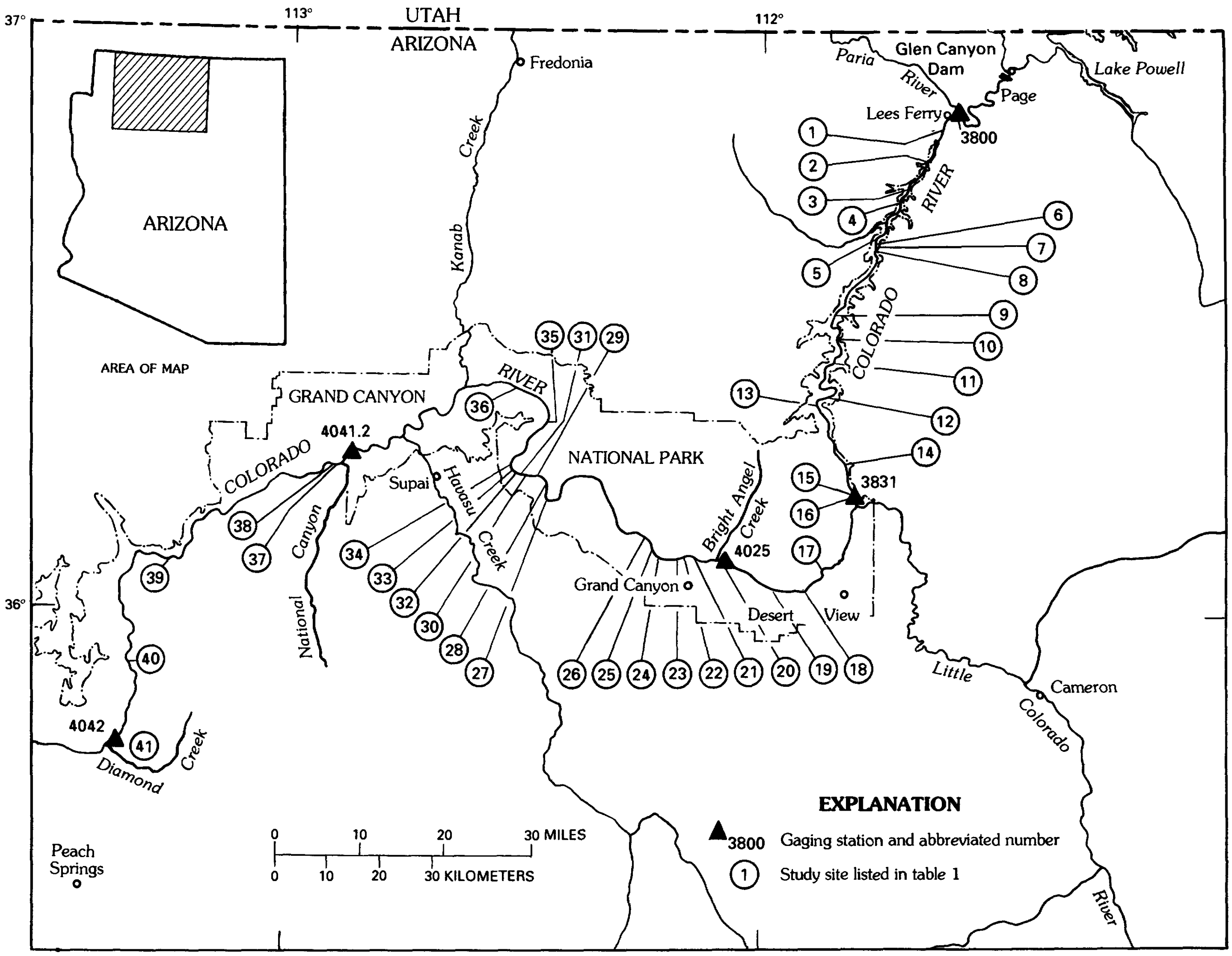


FIGURE 1.—Study area and location of study sites.

PURPOSE AND SCOPE

The present study of alluvial sand deposits along the Colorado River began in 1984 in cooperation with the U.S. Bureau of Reclamation as one phase of a comprehensive investigation of the effects of flow regulation on sediment transport in Grand Canyon National Park. The investigation was initiated in response to a U.S. Bureau of Reclamation proposal to increase peak powerplant discharges from 31,500 to 33,100 ft^3/s. High discharges between 1983 and 1985 also provided an opportunity to investigate the effects of discharges that exceed powerplant capacity. Other phases of the overall study include:

1. Collection and analysis of flow and sediment-transport data at gaging stations (Graf, 1986; Pemberton and Randle, 1986);
2. Analysis of historical data from gaging stations (Burkham, 1986);
3. Mapping of channel-bed materials (Wilson, 1986);
4. Development and application of a sediment-transport model in the main channel (Orvis and Randle, 1986; Randle and Pemberton, 1987); and
5. Evaluation of sediment contributions from ungaged tributaries by debris flows (Webb and others, 1987).

The results of this study will be integrated with results of other phases to determine the effect of flow regulation on sediment transport and storage in the Colorado River in Grand Canyon National Park.

The study involved the evaluation of existing data and the collection of new data. Existing data consist mainly of aerial and ground photography (Laursen and Silverston, 1976; National Park Service, unpublished 1975 photographs on file at Grand Canyon National Park; Turner and Karpiscak, 1980) and topographic surveys of deposits begun in 1974 (Howard, 1975; Beus and others, 1985; Ferrari, 1987). Data for this study were collected from May 1984 to February 1986. These data included measurements of flow velocity, scour-and-fill of sand deposits, topographic and bathymetric surveys, mapping surface-flow patterns, water-surface slope surveys, sedimentological analysis of some sand deposits, and replication of photographs.

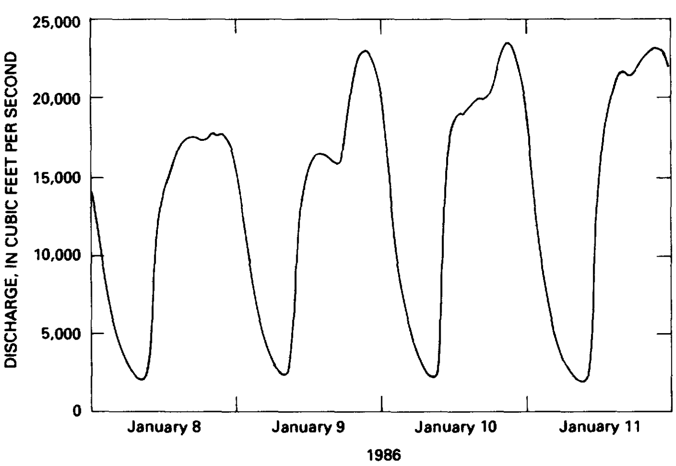


FIGURE 2.—Instantaneous discharge at Lees Ferry gage, January 8–11, 1986, typical of fluctuating flows between 1965 and 1982.

The study area extends from the gaging station (Colorado River at Lees Ferry) at river mile 0 to the gaging station (station 09404200, Colorado River above Diamond Creek, at Peach Springs) at river mile 225 (fig. 1). Most of the fieldwork was done on raft trips beginning at Lees Ferry and ending at either Diamond Creek (river mile 225) or on Lake Mead (river mile 280). A helicopter was used to reach some sites on December 7 and 8, 1985, and on January 8 and 13, 1986.

Forty-one study sites were selected as a representative sample of different types of alluvial sand deposits used as campsites in most major reaches of the Colorado River corridor. The 41 sites and the types of data collected at them are summarized in table 1. The results of topographic and bathymetric surveys at 21 of these sites, referred to as detailed study sites, are discussed in this report.

Bathymetric surveys were limited to reaches where a raft could be safely maneuvered and instruments could receive signals. In spite of the limitations, bathymetric surveys permitted mapping of large areas not otherwise accessible. Topographic surveying was limited to areas of safe wading; however, at low stages, large areas at some study sites could be mapped. Surface-current patterns and shorelines were mapped at two or more discharges. Surface velocities were estimated by timing floating objects and by using current meters. Bathymetric surveys were made at discharges between about 15,000 and 25,000 ft^3/s (table 1). Other observations and surveys were made at discharges between about 3,000 and 45,000 ft^3/s.

The purpose of this report is (1) to present a classification of alluvial sand deposits in the Colorado River, (2) to describe significant characteristics of these deposits, (3) to describe changes in these deposits between June 1983 and January 1986, and (4) to relate these changes to those occurring since completion of the dam. The classification of alluvial sand deposits and identification of 11 reaches within Grand Canyon National Park are presented to provide a framework within which to evaluate changes in deposits. Description of the characteristics of alluvial sand deposits is included to substantiate the classification and to provide a basis for understanding change in spatial distribution of sand. Changes in alluvial deposits were identified by topographic and bathymetric surveys between April 1985 and January 1986 and by analysis of aerial photographs.

ACKNOWLEDGMENTS

The fieldwork accomplished in this project was the direct result of the work of many individuals. Volunteers with the U.S. National Park Service or the U.S. Geological Survey included Bernard O. Bauer, James Harris, Robert Jacobsen, Catherine Hooper, Barbara Rusmore, and John Rusmore. Thanks go to them all as well as to the other field assistants. Dave Steinke made modifications to the equipment used for bathymetric surveys that made those surveys possible. Martha Hahn of the National Park Service arranged for the appointment of volunteers for the National Park Service and obtained unpublished data for our use. Boatmen for the raft trips were Jon Stoner, Stuart Reeder, Bob Grusy, and Owen Baynham; their skilled navigation and professionalism made all our work possible.

TERMINOLOGY

Flow separation and associated secondary circulations are characteristic hydraulic conditions in the Grand Canyon that determine sand-deposit location and extent of change. The phenomenon of flow separation at abrupt channel expansions or contractions is described in basic fluid mechanics texts. When flow separation occurs, the main downstream current becomes separated from the channel banks, and areas of recirculating flow exist between the downstream current and the banks (fig. 3). These **recirculation zones** are composed of one or more **eddies**, a term denoting "any rotating fluid motion which possesses continuity so long as the flow pattern which creates it continues to prevail" (Matthes, 1947). Eddies, as discussed in this report, have a vertical or nearly vertical axis of rotation. Typically, a recirculation zone has a **primary eddy** and may have a **secondary eddy**. That portion of the primary eddy where flow is directed upstream and toward the main downstream current is referred to as the **primary-eddy return current**. The bed of the recirculation zone excavated by this current is termed the **primary-eddy return-current channel**. Other portions of recirculation zones are not organized into a rotation. Currents in these **low-velocity areas** may have a preferential direction, may oscillate in several directions, or may be virtually stagnant.

The point at which downstream-directed flow becomes detached from the channel banks is called the **separation point** (fig. 3*A*). The point at which downstream-directed flow is again adjacent to the banks is called the **reattachment point**. The separation point is the most upstream point and the reattachment point the most downstream point of the recirculation zone. On the Colorado River, these points are actually zones, 5–20 ft wide, within which the separation or reattachment point may migrate. A plane and its surface expression, the **separation surface**, divides the main downstream-directed flow from the recirculation zone.

Two types of alluvial sand deposits within recirculation zones are highest in elevation and are of most interest to whitewater boaters and campers. **Separation deposits** mantle the downstream part of debris fans and are located 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 (fig. 3*B*). At places, the surface of separation and reattachment deposits merge and the deposits cannot be distinguished solely on the basis of location, although they each have distinctive sedimentary characteristics. At other places, one or the other may not be found in a particular recirculation zone.

Alluvial sand deposits are also typically located upstream from constrictions. At least the lower part of many of these **upper-pool deposits** is a reattachment deposit associated with small recirculation zones. The higher parts of these same deposits, however, resemble terraces. Where the origin of alluvial deposits could not be determined on the basis of planimetric shape or location, they are called **channel-margin deposits**. **Point-bar deposits**, which are characteristic of alluvial meandering rivers, are uncommon in the park and are not discussed.

Abrupt changes in flow area cause flow separation. In the Grand Canyon, the channel is typically more narrow and shallow around obstructing debris fans, and this short reach is called the **constriction**. Downstream from the debris fan, a short reach is wider than the average channel width and is called the **expansion**. Downstream from the expansion, the channel typically resumes the dimensions characteristic of the reach upstream from the constriction. The separation point typically is located near the transition from constriction to expansion. Recirculation zones occur in the expansion.

The ratio of channel width at the constriction to average width of the upstream channel is termed the **constriction ratio**. The ratio of channel width at the expansion to channel width at the constriction is termed the **expansion ratio**. The term **elevation** used in this report refers to the distance above or below either an arbitrary local datum or sea level.

METHODS OF ANALYSIS

Between April 1985 and February 1986, sand-deposit change was measured by repeated topographic and bathymetric surveys. These surveys, as well as photographs taken between April and February, were compared with similar types of data collected between 1965

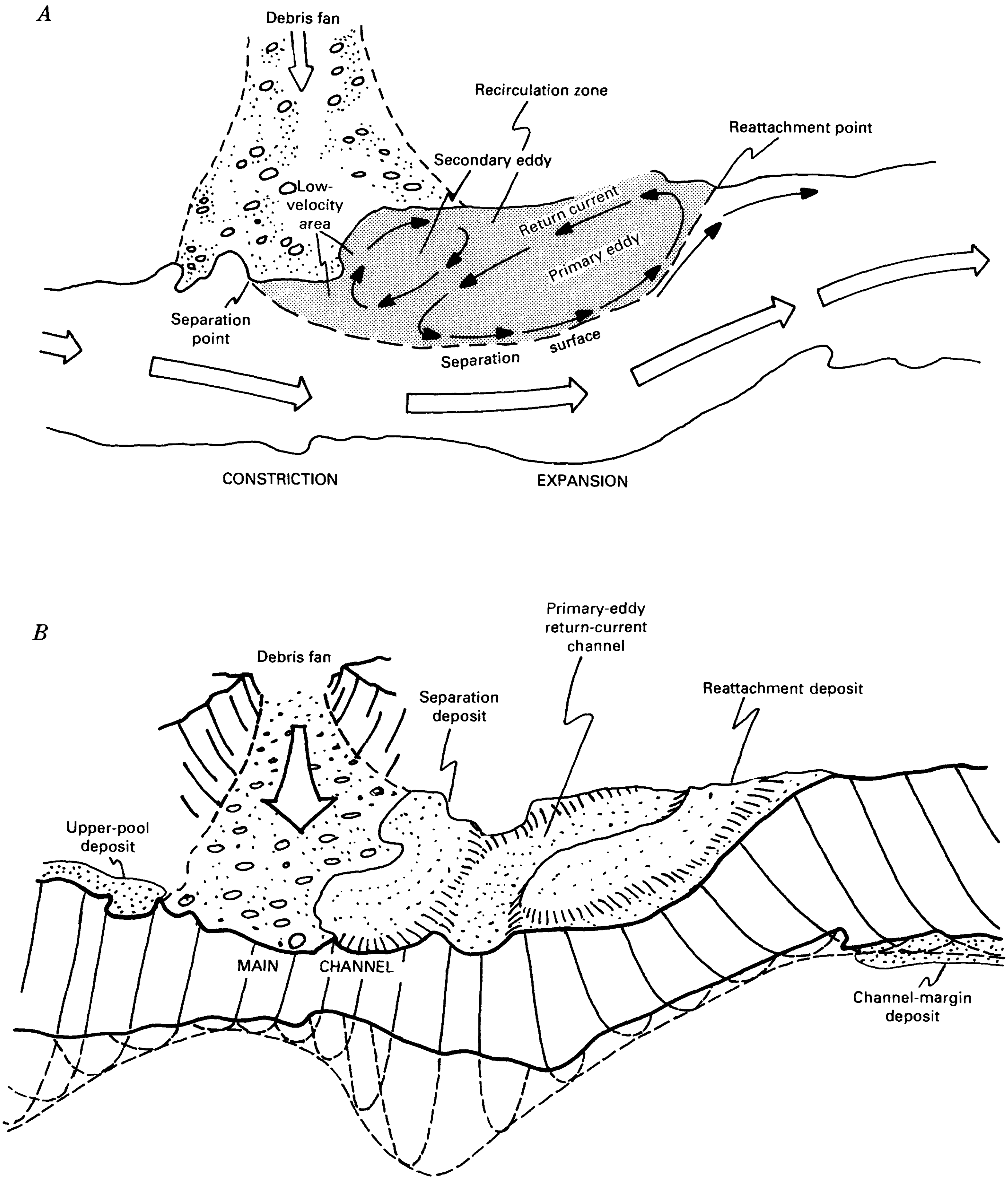


FIGURE 3.—Flow patterns and configuration of bed deposits in a typical recirculation zone. *A*, Flow patterns. *B*, Configuration of bed deposits.

and 1984 in order to measure change over longer time periods. Reference marks established by Howard (1975), Laursen and Silverston (1976), or Ferrari (1987) were used. At new study sites, networks of reference marks were established.

A theodolite distance meter and standard techniques were used for most topographic surveys. About 25 percent of the topographic surveys were made using a hand level and tape. Surveys were made along profile lines, and topographic maps of most sites were made.

Resurveys of reference-mark networks generally differed by less than 0.10 ft from survey to survey. Surveying data were initially plotted in plan view to ensure that repeated surveys matched. Where they did not match, surveying data were adjusted for differences in position on the basis of surveying data of surrounding topography. This technique resulted in accurate depiction of topographic change along specific profile lines. Differences in elevation exceeding 0.25 ft are considered to be significant in this study.

Bathymetric surveys were made from a raft about 35 ft long by using a recording echo-depth sounder and a local microwave positioning system. The positioning system consisted of two remote units mounted on tripods on shore, a master unit mounted on a mast on the raft, and the electronics that control their operation. The distance between the master and each remote is determined by the traveltime of microwaves. The position of the remotes in the local coordinate system was determined by their location in relation to fixed reference marks, and the position of the raft at any time was computed from the known distances between the master unit and each remote. Data from the positioning system and the depth sounder were recorded along with time on a data logger as the raft moved about the study area. The time interval for recording could be changed but generally was 2 seconds. Depths were converted to elevation by reference to elevation of the water surface during the survey. Maps of the data were plotted and contours were drawn by use of a computer-contouring system.

Precision of the recording echo-depth sounder used is 0.1 ft, and accuracy is 0.5 percent of the measured depth or about 0.25 ft at a depth of 50 ft. Although maximum depth was 70 to 80 ft at a few study sites, maximum depth was less than 50 ft at most sites. Water-surface elevation during each survey was monitored either by a temporary recording-stage gage or by periodic reading of a staff gage on shore. Water-surface elevation changed with time during surveys and at a given time was different in different parts of the surveyed area. Change with time was caused primarily by discharge fluctuations or surface waves. During the bathymetric survey, the edge of water was mapped using standard surveying techniques. Depth changes in excess of 0.5 ft are considered significant.

Spurious depths were recorded when air entrained in the water column caused the signal to reflect within the water column rather than off the channel bottom. Spurious numbers in the data set, which were identified by comparing the stored numbers with depths recorded graphically, generally showed shallower depths than preceding or following measurements. In some places, entrained air severely limited the area that could be surveyed, especially downstream from rapids.

Uncertainty of the distance measurement by each microwave unit is about 3 ft. Uncertainty of the raft position computed from the two distances depends mainly on the uncertainty of the distance measurement and on the relative positions of the master and remote units. Highest position accuracy (about 4.3 ft) is obtained when the master and remotes form a 90° angle. The accuracy decreases as the angle increases or decreases from 90° and is about 11.7 ft at angles of 30° and 150°. Remotes were located near the center of the recirculation zone or channel in such a way as to maintain a line of sight and to give as close to a 90° angle as possible over the survey area. The uncertainty of position ranges from the minimum of about 4.3 ft to about 20 ft.

Data points from the positioning system were used to generate a grid of equally spaced values that were in turn used in graphical fitting of contours for computer plotting. Error of the grid was determined by computing the elevation at data locations by linear interpolation from the values at the grid nodes and comparing the calculated value with the measured value. The method of grid generation was selected to minimize interpolation error while maintaining a reasonable amount of smoothing of the data. Uncertainty in the position of contours also depended on the spatial distribution of data points. Where data points were sparse, contour position was extremely uncertain even though the interpolation error was low.

The resulting uncertainty in the bathymetric maps is the sum of errors in microwave system location, computer contouring, and data-point density. The most significant of these is the uncertainty in raft position caused by poor geometry of the master and remote units and sparse distribution of data points. Although no quantitative measure of the map uncertainty was developed, a qualitative judgment was made for each map, and areas judged to have uncertainty too great for meaningful analysis were omitted.

Analysis of sand-deposit change at 13 detailed-study sites since 1965 relied mainly on photographic comparisons. Aerial photography is available for 1965 (U.S. Geological Survey, scale about 1:15,000), 1973 (U.S. Geological Survey, scale about 1:7,200), and 1984 (U.S. Bureau of Reclamation, scale about 1:3,000). Daily mean discharge ranged from 23,100 to 41,200 ft^3/s during the photographic survey of 1965, from 5,930 to 12,100 ft^3/s during the survey of 1973, and from 5,220 to 5,810 ft^3/s during the survey of 1984. Topographic changes at study sites were determined by measuring the area of exposed sand above the stage corresponding to a discharge of about 25,000 ft^3/s. The area of exposed sand was directly measured in the photographs of 1965 for study sites where discharge was about 25,000 ft^3/s. Estimates of the shoreline corresponding to a discharge of about 25,000 ft^3/s, however, had to be made for the 1973 photography. The upper limit of unvegetated sand on the photographs of 1973 was determined to be associated with a stage of approximately 25,000 ft^3/s by comparing topographic surveys and stage-discharge relations at Eighteen Mile Wash and opposite Nineteen Mile Canyon. Below this stage, sand was swept clean by daily fluctuations. The location of the shoreline at discharges of approximately 25,000 ft^3/s was mapped in the field in August 1985 and drawn on 1984 photographs. A zoom transfer scope was used to adjust for differing scales of each aerial photograph survey. A planimeter was used to measure areas for different years, and differences in area of more than 10 percent were considered significant.

Measurements of exposed sand deposits at a discharge of about 6,000 ft^3/s were also made for 1973 and 1984 at about 180 sites. Measurements were made directly on aerial photographs. Accuracy of comparisons of exposed sand area is limited by the different scales of different aerial photographs as well as by the changing scale of each particular year's flight. For example, the ratio of scale difference between a unit area on the 1973 and 1984 photographs varied between 5.0 and 7.7, depending on location. In order to compensate for the errors resulting from varying scale, scale ratios were measured at about 1-mile intervals. Areas of deposits in 1973 were estimated by multiplying the area measured on the aerial photographs by the scale ratio so that comparison could be made with areas measured on the 1984 photographs. Areas in 1973 were estimated to be within a range determined by the highest and lowest scale ratios within about 10 mi of the measured site. Areas on 1984 aerial photographs were considered to be accurate to ± 10 percent. Significant change was considered to have occurred if the estimated 1973 area was entirely beyond the range of the 1984 area estimate.

An inventory of the presence or absence of different types of alluvial sand deposits in 399 recirculation zones was also conducted between river miles 0 and 118 using 1973 and 1984 photography. Criteria used in this inventory are described in the section entitled "Changes in alluvial sand deposits, 1973–84."

Other methods used to interpret or document topographic changes or hydraulic conditions included scour chains, sedimentologic descriptions, water-surface slope surveys, and mapping of surface currents. Chains 2 ft long and having links of about 0.1 ft were inserted vertically into sand deposits along lines that were roughly perpendicular to shore. A metal detector was used to recover the chains; recovery was about 90 percent. Trenches were dug into sand deposits to reveal sedimentary structures. The size of trenches was limited by the time and equipment available. The largest trench was 80 ft long and 4 ft deep at Fern Glen Rapid.

Surveys of water-surface slope were obtained by measuring the water-surface elevation at the edge of water. A staff gage was installed before each measurement, and observed fluctuations in stage were recorded. All surveyed points were located on aerial photographs along with the survey time. The water-surface survey was adjusted to compensate for measured stage changes. In order to decrease the length of time of the survey and therefore the stage changes during the survey, two rod persons usually were used.

The direction of surface currents and location of shorelines were observed from the shore and mapped on aerial photographs. Uncertainty in position of features near the center of the channel is estimated to be about 5 percent of local river width. Noted features such as the location of separation and reattachment points along the shoreline are accurate to within 10 ft.

BACKGROUND

PHYSICAL AND HYDRAULIC CHARACTERISTICS OF THE CHANNEL

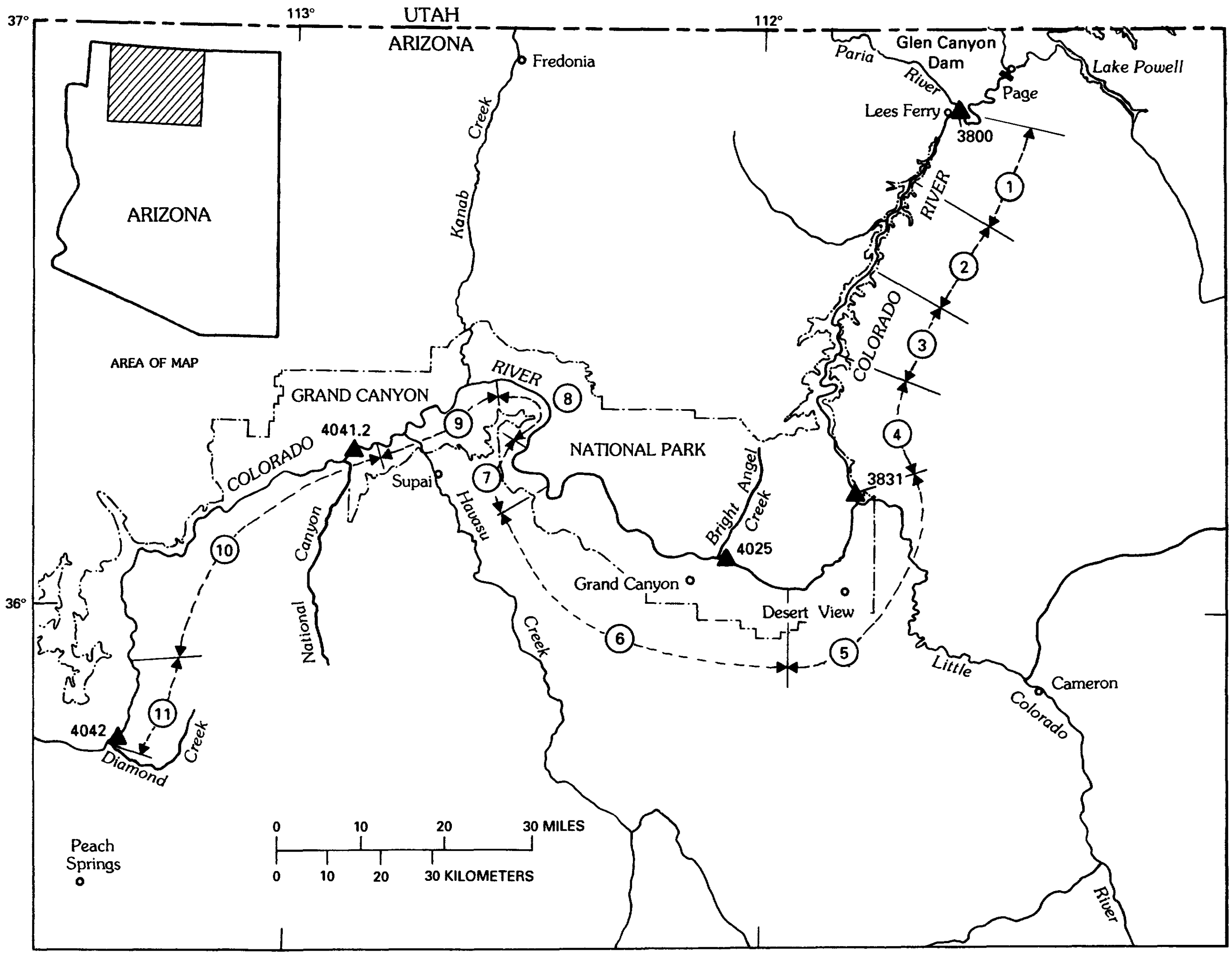
The Colorado River channel is in bedrock or bordered by large talus blocks for most of the 225 mi from Lees Ferry to Diamond Creek. Geomorphic characteristics of the river channel are controlled by bedrock type and structure (Dolan and others, 1978). Channel width and depth, presence of midchannel gravel bars, and the distribution of tributary debris fans are all related to the bedrock geology (Howard and Dolan, 1981).

Eleven reaches of the Colorado River were defined on the basis of type of bedrock exposed at river level, average channel top width, average channel width-to-depth ratio, reach slope, and relation to major tributaries (table 2; fig. 4). The narrow reaches are Upper Granite Gorge, Aisles, Middle Granite Gorge, Muav Gorge, Supai Gorge, Redwall Gorge, and Lower Granite Gorge. The wide reaches are the Permian Section, Lower Marble Canyon, Furnace Flats, and Lower Canyon.

The elevation of the river decreases about 1,780 ft between Lees Ferry and Diamond Creek. The descent takes place primarily in short steep reaches, many of which are the famous rapids of the Grand Canyon. In the first 150 mi downstream from Lees Ferry, 50 percent of the total decrease in elevation takes place in only about 9 percent of the distance (Leopold, 1969). Although the average gradient between Lees Ferry and Diamond Creek is 0.0015, the gradient of many short reaches exceeds 0.01.

Water-surface slope is low in reaches between rapids, and many reaches have a gradient of less than 0.0005 (Birdseye, 1923). Water-surface slope flattens in pools upstream from most major rapids, and mean velocity commonly is less than 3 ft/s. A deep scour hole is present immediately below most rapids (Leopold, 1969; Howard and Dolan, 1981; Wilson, 1986).

Rapids are commonly located where the channel has been constricted by alluvial fans formed by debris-flow



EXPLANATION

1	Permian Section	7	Aisles
2	Supai Gorge	8	Middle Granite Gorge
3	Redwall Gorge	9	Muav Gorge
4	Lower Marble Canyon	10	Lower Canyon
5	Furnace Flats	11	Lower Granite Gorge
6	Upper Granite Gorge	▲3800	Gaging station and abbreviated number

FIGURE 4.—Reaches within the study area.

deposits at the mouths of short, steep tributaries (fig. 3). Debris from these flows also increases local bed elevation of the channel. Kieffer (1985) determined constriction ratios at 54 debris fans in the Grand Canyon, using 1973 aerial photography. She found that the ratio ranged from about 0.3 to about 0.7, and averaged about 0.5. Because discharge in the 1973 photographs ranged from about 4,000 to 15,000 ft^3/s and constriction ratio might vary with discharge and stage, constriction ratios were recomputed from 1984 photography. The mean constriction ratio at the same debris fans measured by Kieffer (1985) was 0.49, indicating that while individual sites might vary in relation to stage and method of measurement, when averaged over a number of sites, the effect of stage on constriction ratios is not significant. Because alluvial deposits large enough to be used as campsites are associated with small debris fans as well as the large fans measured by Kieffer (1985), constriction ratios were computed from 1984 photographs for 70 debris fans associated with alluvial deposits inventoried as campsites (Brian and Thomas, 1984) between river miles 0 and 61. The mean constriction ratio of these sites was 0.54, somewhat greater than that of the sample population of Kieffer (1985). The expansion ratio at the 70 sites ranged from 1.3 to 7.3, with a mean of 2.9. At 59 of these sites where channel-depth data (Wilson, 1986) are available, channel depth at the constriction decreased to as much as 0.30 of the upstream depth and increased in the expansion to as much as nine times the constriction depth.

At most constrictions, recirculation zones exist at discharges between 4,000 and 45,000 ft^3/s, but their sizes are not constant. At most sites, recirculation zones increase in length with increasing discharge at least to 45,000 ft^3/s (Schmidt, 1986). At Badger Creek Rapid, the separation point is farther upstream and the reattachment point farther downstream at a discharge of 44,000 ft^3/s than at a discharge of 5,600 ft^3/s (fig. 5). At extremely low flow, many recirculation zones are greatly reduced in size, and the bed of the recirculation zone may be completely exposed. For example, at Soap Creek Rapid, flow separation does not occur at discharges less than about 5,000 ft^3/s.

At each constriction, the debris fan is overtopped if the discharge is sufficiently high. As discharge increases above this overtopping discharge, the separation point does not migrate farther upstream. For example, overtopping occurs at the low fan at Eighteen Mile Wash between 28,000 and 44,000 ft^3/s (fig. 6). At most sites, the downstream migration of the reattachment point is controlled by the geometry of the channel. Lengthening of the recirculation zone in the downstream direction is ultimately restricted where the downstream-migrating reattachment point encounters another riffle or debris fan farther downstream. An upper limit, therefore, exists on the length of recirculation zones, but the limit is different at different sites.

Sand is stored primarily in main-channel pools and within recirculation zones (Wilson, 1986). Most sand deposits used as campsites are associated with recirculation zones and are formed at discharges typically exceeding 30,000 ft^3/s. Sand stored within recirculation zones typically is very well sorted and fine to very fine grained (fig. 7, curve 7, 8), whereas sand in channel pools is typically medium grained (fig. 7, curve 5, 6).

Channel geometry and hydraulic data based on field mapping of shorelines and currents at various discharges, water-surface slope surveys, and depth-sounder records were collected at 21 detailed study sites (table 3). The mean constriction ratio of these sites is 0.49 and is the same as the mean constriction ratio of the debris fans measured by Kieffer (1985) and less than the mean of 70 fans between river miles 0 and 61 discussed above. The 21 sites, therefore, are representative of more narrow constrictions than are associated with most campsites in the Grand Canyon.

Study sites were concentrated in upstream reaches where the effects of dam operations were initially considered to be most significant. Detailed study sites were located in seven reaches (table 4). Study sites in each of these reaches included the dominant types of deposits used for camping (table 2).

HISTORY OF FLOW AND SEDIMENT TRANSPORT

Two gaging stations provide long-term information on flow and sediment transport. The gage at Lees Ferry (fig. 1) was established in 1895, and in 1922, a gage (station 09402500, Colorado River near Grand Canyon) was established at river mile 87, just above Bright Angel Creek (fig. 1). Suspended-sediment samples were collected at the gage at Lees Ferry during the periods 1929–33, 1942–44, and 1947–65 and near Grand Canyon from 1925 to 1972. Sediment data also were collected at these two gages from June to December 1983 and from October 1985 through January 1986. Three additional gages were operated during the latter two periods. These short-term gages were at river mile 61, just above the confluence with the Little Colorado River (station 09383100, Colorado River above the Little Colorado River, near Desert View); at river mile 166, just above National Rapid (station 09404120, Colorado River above National Canyon, near Supai); and at river mile 225, just above Diamond Creek Rapid (fig. 1).

Before closure of Glen Canyon Dam in March 1963, discharge at Lees Ferry typically reached its annual peak in June in response to snowmelt runoff from the upper basin. Smaller peaks occurred during the late summer and fall in response to rain in tributary watersheds downstream from Lees Ferry (fig. 8). Suspended-sediment concentrations tended to be highest during these periods of tributary flow, and suspended sediment was dominated by silt- and clay-sized material (fig. 7, curve 2).

Daily mean discharge of water for 1982 (fig. 9) was typical of the period 1965–82. During that period, short-term discharge fluctuations dominated, and discharge exceeded powerplant capacity of 31,500 ft^3/s only in

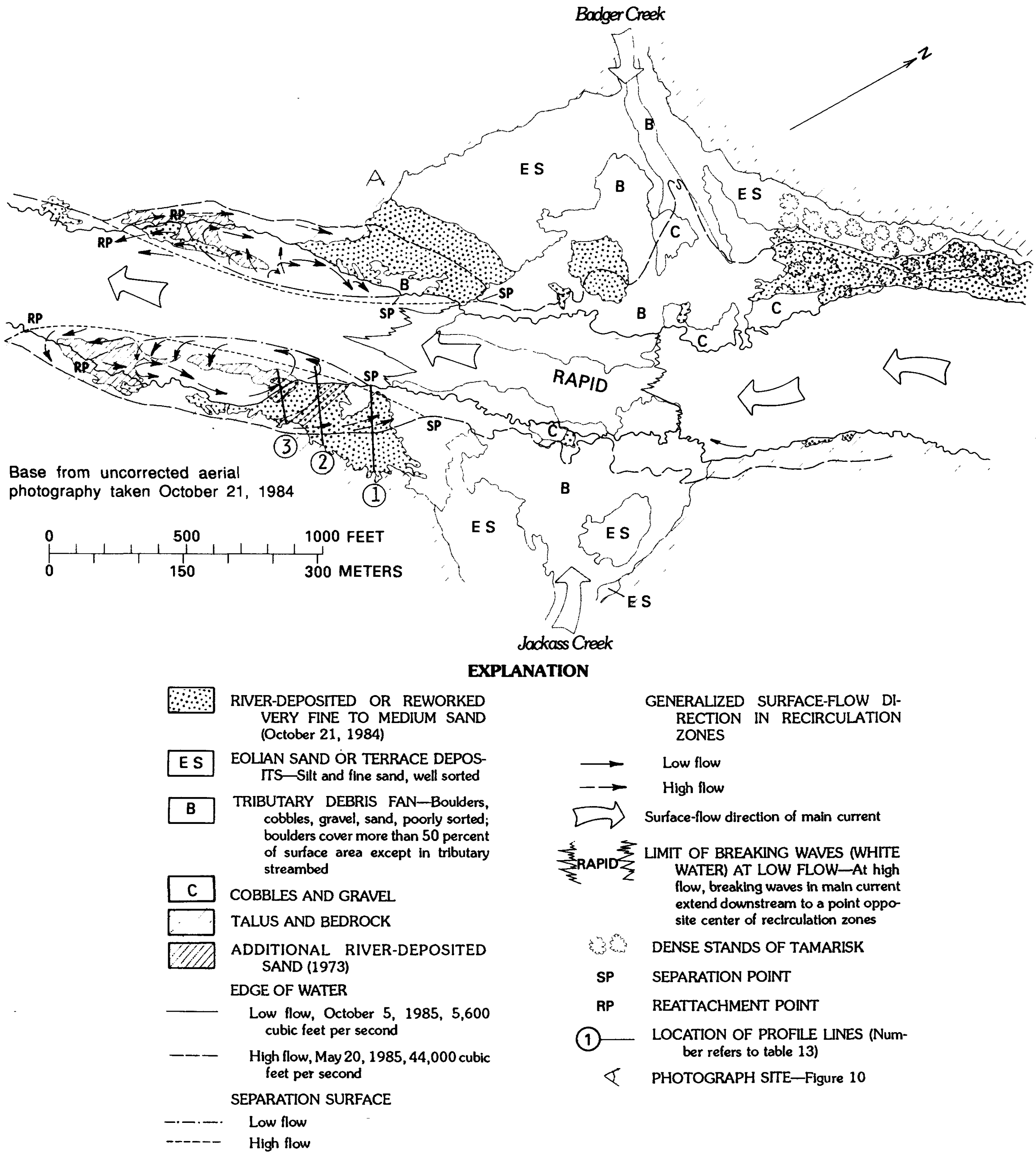


FIGURE 5.—Surficial geology and hydraulic features at Badger Creek Rapid.

April, May, and June 1965 and for a very short period in late June and early July 1980. Maximum instantaneous discharge at Lees Ferry was 60,200 ft^3/s in 1965 and 44,800 ft^3/s in 1980. Annual suspended-sediment load past Lees Ferry decreased from 76.3×10^6 tons/yr in the period just before construction of the dam (1948 to 1958) to 8.6×10^6 tons/yr just after dam completion (1963 to 1965) (Laursen and others, 1976), which is a decrease of almost 90 percent. For the same periods, volume of water passing Lees Ferry decreased about 55 percent (Anderson and White, 1979).

The present study was planned and initiated in 1982 and early 1983, when flows such as those illustrated in figure 2 had prevailed for nearly 20 years. An exceptional combination of weather conditions and management decisions during the winter of 1982–83, however, caused subsequent flows to deviate from the previous regime (fig. 9). A record post-dam high instantaneous discharge of 97,300 ft^3/s passed Lees Ferry on June 29, 1983. From June 1983 until October 1, 1985, discharges were higher and steadier than ever experienced since closure of the dam. Discharges of as much as 46,000 ft^3/s can be released without using the spillways; 31,500 ft^3/s can be released through the powerplant and 14,500 ft^3/s through river outlet works (David Wegner, U.S. Bureau of Reclamation, oral commun., 1986). The flat-topped hydrographs of the summers of 1984 and 1985 (fig. 9)

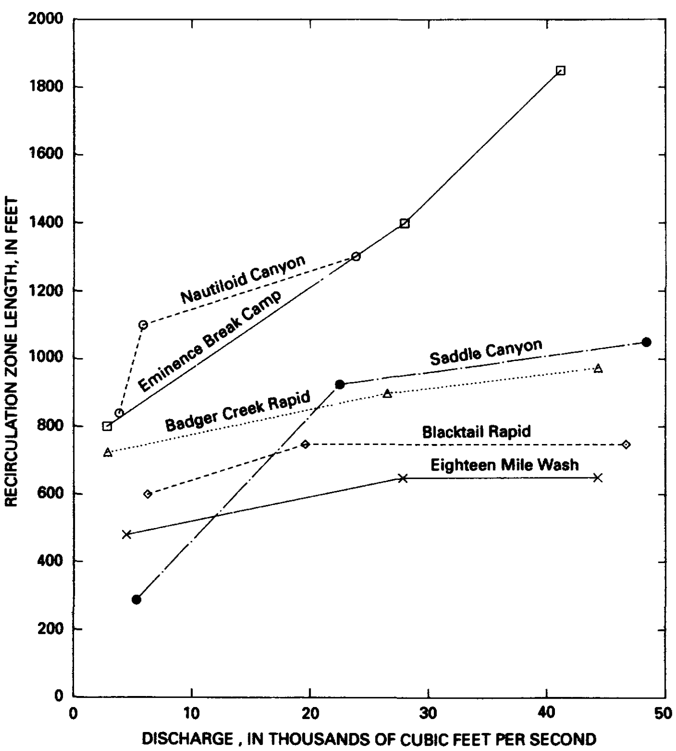


FIGURE 6.—Change in length of recirculation zone with discharge at six sites.

resulted from maximum releases through the river outlet works and powerplant. Discharges in June 1983 exceeded powerplant and outlet work capacity, and spillways were used. Only during a special fluctuating-flow study period—October 1, 1985, to January 15, 1986—did releases resemble those characteristic of the 1965–82 period. The special fluctuating-flow study was planned and carried out for the purpose of providing a period in which to investigate the response of the river to typical powerplant releases.

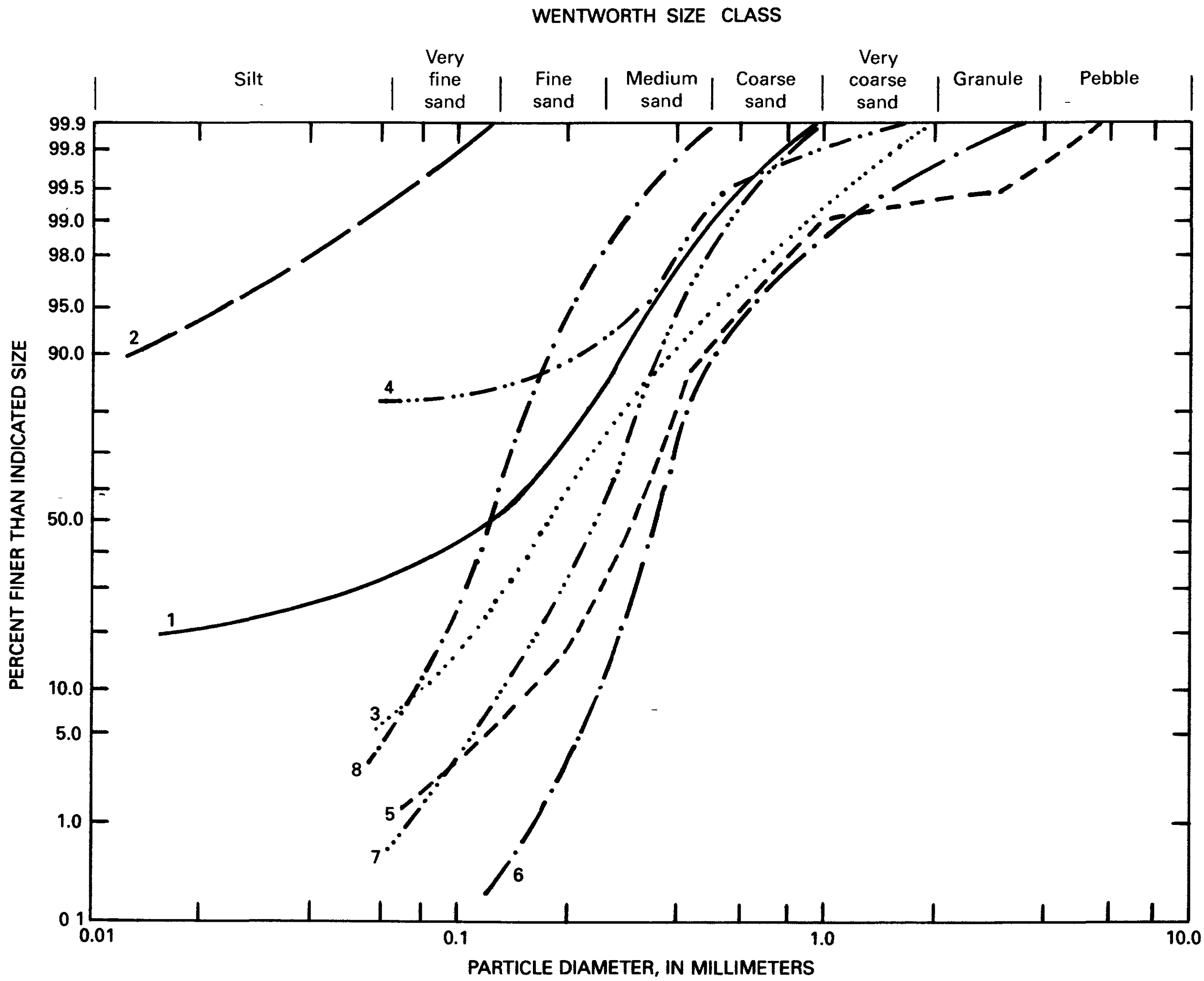
CHARACTERISTICS AND CLASSIFICATION OF ALLUVIAL SAND DEPOSITS

Fine-grained sediments are stored in channel pools, in recirculation zones, and in deposits that continuously line the wider sections of the river. Except for the widest reaches, most alluvial deposits are associated with the recirculation zones caused by minor bedrock or talus abutments or by large debris fans. In parts of the widest reaches of the Grand Canyon, terracelike deposits exist. Deposits associated with large recirculation zones are the most numerous and extensive alluvial sand deposits in Grand Canyon National Park.

Side-scan sonar surveys, recording depth-sounder surveys (Wilson, 1986), and photography taken at low river stage demonstrate that the average bed elevation of recirculation zones is much higher than that of the adjacent channel. A pool or scour hole occurs immediately downstream from the constriction. Adjacent to and downstream from this scour hole, the channel rises to the higher surface of a sandy alluvial deposit (fig. 3*B*). The upper surface of the sandy deposit typically has relief of 10 to 50 ft. The difference between the average bed elevation within a recirculation zone and the elevation of the adjacent thalweg varies from site to site. For example, at Blacktail Rapid, the elevation difference exceeds 80 ft, and at National Rapid and Eminence Break Camp, the elevation difference exceeds 40 ft.

The separation and reattachment deposits associated with recirculation zones are composed primarily of medium to very fine sand. Between Lees Ferry and Bright Angel Creek, 22 deposits created since 1983 were sampled (table 5). Of the 55 samples taken at these deposits, only 4 contained less than 90 percent sand, and none of these samples contained more than 1 percent very coarse sand (greater than 1 mm).

All samples of deposits between Lees Ferry and Bright Angel Creek that were inundated in 1983 or more recently have graphic means (Folk, 1968) between 0.095 and 0.39 mm. Of the 33 samples of deposits created by the discharges of 1983, 25 are fine sand and most are moderately well sorted. Fewer samples were collected of sediments deposited in 1984 and 1985, and half of these samples are medium sand between 0.25 and 0.50 mm.



EXPLANATION

Curve	Date	Description	Discharge, in cubic feet per second	Concentration, in milligrams per liter
1	June 13, 1957	Pre-dam, snowmelt runoff	123,000	7,980
2	October 18, 1957	Pre-dam, tributary flow	15,600	17,000
3	October 22, 1983	Post-dam, no tributary flow	23,800	409
4	October 2, 1983	Post-dam, tributary flow	31,400	16,600
5	October 27, 1983	Bed material		
6	December 18, 1985	Bedload		
7	August 13, 1985	1983, reattachment deposit, Saddle Canyon		
8	August 3, 1985	1985, separation deposit, Eighteen Mile Wash		

FIGURE 7.—Typical particle-size distributions for samples of suspended sediment, bedload, and bed material from the Colorado River near Grand Canyon at river mile 87 and for two alluvial sand deposits.

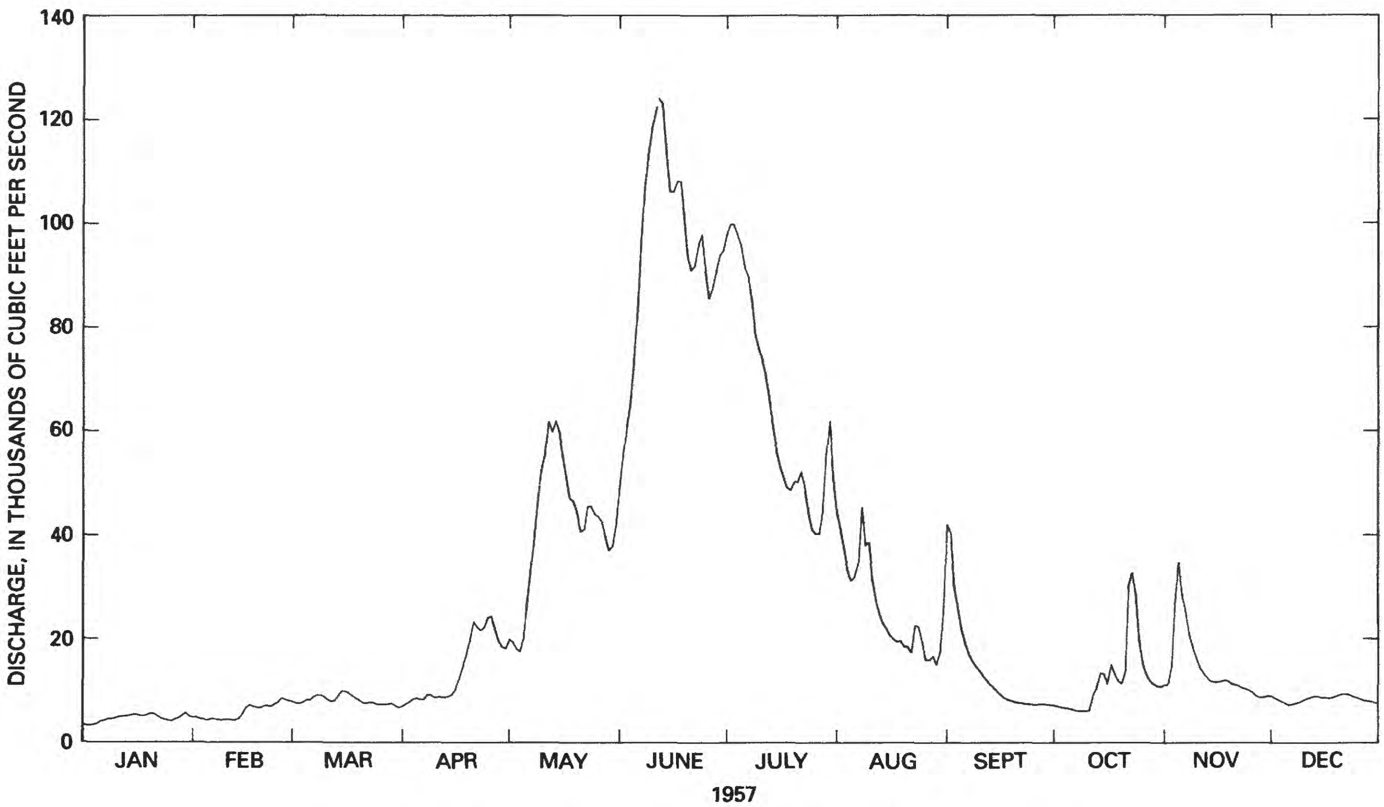


FIGURE 8.—Daily mean discharge of the Colorado River at Lees Ferry, 1957.

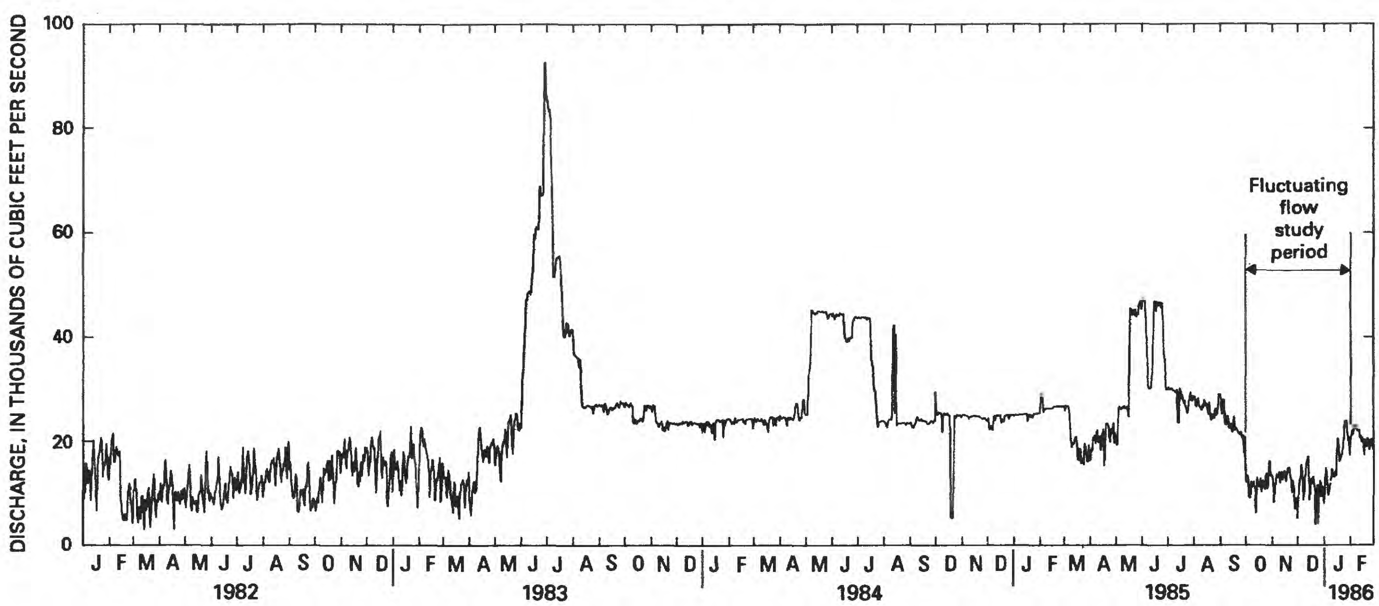


FIGURE 9.—Daily mean discharge of the Colorado River at Lees Ferry, 1982 to February 1986.

SEPARATION DEPOSITS

Separation deposits mantle and typically extend downstream from a debris fan. A zone of interspersed sand and boulders separates the separation deposit from the debris-flow deposits located upstream (fig. 10). The separation deposit generally forms one continuous gradual slope from crest to water's edge, but discrete terracelike levels may exist.

The most upstream part of most of these deposits commonly does not border the low-flow river channel; boulders are found between the sand deposit and the water's edge (fig. 5). Downstream migration of separation points with decreasing discharge probably causes erosion of sand in the upstream low-elevation portion of the separation deposit, resulting in this depositional pattern.

Separation deposits form in low-velocity areas and in secondary eddies upstream from the primary-eddy return-current channel. At some sites, a bar forms in a secondary eddy and the upstream-facing slipface of this deposit migrates upstream and eventually becomes attached to the debris fan. This process was observed at Eighteen Mile Wash, where a separation deposit (fig. 11) formed in a secondary eddy at a discharge of 45,000 ft^3/s. At this discharge, the downstream part of the Eighteen Mile Wash debris fan was inundated. Velocity of this secondary eddy was much less than that of the main channel. Surface velocity through the riffle, at a discharge of 45,000 ft^3/s on May 22, 1985, was measured to be about 16 ft/s on the basis of timing drifting boats. Mean velocities over the deposit in the low-velocity area at the same time did not exceed 1.5 ft/s (fig. 12*B*). Discharge over the deposit was about 160 ft^3/s, which was only 0.4 percent of the main-channel discharge. The measured mean velocities at Eighteen Mile Wash are characteristics of velocities in low-velocity areas measured elsewhere.

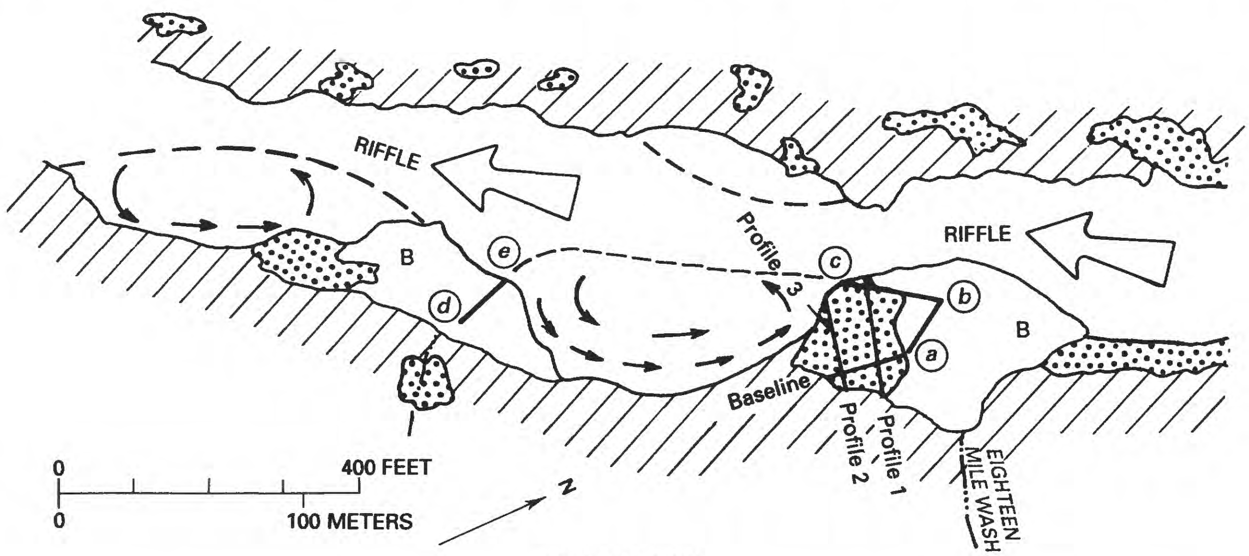
Sand transport in the low-velocity area at 45,000 ft^3/s was upstream, away from the primary-eddy return current. Comparison of topographic surveys shows that approximately 13,000 ft^3 of very fine and fine sand was deposited between May 22 and the recession of high flows 33 days later. Aggradation occurred by upstream migra-

FIGURE 10.—Separation deposits downstream from Badger Creek Rapid, July 30, 1985. Separation deposits mantle Badger Creek debris fan in foreground and Jackass Creek debris fan on opposite bank. Photograph site shown on figure 5.

tion of the slipface (fig. 13) and by deposition on the downstream-facing slope. Sedimentary structures within the deposit consisted mainly of climbing ripples in the downstream part and planar foreset beds of the advancing slipface in the upstream part. If the measured volume change resulted from continuous deposition over the 33 days when the deposit was submerged, then the rate of deposition was about 390 ft^3/d or about 0.03 vertical ft/d. It is possible, however, that deposition occurred more rapidly in only a small percentage of the total inundation period. The low discharge across the deposit and the fact that climbing ripples do not have supercritical angles of climb, however, suggest that the deposition was at a slow rate. Supercritically climbing ripples, in which all parts of the ripple surface are preserved, are associated with high sedimentation rates (Hunter, 1977).

Comparison of currents at Eminence Break Camp (fig. 14) and bathymetric maps (fig. 15) and bed-surface profiles (fig. 16) for the high-elevation part of profile 2 between April and September 1985 also shows aggradation in areas upstream from the primary-eddy return-current channel. The area was inundated by a secondary eddy and low-velocity area during the bathymetric surveys made at 26,000 and 27,200 ft^3/s and during the high flows of May and June 1985.

Separation deposits typically have a spit near the junction between the shoreline that faces the main current and the shoreline that faces the recirculation



EXPLANATION

- RIVER-DEPOSITED OR REWORKED VERY FINE TO MEDIUM SAND (October 21, 1984)
- B — TRIBUTARY DEBRIS FAN—Boulders, cobbles, gravel, sand, poorly sorted; boulders cover more than 50 percent of surface area except in tributary streambed
- TALUS AND BEDROCK
- a — LOCATION OF SEPARATION POINT, 45,000 CUBIC FEET PER SECOND, MAY 22, 1985
- b — LOCATION OF SEPARATION POINT, 28,000 CUBIC FEET PER SECOND, AUGUST 2, 1985
- c — LOCATION OF SEPARATION POINT, 4,200 CUBIC FEET PER SECOND, OCTOBER 9, 1985
- d — LOCATION OF REATTACHMENT POINT, 28,000 CUBIC FEET PER SECOND, AUGUST 2, 1985
- e — LOCATION OF REATTACHMENT POINT, 4,200 CUBIC FEET PER SECOND, OCTOBER 9, 1985
- d—e PATH OF MOVEMENT OF SEPARATION OR REATTACHMENT POINTS
- GENERALIZED SURFACE-FLOW DIRECTION IN RECIRCULATION ZONES, 4,200 CUBIC FEET PER SECOND
- SURFACE-FLOW DIRECTION OF MAIN CURRENT, 4,200 CUBIC FEET PER SECOND
- APPROXIMATE LOCATION OF SEPARATION SURFACES, 4,200 CUBIC FEET PER SECOND
- Profile 1— LOCATION OF PROFILE; SEE TABLE 13—Profiles 1 and 2 shown in figure 12

FIGURE 11.—Surficial geology and hydraulic features near Eighteen Mile Wash.

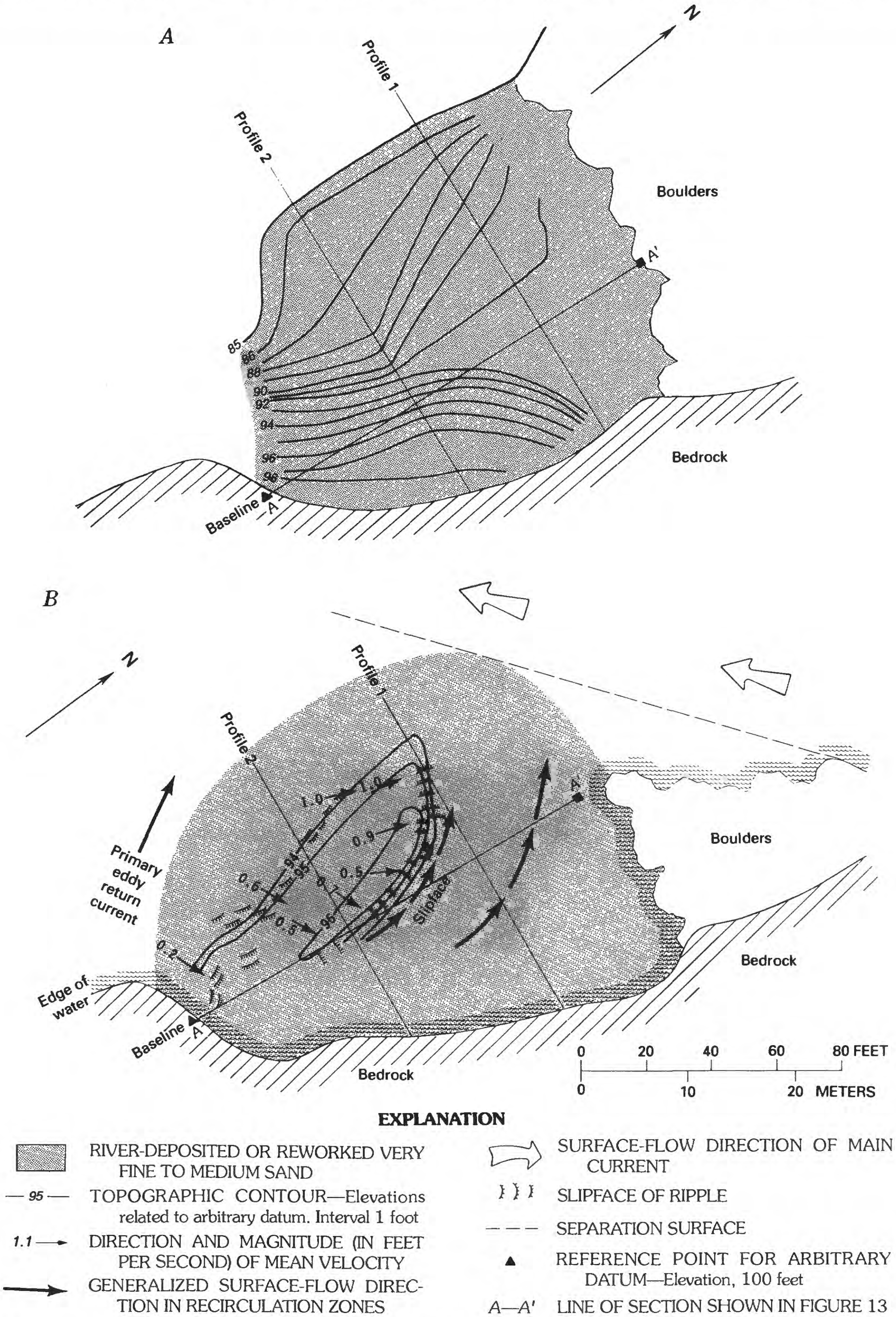


FIGURE 12.—Topography of a separation deposit at Eighteen Mile Wash in 1975 and at selected times in 1985. *A*, July 7, 1975, on the basis of cross-section surveys (Howard, 1975) and ground photography. *B*, May 22, 1985, discharge 45,000 ft^3/s. *C*, August 2, 1985, discharge 30,000 ft^3/s. *D*, October 9, 1985, discharge 4,100 ft^3/s.

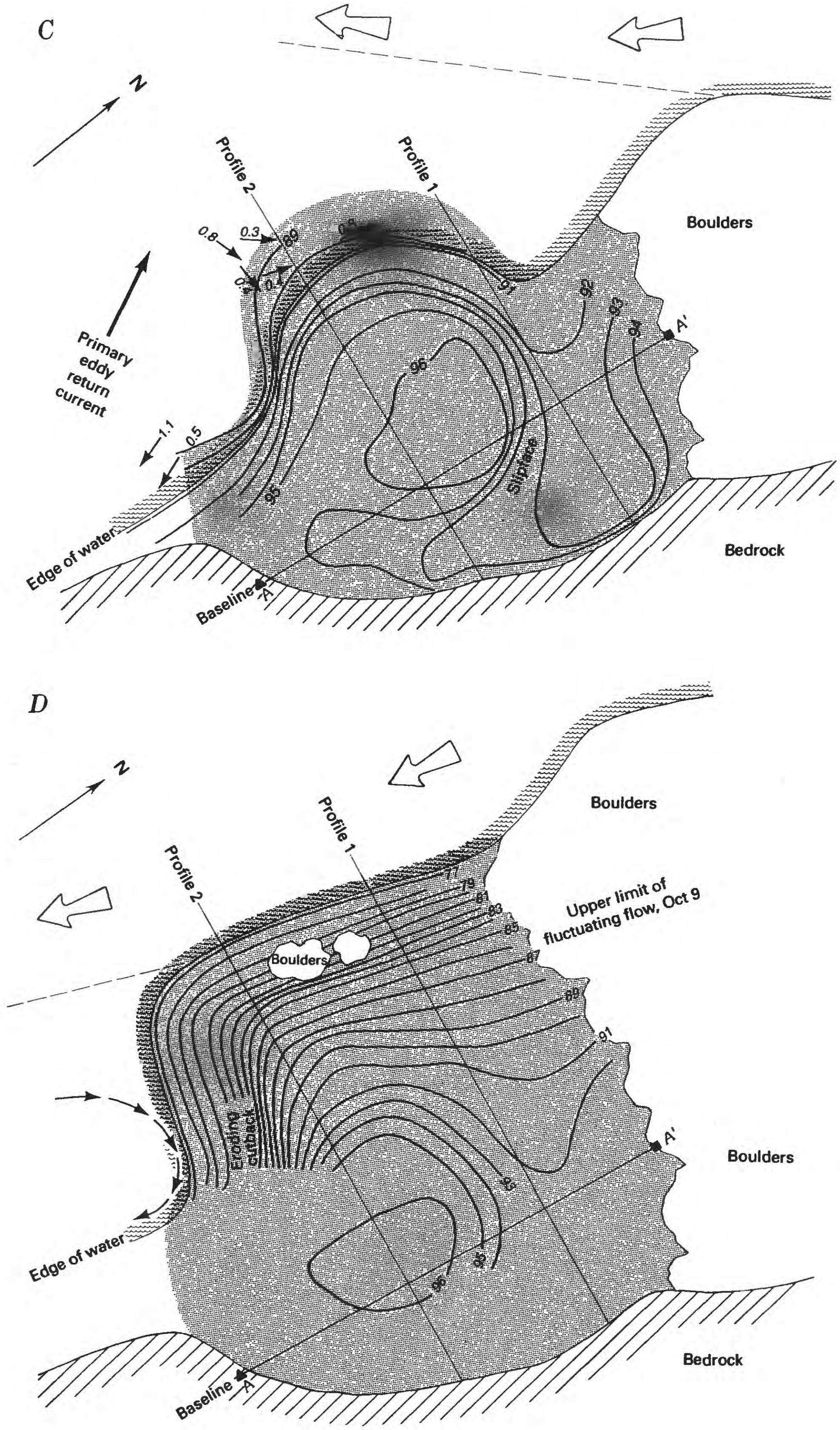
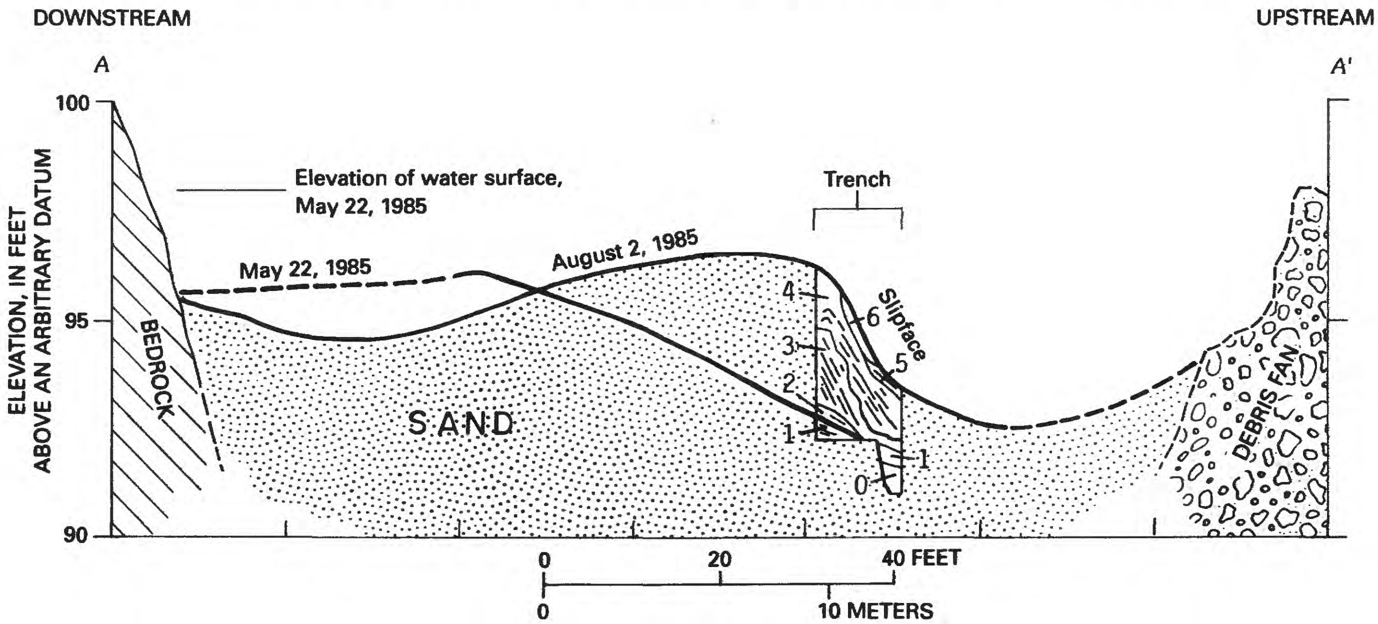


FIGURE 12.—*Continued*

zone, such as the spit at Eminence Break Camp (fig. 14). Observations at National Rapid in June 1985 suggest that these spits form where sediment transported by a primary or secondary eddy is rapidly deposited into a low-velocity area.

Separation deposits are not found downstream from all debris fans. For separation deposits to form, a stage-discharge relation and local topography must result in the existence of a low-velocity area and (or) secondary eddies upstream from the primary-eddy return current at some discharges. Debris fans with steep, high slopes do not typically have separation deposits because no discharges occur at which a low-velocity area or secondary eddy exists. At the study site Above Cathedral Wash, only discharges much greater than 100,000 ft^3/s would overtop the constricting fan. Some fine sediments exist on the talus at elevations associated with floods in excess of 100,000 ft^3/s. No low-elevation part of the separation deposit projects downstream, however, because the primary-eddy return current is adjacent to the talus at discharges less than 100,000 ft^3/s. In contrast, at Eminence Break Camp, a large low-velocity area exists between the debris fan and the primary-eddy return current at discharges between 21,000 and at least 44,000 ft^3/s (fig. 14, bottom). Mean velocities in this area at Eminence Break Camp were always less than 1.0 ft/s. At Saddle Canyon, separation deposits mantle the upper surface of the debris fan but do not project offshore. Low-velocity areas are present upstream from the primary-eddy return current only at discharges above about 31,500 ft^3/s, and the separation deposit is confined to a small high-elevation area (fig. 17).

Separation deposits may be subjected to significant wave action, particularly near steep rapids such as Nevills Rapid at river mile 75.5 and Granite Rapid at river mile 93.5. Howard and Dolan (1981) found that alluvial deposits had been reworked during approximately 10 years of operation of Glen Canyon Dam.



EXPLANATION

6 WINDBLOWN SAND

5 FINE TO VERY FINE SAND—Ripple crosslamination in wash, some planar lamination

4 VERY FINE SAND—Complex ripple crosslaminae and climbing ripples, grade offslope into organic-rich sand

3 FINE SAND—Steep foresets, disturbed upper surface, distinct avalanche laminae below, grades into "structureless" sand in wash below organic-rich sand of unit 4

2 FINE TO VERY FINE SAND—Planar foreset laminae and irregular distorted crosslaminae in sets

1 FINE TO VERY FINE SAND—Highly truncated ripple crosslaminae with organic lenses

0 RED SANDY GRAVEL—1984(?) flash flood deposit

FIGURE 13.—Topography and sedimentology associated with upstream advancement of slipface, May 22, 1985, and August 2, 1985, at Eighteen Mile Wash. Location of section shown in figure 12. Descriptions by J.N. Moore, University of Montana, August 2, 1985. Vertical exaggeration 5×.

Adjustment to the different intensities of current and wave action that exist at different sites had occurred. For example, they found that where nearshore currents exceeded 1 ft/s or where swash runup exceeded 3 ft, parts of the deposit within the zone of fluctuating discharges had low gradients (approximately 3° to 9°) and were composed of medium sand (0.19 mm median grain size). Where nearshore currents and swash were less intense, the median grain size was less than 0.14 mm and gradients exceeded 10°. Sampling of deposits formed in 1983 or later does not demonstrate this kind of sorting. For example, some of the coarsest deposits reported by Lojko (1985) are at low-energy sites and some of the finest are at high-energy sites. The lack of sorting observed in deposits formed since 1983 is due to the fact that these primary fluvial deposits had not yet been subjected to fluctuating flows when they were sampled.

Separation deposits may be finer grained than reattachment deposits. Graphic means (Folk, 1968) were calculated for each of 67 samples collected at 22 sites between Lees Ferry and Bright Angel Creek (table 6). The mean value of the graphic means of each of 12 samples of 7 separation deposits deposited after 1983 was 0.17 mm. A similar mean value was computed for 10 samples of 2 reattachment deposits; the sample mean was 0.25 mm. In terms of the total number of samples of these two deposits, the two sample means differ significantly at the 95-percent confidence level. The small number of sample sites, however, precludes definitive statistical conclusions. This difference between grain size of separation and reattachment deposits is spatially illustrated at Saddle Canyon. Three samples of separation deposits at elevations associated with discharges in excess of 45,000 ft^3/s had graphic means between 0.10 and 0.13 mm (fig. 17). Samples of reattachment deposits associated with discharges exceeding 25,000 ft^3/s were all equal to or coarser than 0.15 mm. The grain-size difference between separation and reattachment deposits is related to the lower mean velocities associated with low-velocity areas, which are the depositional environment of separation deposits, in contrast with the higher mean velocities of reattachment point areas.

REATTACHMENT DEPOSITS

Reattachment deposits occur at the downstream end of many recirculation zones and project upstream as spits (fig. 3). A slipface typically exists along the shoreward side of the spit (fig. 18). The form of these deposits is well displayed in aerial photographs (fig. 14) taken at low discharges of about 6,000 ft^3/s. These deposits were directly observed during clear-water flows at discharges of 30,000 and 45,000 ft^3/s and were mapped during bathymetric surveys at discharges of 15,000 to 25,000 ft^3/s. Although the deposits tend to move and adjust to changing discharge, the basic shape remains the same.

Reattachment deposits form in primary eddies and build upstream from the reattachment point. Direct observations of surface-current patterns, migrating bedforms, and bedform-migration directions exposed in trenches show that sand transport over most of these deposits is away from and perpendicular to the main current direction. Sand is transported across the top of the deposit, cascades down the slipface, and is swept upstream by the primary-eddy return current.

Reattachment deposits fill recirculation zones to a varying extent. The low flows of October 1984 (fig. 9) exposed much of the bed of the recirculation zone at some locations (fig. 17), whereas at other locations, only a part of the deposit was exposed. Comparison of the area of reattachment deposit exposed at low discharge in 1973 with the area exposed in 1984 for selected sites shows that at sites where exposed area decreased, the decrease occurred in the upstream part of the deposit (fig. 19). Topographic and side-scan sonar data indicate that the decrease in exposed area is due to (1) loss of sand from recirculation zones and (2) redistribution of the same mass into a smaller area of higher relief.

The topography of a typical reattachment deposit consists of a mound of sand or crest near the center of the deposit and a lower elevation extension of the crest downstream and onshore (fig. 18). A third area of higher elevation formed by high discharges may exist farther downstream.

The higher parts of reattachment deposits typically extend the farthest downstream. This pattern is related to the hydraulic changes in recirculation zones that occur with decreasing discharge. Reattachment points typically migrate downstream with increasing discharge and migrate upstream as discharge subsequently decreases (fig. 5). Therefore, alluvial deposits created at the highest discharges near the high-discharge reattachment point are abandoned by the recirculation zone as it decreases in size. Any downstream part of the sand deposit is subjected to downstream-directed flow, and eroded sand from these high banks is deposited in the main channel and not in the recirculation zone (fig. 20). Erosion or redistribution of sand upstream from the migrating reattachment point results in redistribution of sand within the recirculation zone and upstream migration of the slipface. Fluctuating flows may result in further redistribution of sand within recirculation zones. The crest of a reattachment deposit formed under steady flows may be changed to a gently sloping continuous surface under fluctuating flows, such as occurred at Blacktail Rapid (figs. 21, 22, and 23). The farthest downstream part of the reattachment deposit nearly always degrades during fluctuating flows. For example,

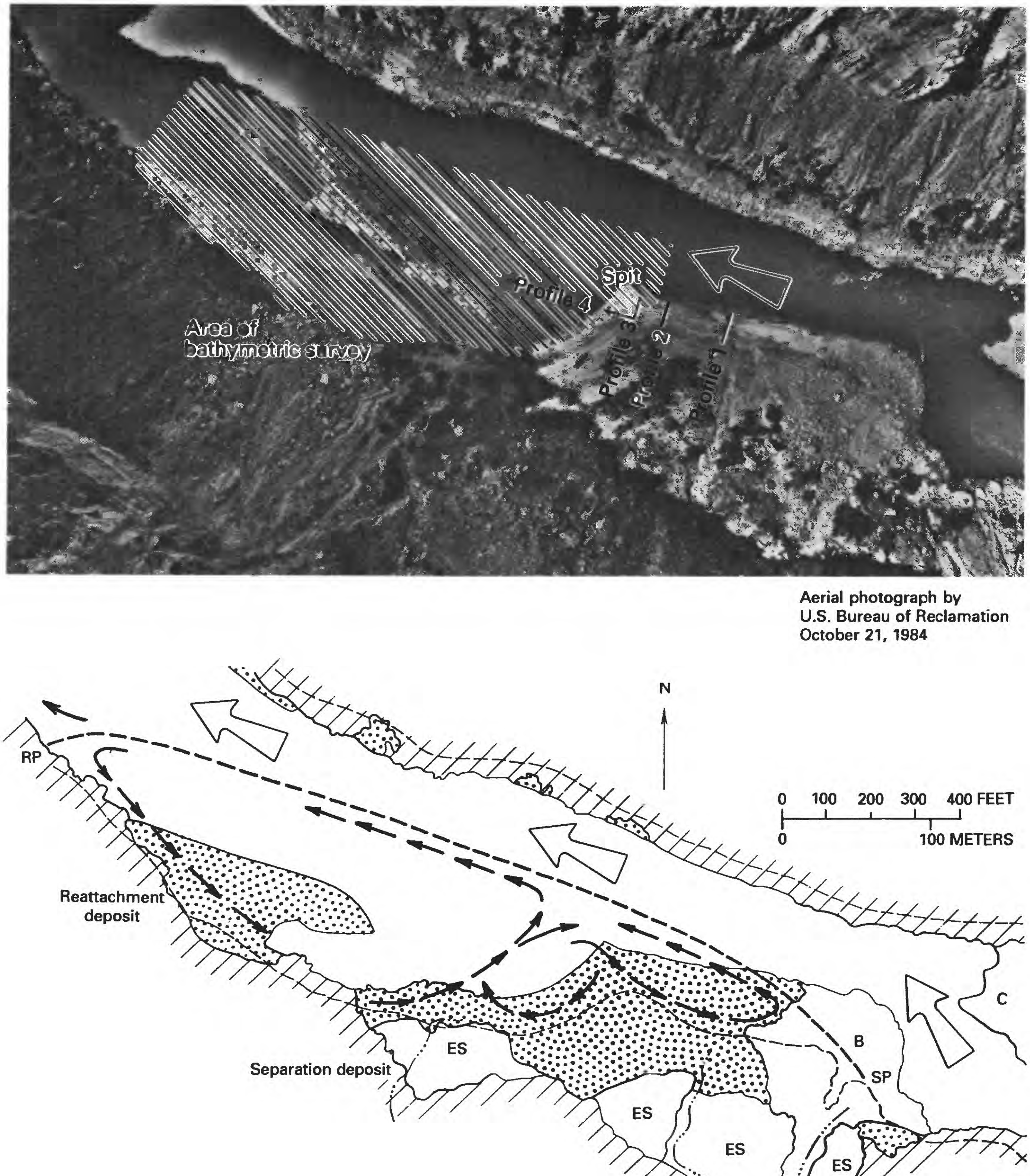


FIGURE 14.—Surficial geology and hydraulic features at Eminence Break Camp. North is toward the top.

surveys at Blacktail Rapid (fig. 23, profile 1) and One Hundred and Twenty-Two Mile Creek showed significant bank retreat in this area between October 1985 and January 1986.

The effect of flow recession and recirculation zones that decrease in length on erosion of downstream parts of reattachment deposits was observed at Stone Creek where a steady discharge of about 40,000 ft^3/s decreased to about 35,000 ft^3/s in June 1985. Overnight, a cutbank downstream from the new reattachment point retreated 2.75 to 3.5 ft and degraded about 1 ft. Two months later, the entire bar had been uniformly degraded to a new lower level.

Substantial reworking of reattachment deposits may occur at high discharges. At the site Above Cathedral Wash, a truncated pre-1983 deposit was exposed in a trench, indicating that sand close to the river channel had been transported and redeposited since deposition of the older buried surface (fig. 24). Opposite Nineteen Mile Canyon, a similar buried pre-1983 surface was eroded but not entirely truncated. The existence of major truncation surfaces within reattachment deposits and the evidence that some reattachment deposits were significantly eroded by the 1983 high flows (see section entitled "Aggradation and Degradation of Alluvial Sand Deposits, 1965–86") indicate that much of the sand in reattachment deposits is scoured, transported, and redeposited by high discharges. The form and sedimentology of reattachment deposits demonstrate that the final form is determined during flow recession. The discharge and sediment-transport characteristics of that recession, therefore, are important in determining the form and extent of the resulting deposit.

Bedload samples were collected using a wading-type Helley-Smith sampler (Helley and Smith, 1971) in recirculation zones below Kwagunt Rapid (river mile 56) and above the confluence with the Little Colorado River (river mile 60) (table 5). These sites generally are representative of recirculation zones at moderate discharges of about 28,000 ft^3/s. Mean velocities probably were less than 2 ft/s where samples were collected. At both sites, the samples collected were well-sorted medium sand (mean value of samples 0.30 mm). Coarser sand, therefore, was in transport at a discharge of 28,000 ft^3/s in the recirculation zones than is found in typical separation or reattachment deposits. This comparison suggests that separation and reattachment deposits can be redistributed in at least some recirculation zones at moderate discharges.

Reattachment deposits tend to be coarser than separation deposits (table 6). Reattachment deposits may also coarsen with decreasing elevation at a site, such as at Saddle Canyon (fig. 17). Three samples of 1983 deposits at that site are fine sand (table 5, JCS–10, JCS–11, JBG–18) or medium sand (JBG–17). Samples from areas inundated by flows less than 25,000 ft^3/s (table 5, JCS-6, JCS-7, JCS-8, JCS-9) are medium sand except for one sample (JCS–5) of a rippled veneer of very fine sand. This latter deposit is representative of mainstem deposition when tributaries are contributing sediment to the Colorado River.

UPPER-POOL DEPOSITS

Upper-pool deposits line the channel banks upstream from many debris-fan constrictions. The deposits are used as campsites where vegetation has been cleared or where tamarisk trees do not densely cover an area, such as above North Canyon Rapid at river mile 20.3 and above Crystal Rapid at river mile 98.0. In plan view, these deposits are linear and parallel to the channel, consist of different terrace levels, and typically have a low-elevation spit that projects into the channel in an upstream direction. Where spits exist, they are associated with small recirculation zones upstream from a rapid and are formed by the same processes that form reattachment deposits.

EXPLANATION

RIVER-DEPOSITED OR REWORKED VERY FINE TO MEDIUM SAND (October 21, 1984)

ES — EOLIAN 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

EDGE OF WATER—May 25, 1985, 41,000 cubic feet per second

SEPARATION SURFACE—42,000 cubic feet per second

GENERALIZED SURFACE-FLOW DIRECTION IN RECIRCULATION ZONES—41,000 cubic feet per second

SURFACE-FLOW DIRECTION OF MAIN CURRENT

SP — SEPARATION POINT

RP — REATTACHMENT POINT

Profile 1— LOCATION OF PROFILE LINES (Numbers refer to table 13)

FIGURE 14.—*Continued*

High-elevation parts of upper-pool deposits probably are created by low-velocity downstream-directed overbank flows. An example of an upper-pool deposit is the campsite upstream from Granite Rapid. This deposit is adjacent to the pool above the rapid. The plan-view form of the deposit exposed at low flow includes a spit projecting upstream into the channel with a slipface on the shoreward side. At about 25,000 ft³/s this deposit is located at the downstream end of a recirculation zone. Higher exposures of sediment deposited during 1983

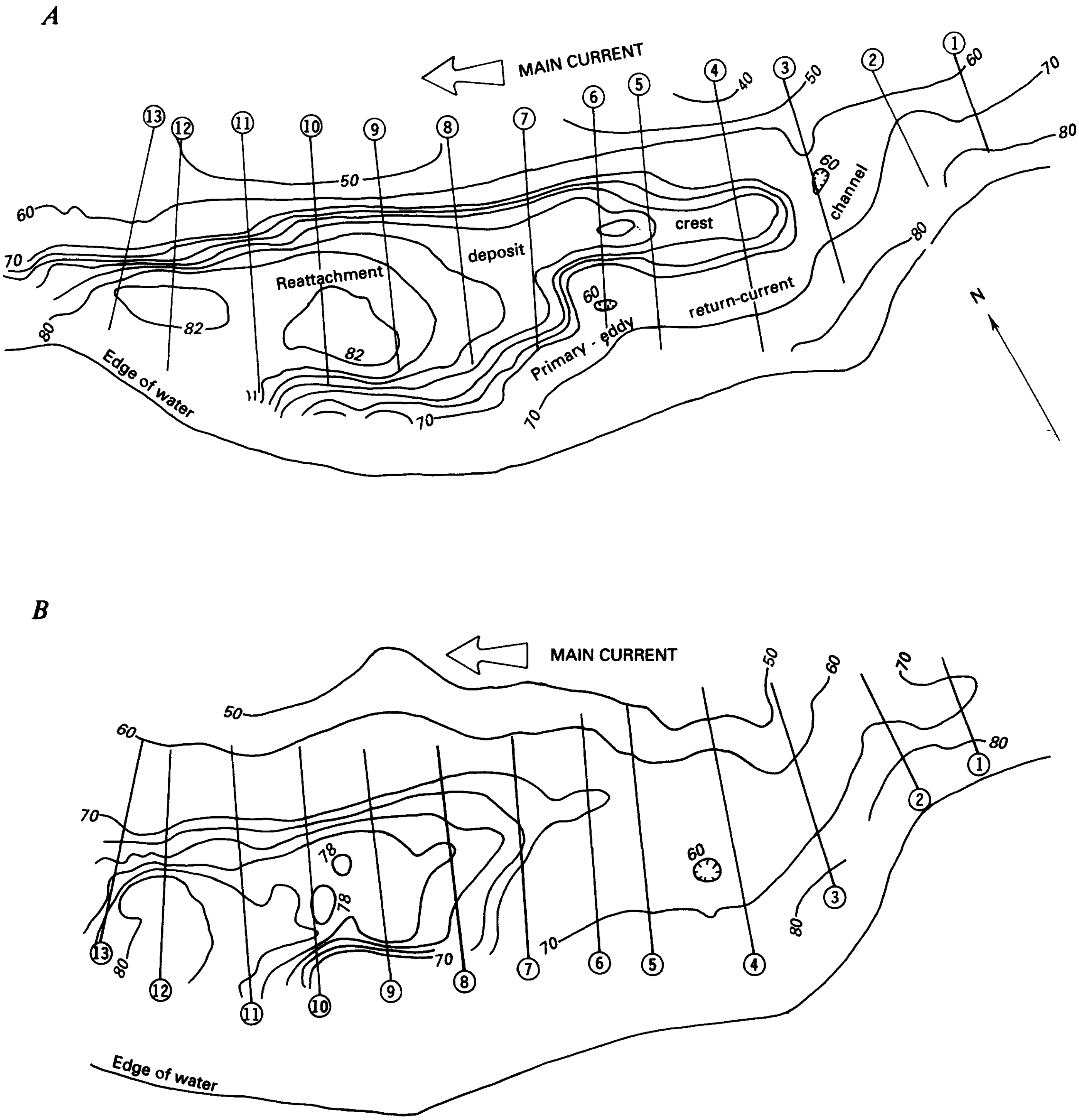


FIGURE 15.—Bathymetric contours within the recirculation zone at Eminence Break Camp. *A*, April 16, 1985, discharge 26,100 ft³/s. *B*, September 2, 1985, discharge 27,200 ft³/s. *C*, January 16, 1986, discharge 23,600 ft³/s.

show that at least a part of the deposit was created by upstream-directed flows, which indicates that this recirculation zone was larger at higher discharges.

Upper-pool deposits may be subjected to erosive downstream-directed currents when the downstream constriction is overtopped. In August 1985, upper-pool deposits at Cathedral Wash at river mile 2.3 and Six Mile Wash at river mile 5.7 were examined briefly to determine the effects of discharges of about 45,000 ft^3/s. At each site, the upper-pool deposits had been eroded.

CHANNEL-MARGIN DEPOSITS

In some reaches, particularly where the channel is wide, sand deposits line the channel from a few hundred feet to nearly a mile. Channel-margin deposits are deposits that either lack the characteristic form of separation or reattachment deposits, or whose location in relation to recirculation zones was not known. Few channel-margin deposits were investigated in detail; however, sedimentary structures within three such deposits (left bank beneath the U.S. Geological Survey cableway above the Little Colorado River confluence, Above Grapevine Rapid at river mile 81.1, and Pumpkin Springs at river mile 212) indicate that the deposits were formed by recirculating currents. Typically, these deposits mantle bedrock or talus. At low discharges, bedrock or talus may exist between the deposit and the water's edge. At other locations, parts of the channel-margin deposit have the form of a reattachment deposit. At low discharge, these deposits are adjacent to the water's edge.

DISTRIBUTION OF DEPOSITS

Alluvial deposits large enough for use as campsites are most numerous between river miles 45 and 75, 115 and 140 (fig. 25), and 160 and 225. These areas are within

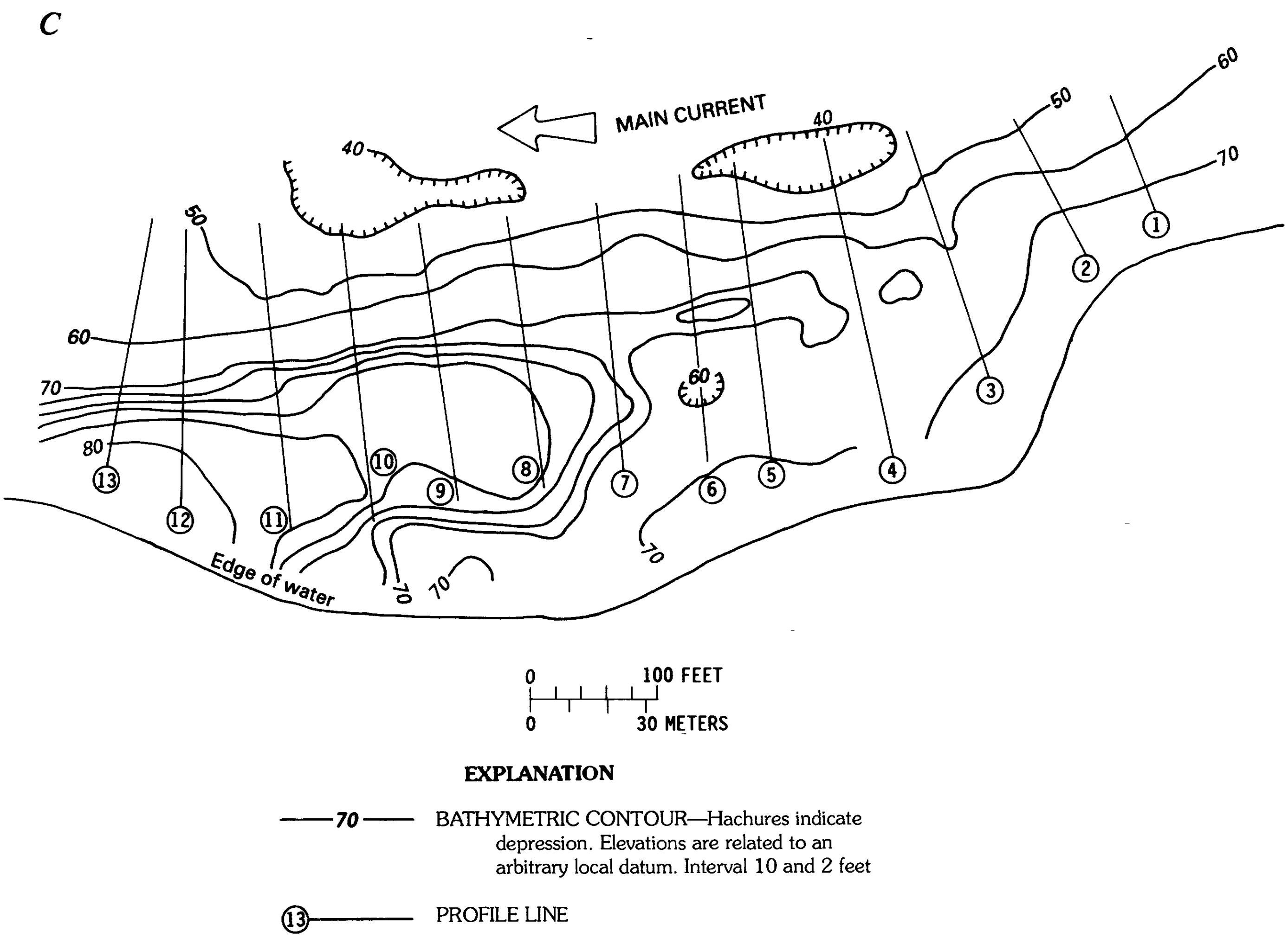


FIGURE 15.—*Continued.*

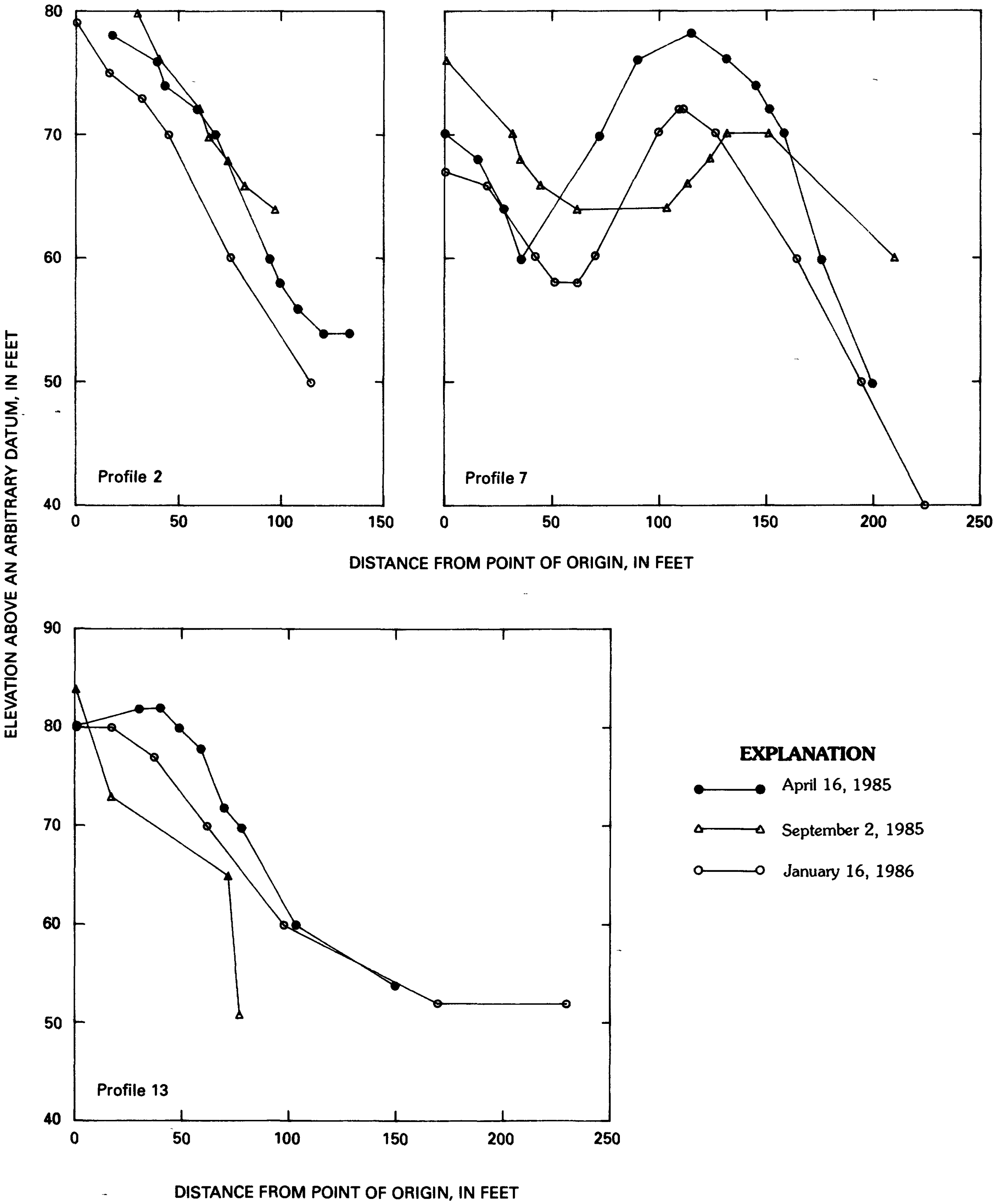


FIGURE 16.—Bed-surface profiles (see figure 15 for locations) of a recirculation zone at Eminence Break Camp.

Lower Marble Canyon, Furnace Flats, Aisles, Middle Granite Gorge, and the Lower Canyon. These reaches include all those designated as wide (table 2) except the Permian Section, where availability of campsites is limited by dense tamarisk tree groves and not by small alluvial sand deposits. Although the Aisles and Middle Granite Gorge reaches are designated narrow, there is great variability in channel width in these reaches, and campsites are located in parts of the reaches with wide channels or large expansions. Measurements of the area of major alluvial sand deposits in seven reaches show that average deposit size is also largest in the widest reaches (table 7). At a discharge of 5,600 ft^3/s, average campsite size was 60,000 ft^2 in Lower Marble Canyon but 8,200 ft^2 in the Muav Gorge. The smallest campsites are associated with reaches where channel-margin deposits are the main type (table 2). The largest campsites in Lower Marble Canyon are large reattachment deposits exposed at low discharge. Channel-margin and separation deposits are large in this reach as well.

Campsites noted on figure 25 are those inventoried by Brian and Thomas (1984) and are listed in appendix A. The type of each deposit was determined by locating campsites on aerial photographs and comparing their form with the characteristic shapes of different types of deposits as described in this section. Observations of surface-current patterns at these sites aided in classifying some sites.

The number of separation deposits ranges between 0.2 and 1.0 deposits per mile throughout most of the river (table 2). The number of separation deposits used as campsites does not increase in wide reaches, although total number of campsites increases (fig. 25). Average area of major separation deposits is greater in wide reaches and varies in seven reaches between 14,500 and 57,000 ft^2. As described above, local topography of debris fans is the most important determinant in the occurrence of separation deposits. These deposits form wherever local site conditions permit, regardless of reach characteristics.

Channel-margin deposits are common in Lower Marble Canyon, Furnace Flats, and the Muav Gorge. At low discharges, these deposits have an average area of 73,000 ft^2 in Lower Marble Canyon but only 7,500 ft^2 in the Muav Gorge (table 7). The largest channel-margin deposit in the Muav Gorge is 23,000 ft^2 (river mile 140.2). Campsites in Furnace Flats are similar in size to those of Lower Marble Canyon. Large campsites are typically associated with reattachment deposits and may be formed by similar processes. In Muav Gorge, channel-margin deposits typically mantle talus or bedrock in small reentrants. Reattachment deposits large enough to be used as campsites are numerous only between river miles 45 and 60 and between river miles 115 and 125.

AGGRADATION AND DEGRADATION AT EIGHTEEN MILE WASH, 1965–86

At some sites, we have enough data to develop a history of aggradation and degradation from 1965 to 1986. The interpretation of data in the following section is illustrative of the interpretation of changes at other sites summarized in the section entitled "Aggradation and Degradation of Alluvial Sand Deposits, 1965–86."

HYDRAULIC CONDITIONS

A small separation deposit mantles the downstream part of a low debris fan at the mouth of Eighteen Mile Wash about 18.1 river miles downstream from Lees Ferry (fig. 11). About 15,000 ft^2 of sand was exposed at 5,600 ft^3/s and covered about 30 percent of the Eighteen Mile Wash debris fan in October 1984. Boulders exposed along the edge of water at the base of much of the sand deposit at 2,500 ft^3/s in October 1985 demonstrate that the sand deposit mantles the debris fan.

The Colorado River flows through a riffle of only slightly steepened water slope as it flows around the debris fan. A slope of 0.002 to 0.003 over a 600- to 700-ft reach exists at discharges between 4,000 and 45,000 ft^3/s. The reach has a total elevation drop of about 3 ft or about one-fifth the drop of major Grand Canyon rapids. A large, deep recirculation zone exists on the left side of the channel immediately below the riffle. Bathymetric surveys at a discharge of about 30,000 ft^3/s indicated average water depths of 20 ft and a maximum depth of 37 ft in this zone. The deepest part of the nearby main channel is about 50 ft. The recirculation zone exists at all discharges between at least 2,500 and 45,000 ft^3/s and extends in length by 35 percent as discharges increase from 3,000 to 45,000 ft^3/s (fig. 6). Over this discharge range, the separation point is located on the downstream margin of the exposed boulder deposit and migrates downstream along the slope of the separation deposit as the discharges decrease below about 25,000 ft^3/s (fig. 11). The location of the upstream part of the primary-eddy return current changes little with discharge.

Stage changes are significant in this reach where the channel width-to-depth ratio is less than 10. Between 5,000 and 45,000 ft^3/s, stage rises 20 ft; within the normal fluctuating flow range of 5,000 to 30,000 ft^3/s, stage changes are about 14 ft. At the highest observed discharges (45,000 ft^3/s), most of the Eighteen Mile Wash fan and the entire sand bar are submerged (fig. 12*B*). On May 22, 1985, at a discharge of 45,000 ft^3/s, the entire deposit was submerged by a low-velocity area, as described in the previous section. Current directions and bedform migration at this discharge show that flow and sediment transport over the deposit was upstream. A

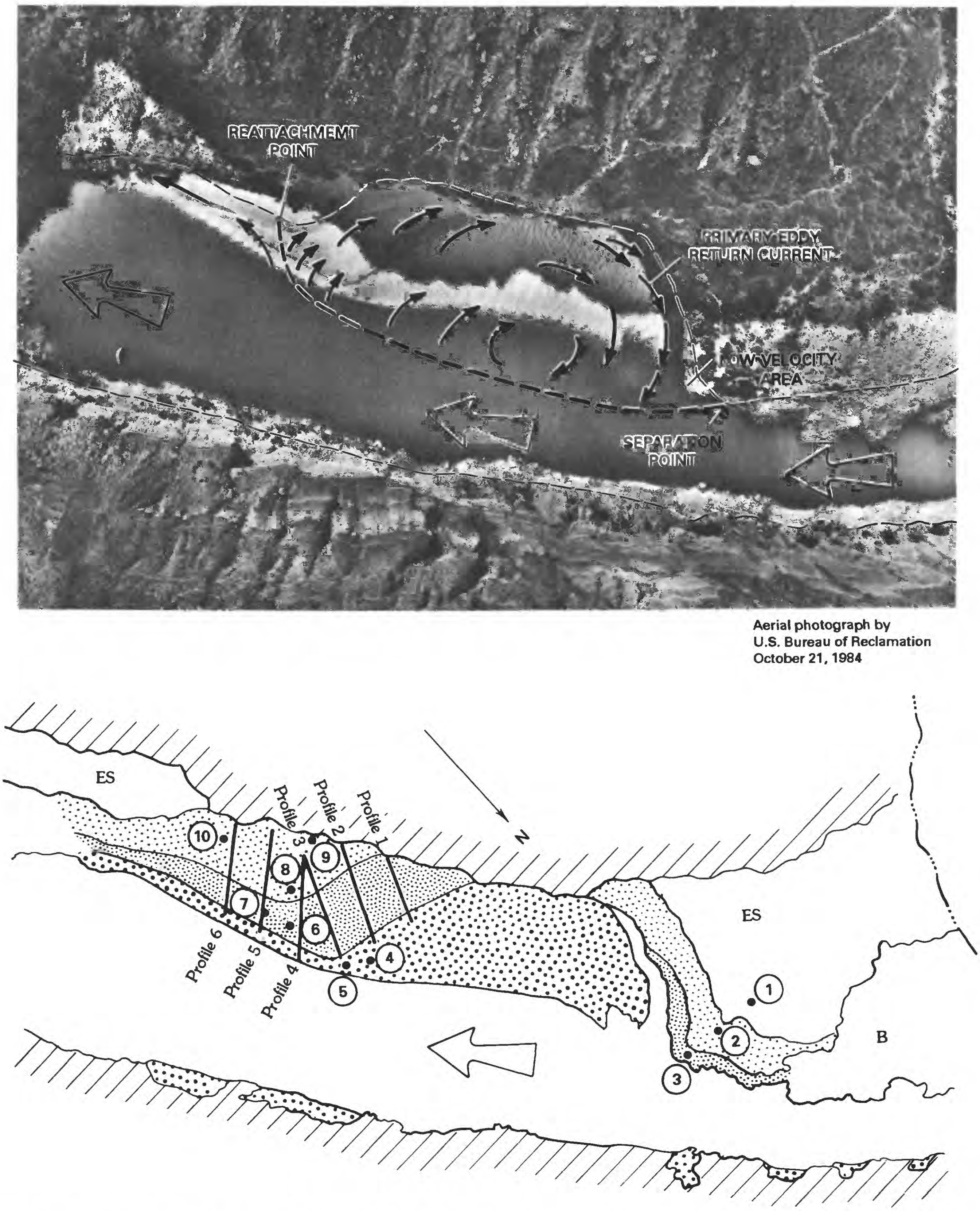


FIGURE 17.—Surficial geology, hydraulic features, area of sand inundated at different discharges, and sediment-sampling sites at Saddle Canyon.

channel existed upstream from the slipface where flow was directed toward the main current.

In August 1985, conditions in the recirculation zone were observed at a discharge of about 28,000 ft^3/s. The primary eddy was in approximately the same location; however, the entire surface of the deposit was exposed (fig. 12*C*). A small secondary eddy existed offshore from the downstream part of the deposit, and the mean velocities in this eddy did not exceed 1.2 ft/s. Elsewhere along the deposit face, measured mean velocities did not exceed 1 ft/s.

TOPOGRAPHIC CHANGES OF THE SEPARATION DEPOSIT

The first available aerial photograph showing topography of the deposit (fig. 26*A*) was taken May 14, 1965, at a daily mean discharge of about 26,700 ft^3/s and at a stage of about 91 ft. Elevation of stage was estimated by comparison of shorelines in the 1965 photograph with mapping of the shoreline in 1985 at various discharges.

EXPLANATION

RIVER-DEPOSITED OR REWORKED FINE TO MEDIUM SAND—Inundated by discharges less than 22,000 cubic feet per second

RIVER-DEPOSITED OR REWORKED VERY FINE TO MEDIUM SAND—Inundated by discharges between 22,000 and 48,500 cubic feet per second

RIVER-DEPOSITED OR REWORKED VERY FINE TO FINE SAND—Inundated by discharges between 48,500 and 97,300 cubic feet per second

ES EOLIAN SAND OR TERRACE DEPOSITS—Silt to 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

TALUS AND BEDROCK

EDGE OF WATER—May 15, 1986, 48,500 cubic feet per second

SEPARATION SURFACE—48,500 cubic feet per second

GENERALIZED SURFACE-FLOW DIRECTION IN RECIRCULATION ZONES—48,500 cubic feet per second

SURFACE-FLOW DIRECTION OF MAIN CURRENT

•2 SEDIMENT SAMPLE SITE, TABLE 5

1 - JCS-13	6 - JCS-10
2 - JCS-14	7 - JBG-17, -18
3 - JCS-15	8 - JCS-11
4 - JCS-05, -06, -07	9 - JCS-12
5 - JCS-08, -09	10 - JBG-16

FIGURE 17.—*Continued*

The shoreline along bedrock, talus, and the debris fan are very similar to the shoreline mapped in August 1985 at a discharge of about 28,000 ft^3/s. River stage in the photograph of 1965 was estimated by referring to the surveyed elevation of the water surface in August 1985. Sand exposed in the photograph of 1965 exceeds the elevation of the observed water surface and thus must be higher than 91 ft (fig. 27).

In 1965, the deposit had an L-shape and bedrock was exposed between the deposit and water's edge at the downstream end. The part protruding toward the opposite bank may actually have been smaller than in 1985. A low area between the exposed debris fan and the sand deposit is believed to be a remnant return-flow channel.

Better topographic control exists for the data of the mid-1970's. An aerial photograph was taken on June 16, 1973, at a discharge of about 4,500 ft^3/s (fig. 26*B*). River stage was estimated to be about 78 ft. In the same year, photographs were taken from nearby cliffs accessible from the river, and on July 7, 1975, Howard (1975) surveyed the topography of the deposit along two profiles.

A topographic map of the deposit as it existed in 1975 was constructed from these data (fig. 12*A*). The exposed fan and separation deposit in a photograph taken October 21, 1984, at a discharge of 5,600 ft^3/s (fig. 26*C*) are similar in plan view to these deposits in 1973 and 1975. Data from the topographic survey of 1975, however, show that the shoreward part of the deposit was about 87 ft in elevation and that the sand surface rose to about 98 ft in elevation near the bedrock wall (fig. 27). A substantial part of this deposit, therefore, degraded at least 4.5 ft between 1965 and 1973. If the assumption is made that no change occurred in the estimated stage-to-discharge relation, this surface would be just overtopped by a discharge of 18,000 ft^3/s. Between 1965 and 1973, maximum powerplant flows were about 24,000 ft^3/s (Howard, 1975) or a stage of 89.5 ft, which is sufficient to inundate the main surface to a depth of about 2.5 ft. The air and ground photographs of the mid-1970's also document tamarisk trees at approximately a stage associated with flows of 24,000 ft^3/s. The deposit was armored on all sides in 1973 (fig. 26*B*).

After the flood of 1983, a resurvey of the deposit on September 13, 1983 (Beus and others, 1985), showed aggradation of about 6.5 ft on the stream side and about 4 ft of erosion of the high sand bank that had existed along the bedrock cliff (fig. 27). The elevation of the crest of the deposit was about 94 ft. Comparison of the discharge record of 1983 and the stage-to-discharge relation shows that the lowest discharge immediately before exposure of the deposit on August 10 was about 36,000 ft^3/s (stage, 94 ft). This discharge had existed for about 8 days (fig. 28*A*). At that time, the separation deposit was within 1 ft of this stage. The river had been receding from its peak discharge of 97,300 ft^3/s, which had occurred on June 29, 1983.

A survey of the deposit on August 1, 1984 (Beus and others, 1985) (fig. 27), documented further aggradation of about 2 ft on the main surface to an elevation of about 96 ft. On the basis of the hydrograph of that year (fig. 9) and the local stage-to-discharge relation, the only flows that could have caused this aggradation were the high releases of May to July 1984, when daily mean discharge was about 45,000 ft^3/s and stage was about 98 ft (fig. 28*B*). The bar aggraded to within 2 ft of the water surface. Although data are not available to date this aggradation more precisely, data collected in 1985 provide an insight into deposit response during high flows.

A resurvey of the deposit on May 22, 1985, showed that the deposit was much smaller than in 1984 (figs. 12B and 27). The river had been flowing between 38,000 and 46,000 ft^3/s since May 17, 1985 (fig. 9). Aside from a 6-day period when daily mean discharge was about 30,000 ft^3/s, discharges exceeding 40,000 ft^3/s continued until June 25 (fig. 28*C*). On the basis of the stage-to-discharge relation, the deposit would have been exposed on June 28 when discharges receded below 40,000 ft^3/s. Resurveying on August 2, 1985 (figs. 12*C* and 27) showed that at least 2,900 ft^3 of sand, and more likely 13,000 ft^3, had been deposited since the survey of May 22 despite the fact that the crest of the deposit had not increased in elevation. The latter estimate is based (1) on projection of surveyed slopes for unsurveyed areas by assuming the angle of repose and (2) on extension to known debris-fan deposits at depth.

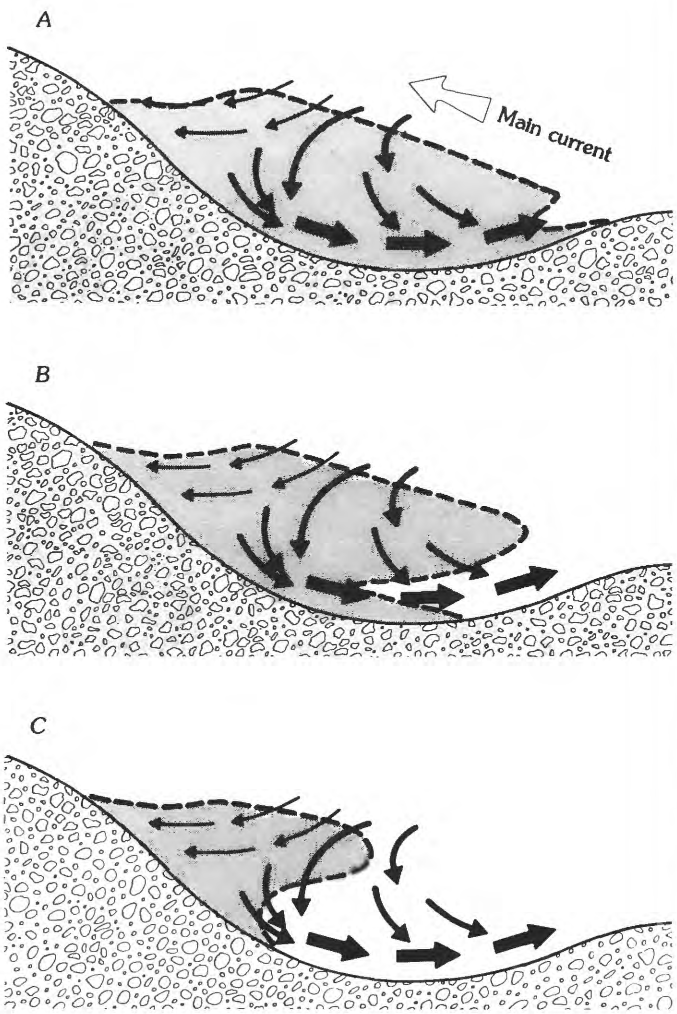
Analysis of sedimentary structures within this deposit showed that aggradation generally was consistent with directions of the current as measured in May. Steep planar foreset crossbeds document the upstream migration of the deposit (fig. 13); however, the deposit also aggraded on its downstream-facing slope (fig. 27).

Comparison of the surveys of August 1984 and May 1985, therefore, suggests that degradation is associated with the initial rise of discharge. This interpretation is reasonable despite the fact that from August 11 until August 15, 1984, spillway tests were run at Glen Canyon Dam and instantaneous peak discharges reached 56,600 ft^3/s (fig. 9). Daily mean discharges exceeded 40,000 ft^3/s on three days. The extent of aggradation or degradation

FIGURE 18.—Reattachment deposit at Eminence Break Camp, October 12, 1985, discharge 3,000 ft^3/s.

on these days of high flow is not precisely known. However, the high flows likely resulted in only minor erosion at this site, because aerial photography for October 21, 1984 (fig. 26C) shows a deposit similar to that mapped earlier in 1984.

The exposed deposit surveyed on August 2, 1985, was slightly smaller than at the time of the survey of August 1984 (fig. 27). The deposit may have been larger immediately after recession of the flows of 1984 than the same deposit immediately after recession of the flows of 1985; however, erosion may have occurred in 1985 between the day of initial exposure, June 25, and the date of the survey, August 2. Thus, despite substantial scour of the

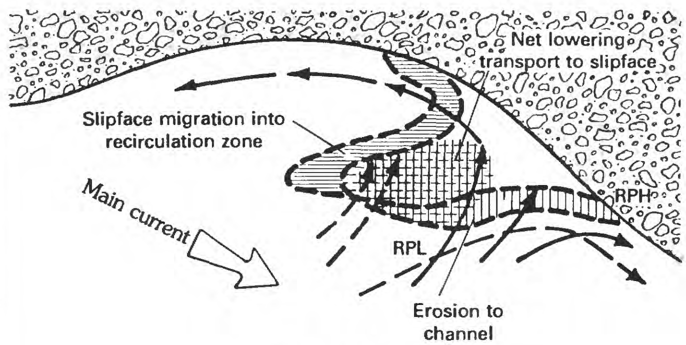


EXPLANATION

REATTACHMENT DEPOSIT

DIRECTION OF FLOW NEAR REATTACHMENT DEPOSIT—Proportioned to volume of flow; largest arrows, greatest volume of flow

FIGURE 19.—Reattachment deposit at low discharge. *A* and *B*, Pattern typical of the mid-1970's. *C*, Typical pattern following recession of high flows in 1984 and 1985; smaller area of exposed sand may be of higher elevation than larger exposed areas of the mid-1970's.



EXPLANATION

SURFACE-FLOW DIRECTION, HIGH FLOW

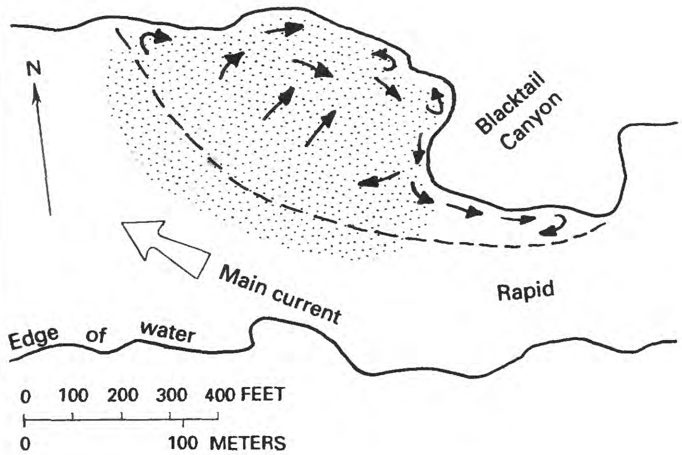
RPH REATTACHMENT POINT, HIGH FLOW

SURFACE-FLOW DIRECTION, LOW FLOW

RPL REATTACHMENT POINT, LOW FLOW

EDGE OF REATTACHMENT DEPOSIT

FIGURE 20.—Response of a reattachment deposit to decreasing discharge.



EXPLANATION

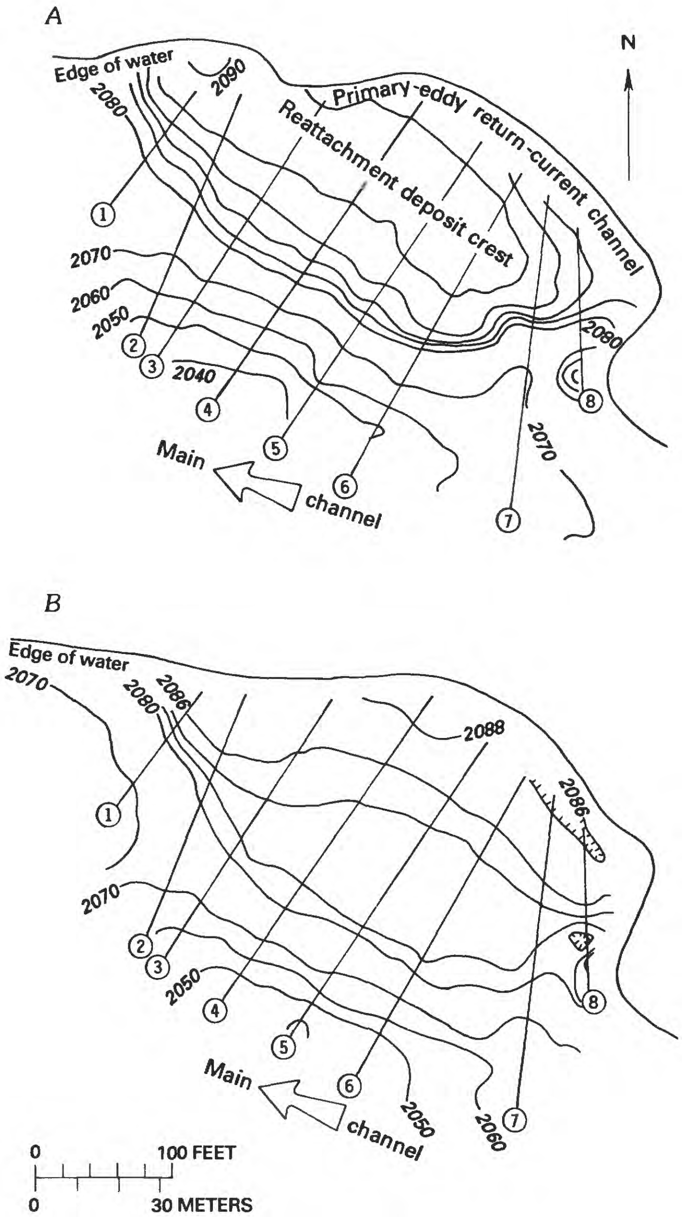
LOCATION OF SEPARATION SURFACE, 20,000 CUBIC FEET PER SECOND, AUGUST 12, 1985

GENERALIZED SURFACE-FLOW DIRECTION IN RECIRCULATION ZONE, 20,000 CUBIC FEET PER SECOND

AREA OF BATHYMETRIC SURVEYS

FIGURE 21.—Area of bathymetric surveys and hydraulic features at Blacktail Rapid.

deposit during the 1985 flood, the deposit likely never aggraded higher than 1 to 2 ft below the water surface in 1984 or 1985. Each year, the deposit was reestablished in approximately its same shape. In each of these years, the flow receded in a similar pattern. In 1983, aggradation was well documented, but the resulting deposit was of lower elevation. The deposit was reworked by flows of 36,000 ft^3/s during flow recession. At that discharge, the deposit would also have been about 1 ft below water surface. The level to which the deposit typically restabilizes after initial scour may be a direct function of the rate of decrease in discharge during flow recession.



EXPLANATION

—*2086*— BATHYMETRIC CONTOUR—Hachures indicate depression. Elevations are related to National Geodetic Vertical Datum of 1929. Interval 10 and 2 feet

②——— PROFILE LINE

FIGURE 22.—Bathymetric contours within a recirculation zone below Blacktail Rapid. *A*, September 7, 1985, discharge 22,600 ft^3/s. *B*, January 24, 1986, discharge 20,100 ft^3/s.

Net aggradation between 1983 and 1984 probably does not reflect greater sediment transport during the latter event, although sediment-transport data are not available to document main-channel conditions. Local geometry of the Eighteen Mile Wash debris fan is such that between 36,000 and 28,000 ft^3/s, flow is diverted away from the separation deposit. Therefore, in 1984, separation-deposit elevation was related to the 45,000 ft^3/s discharge, but in 1983 the deposit continued to be reworked until discharge dropped from 36,000 to 25,000 ft^3/s. In each case, equilibrium conditions limit aggradation to about 1–2 ft below the water surface in the low-velocity area.

After October 1, 1985, discharge never exceeded 20,000 ft^3/s or a stage of 88 ft during this study. Stage was sometimes as low as 76 ft. During this time, the downstream part of the deposit eroded rapidly (fig. 27). In January 1986, after 3 months of fluctuating flow, a 3-ft-high cutbank still existed. It had retreated horizontally 15 to 25 ft between August and early January. All erosion between October and January can be attributed to strongly fluctuating flow, and at least part of the erosion from August to October probably is associated with the first few days of fluctuating flows before the survey in October. The base of the cutbank developed at the approximate elevation of the highest discharge of the fluctuations from October to mid-January. Most of the retreat, therefore, was caused by bank collapse from saturation and undermining of the well-sorted fine sand. Nearshore velocities did not exceed about 1 ft/s. Waves were not present at this site. Degradation of the slope below the cutbank, subject to daily discharge fluctuations, was at a lower rate than degradation of the high exposed cutbank.

Aggradation caused by the high releases of 1983 more than compensated for the erosion that had occurred between 1965 and 1975 (fig. 29). Data are not available for 1975–83. Howard and Dolan (1981), however, observed that alluvial deposits had stabilized by the late 1970's. The alternating pattern of aggradation and degradation between June 1983 and May 1985 related to annual high flows is estimated on the basis of measured erosion and deposition during high releases in 1985 described above. The amount of degradation between August 1985 and January 1986 is similar to the net change between 1965 and 1975. The rate of change measured in 1985 and 1986 far exceeds the average rate for the earlier period. The existence of a cutbank at the end of the special fluctuating-flow period suggests that erosion would have continued if strong fluctuations had continued beyond mid-January. Therefore, at this site, newly aggraded deposits formed and reworked by flows in 1983, 1984, and 1985 were unstable under strongly fluctuating discharge. Upslope projection of the lower part of the January 1986 profile gives a likely minimum erosion that would have occurred if fluctuations had continued. A likely maximum extent of erosion would be degradation to the profile surveyed in 1975.

BATHYMETRIC SURVEYS

Short-term topographic changes in recirculation zones were measured by repetitive bathymetric surveys. The time of day and discharge during each survey are listed in table 1. Because these surveys are primarily of the lower elevation parts of recirculation zones, surveyed areas are not used as campsites; however, they are the major sand storage sites in recirculation zones.

The recirculation zone at river mile 120.1 just below Blacktail Rapid was surveyed with 710 data points in September 1985 and January 1986 (table 1). The zone is nearly circular in plan view (fig. 21). The primary eddy covers most of the area, although small secondary eddies were observed along the banks during both surveys. The zone has an excellent geometry for bathymetric surveying. Uncertainty in position is less than 5 ft over most of the area but reaches almost 18 ft at the extreme downstream end of the surveyed area.

The bathymetric map of September (fig. 22*A*) illustrates the characteristic shape of the sand deposit within the recirculation zone. The sand deposit had a relatively level upper surface and a steep slope into the main channel. A reattachment deposit and primary-eddy return-current channel were present on the upper surface. A small separation deposit was present at the upper end of the zone upstream from the return-current channel but was a minor part of the total zone. A bathymetric map based on the January survey shows that considerable changes had taken place in these features (fig. 22*B*). Volume changes estimated for this recirculation zone by comparison of bathymetric maps represent change in

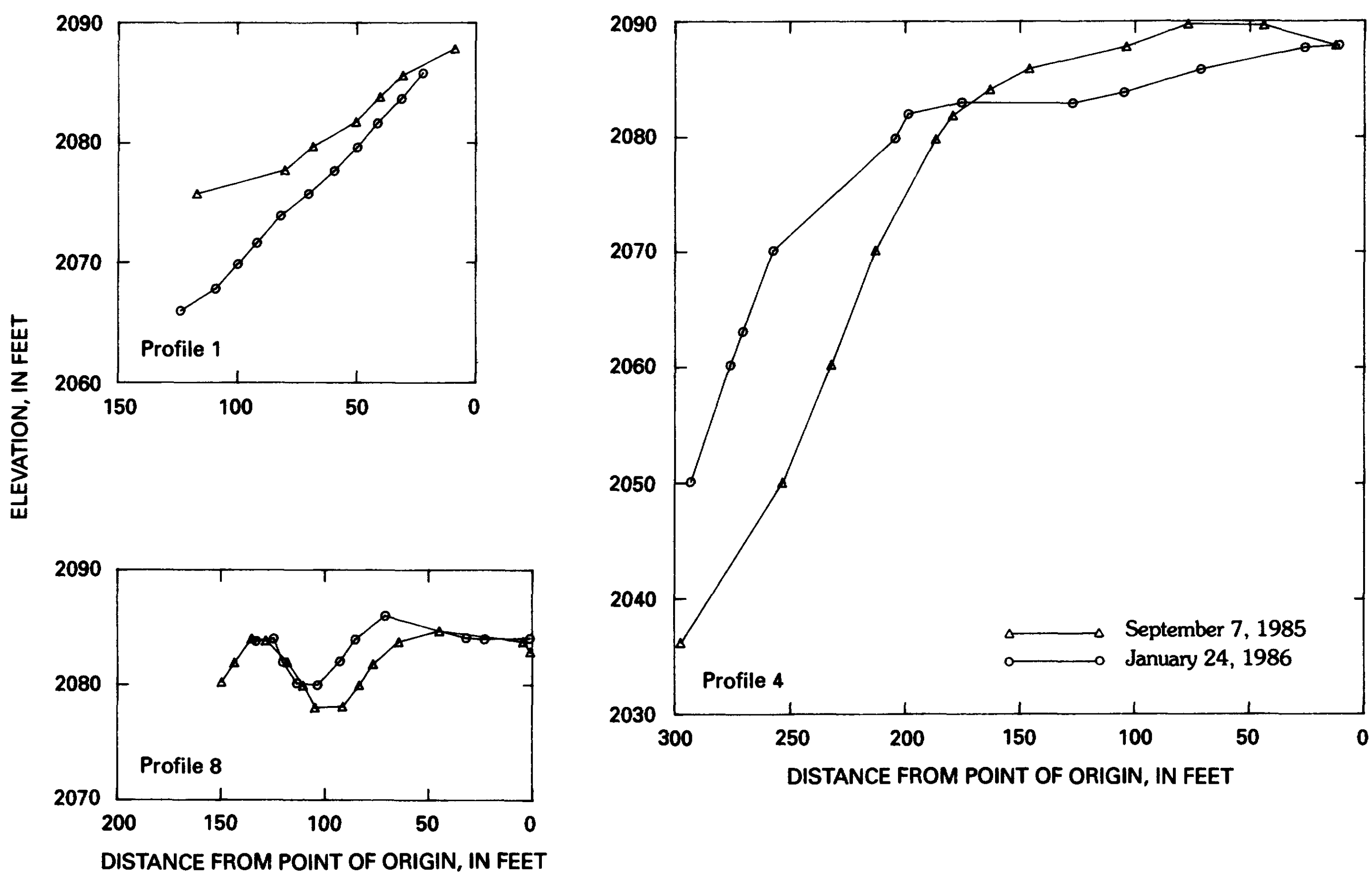
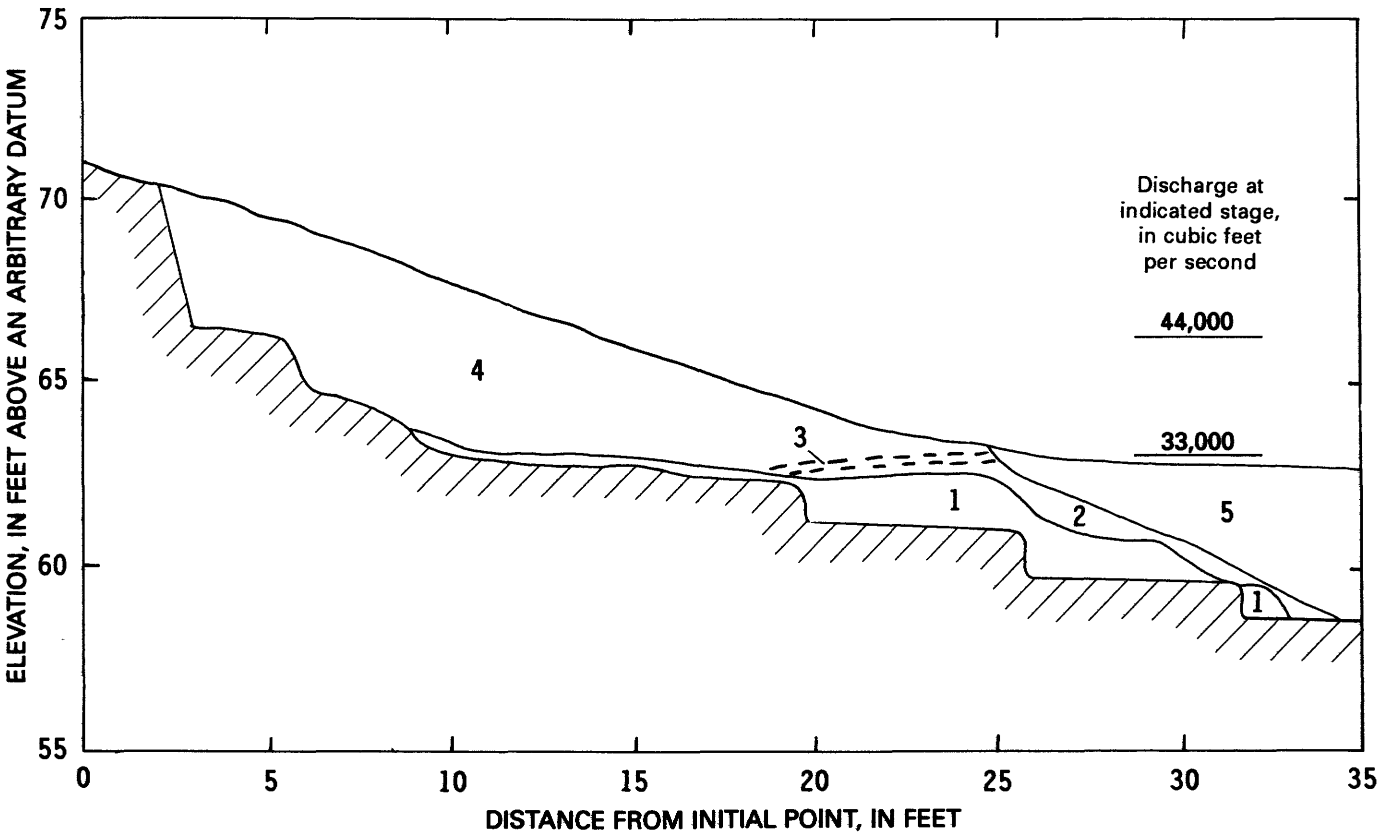


FIGURE 23.—Bed-surface profiles (see figure 22 for locations) of a recirculation zone below Blacktail Rapid.

volume of sand below the stage corresponding to the discharge at the time of the surveys. Discharge was strongly fluctuating for most of the period between the surveys, but fluctuated less strongly (15,000–21,000 ft^3/s) for the eight days before the January survey. Therefore, the observed changes may not be solely related to the effects of strongly fluctuating flow.

The return-current channel was shallower and less well developed during both surveys at this site than in other surveyed recirculation zones, and it was shallower and less distinct in January than in September. The elevation of much of the reattachment deposit was 2–4 ft lower in January than in September, and the slope had flattened and moved toward the channel thalweg. Profiles drawn from bathymetric maps illustrate and quantify these changes (fig. 23). Profiles 1, 4, and 8 show how changes varied over the zone. The extreme downstream end of the zone (profile 1, fig. 23) and most of the crest of the



EXPLANATION

5 FINE TO MEDIUM SAND—Current ripples that migrate upstream on foresets that dip toward river, amplitude of current ripples decreases upslope

4 FINE SAND—Current ripples, current direction upstream away from main channel

3 INTERBEDDED FINE SAND AND SILT—Unit dips at low angle away from main channel or in downstream direction. Entire unit grades upward into unit 4

2 FINE SAND—Generally massive with abundant roots and organic debris, includes an organic-rich lens that dips toward main channel. Laminae above the lens is contorted. Entire unit grades upward into unit 3 and pinches out 17 feet from initial point

1 BLACK AND GRAY CLAYEY AND SILTY FINE SAND—Layers of sand define irregular bedding, upper contact is erosional and includes a vertical cutbank 33 feet from initial point. Interpreted to be pre-1983 deposit

FIGURE 24.—Sedimentology exposed in a trench through the reattachment deposit at the site Above Cathedral Wash. Descriptions by T.R. Clifton, University of California, Santa Cruz, January 9, 1986.

reattachment deposit degraded, whereas the slope into the main channel aggraded (profile 4, fig. 23). At the upstream end, aggradation on the downstream side of the return-current channel caused the channel to shift toward the bank and to become shallower (profile 8, fig. 23). On all profiles, the point of zero change is roughly coincident with the break in slope between the upper surface of the sand deposit and the slope into the main channel. In January the sand deposit sloped uniformly and gently toward the main channel and did not have a distinct reattachment-deposit crest and primary-eddy return-current channel.

The amount of change between the two surveys was estimated by measuring the area between profile lines for successive surveys (fig. 23, table 8). Along all profiles, degradation totaled 1,100 ft^2 and aggradation totaled 3,010 ft^2. Net change was 1,910 ft^2 of aggradation. Vertical change along profiles was estimated by dividing the area of change by the length of the profile. An average of 1–2 ft of degradation occurred over the upper

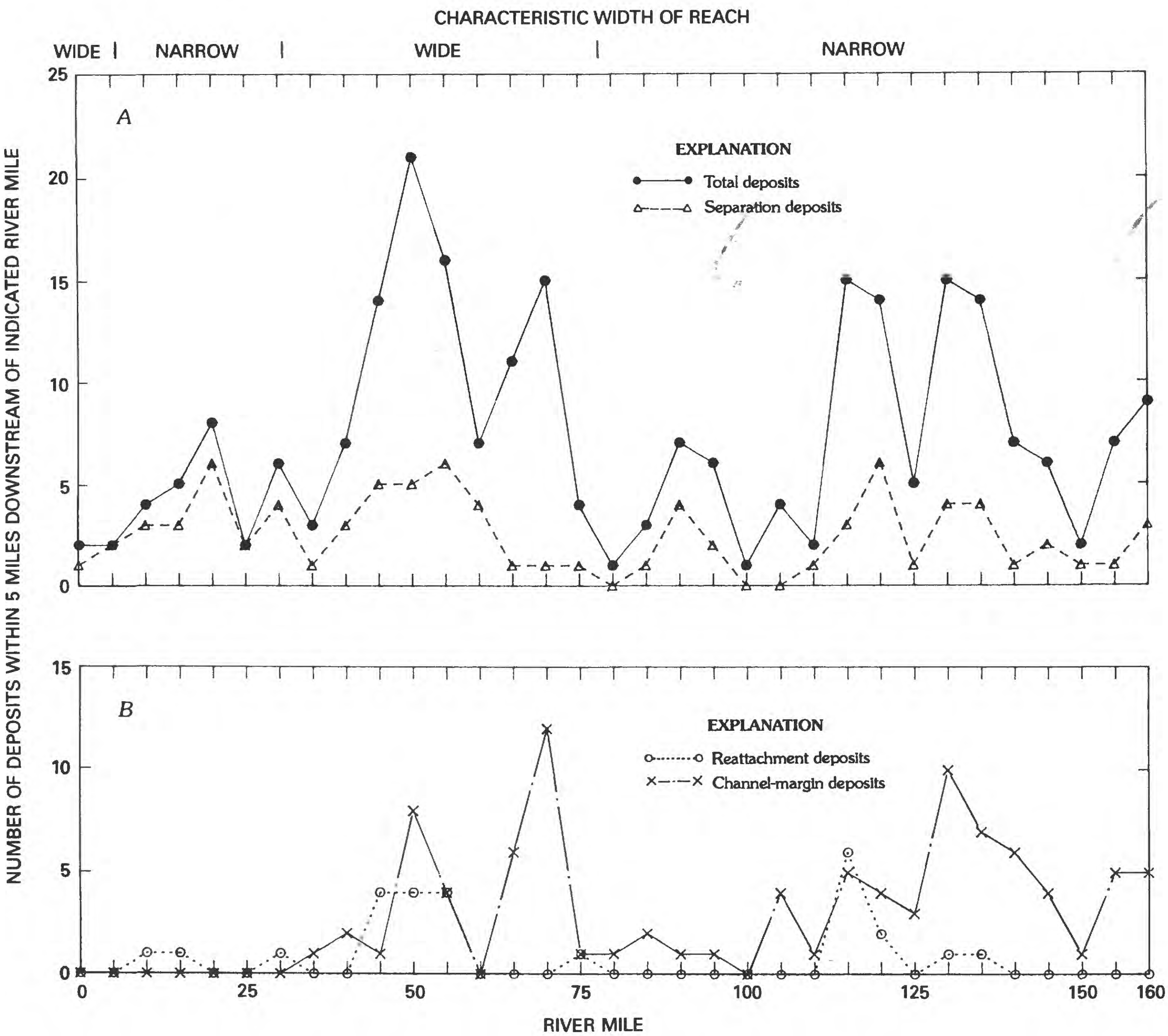


FIGURE 25.—Variation with river mile in number of alluvial deposits identified in 1983 (Brian and Thomas, 1984) as campsites. *A*, Total number of deposits and number of separation deposits. *B*, Number of reattachment deposits and channel-margin deposits between Lees Ferry and National Rapid.

A

B

C

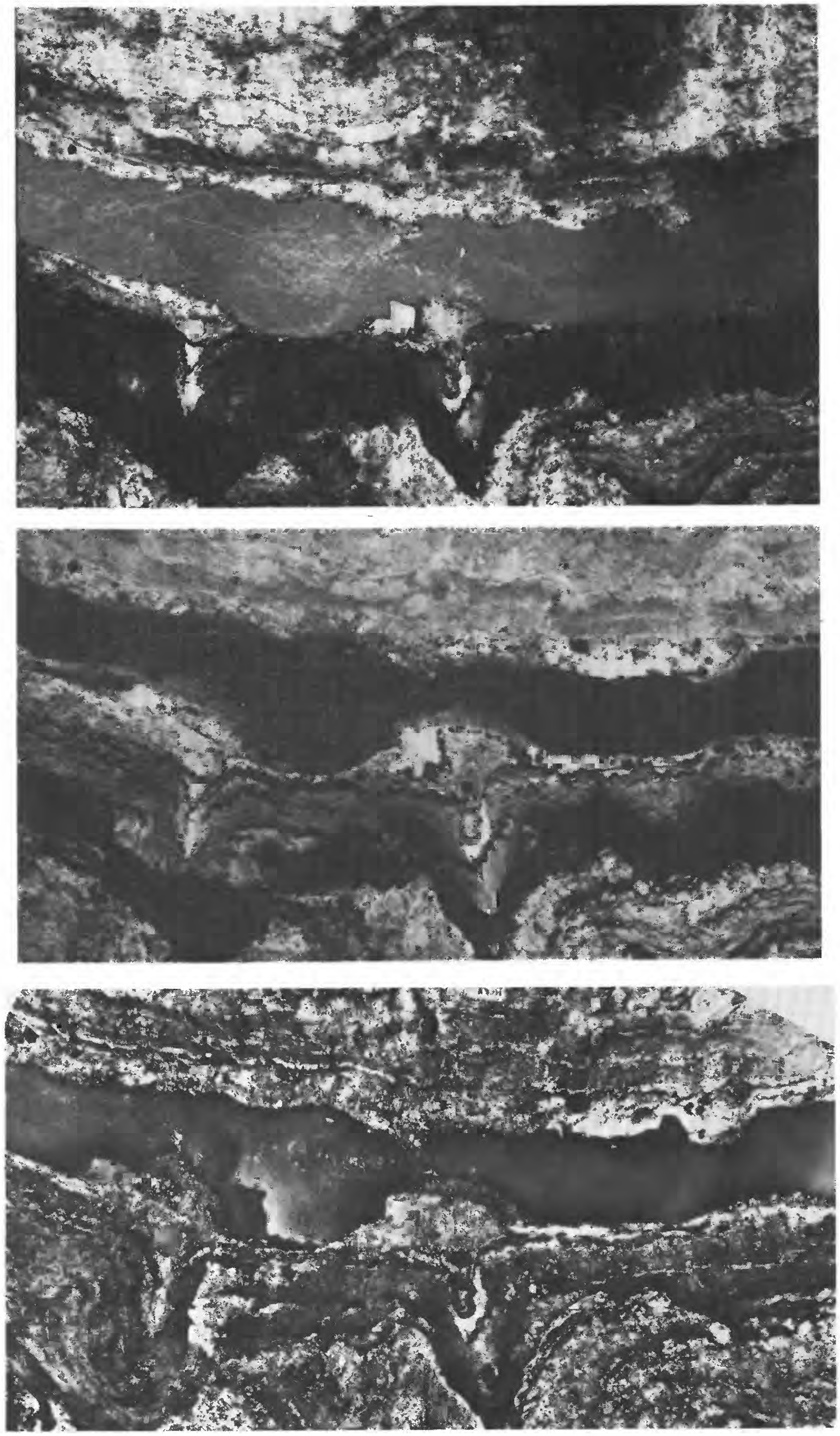
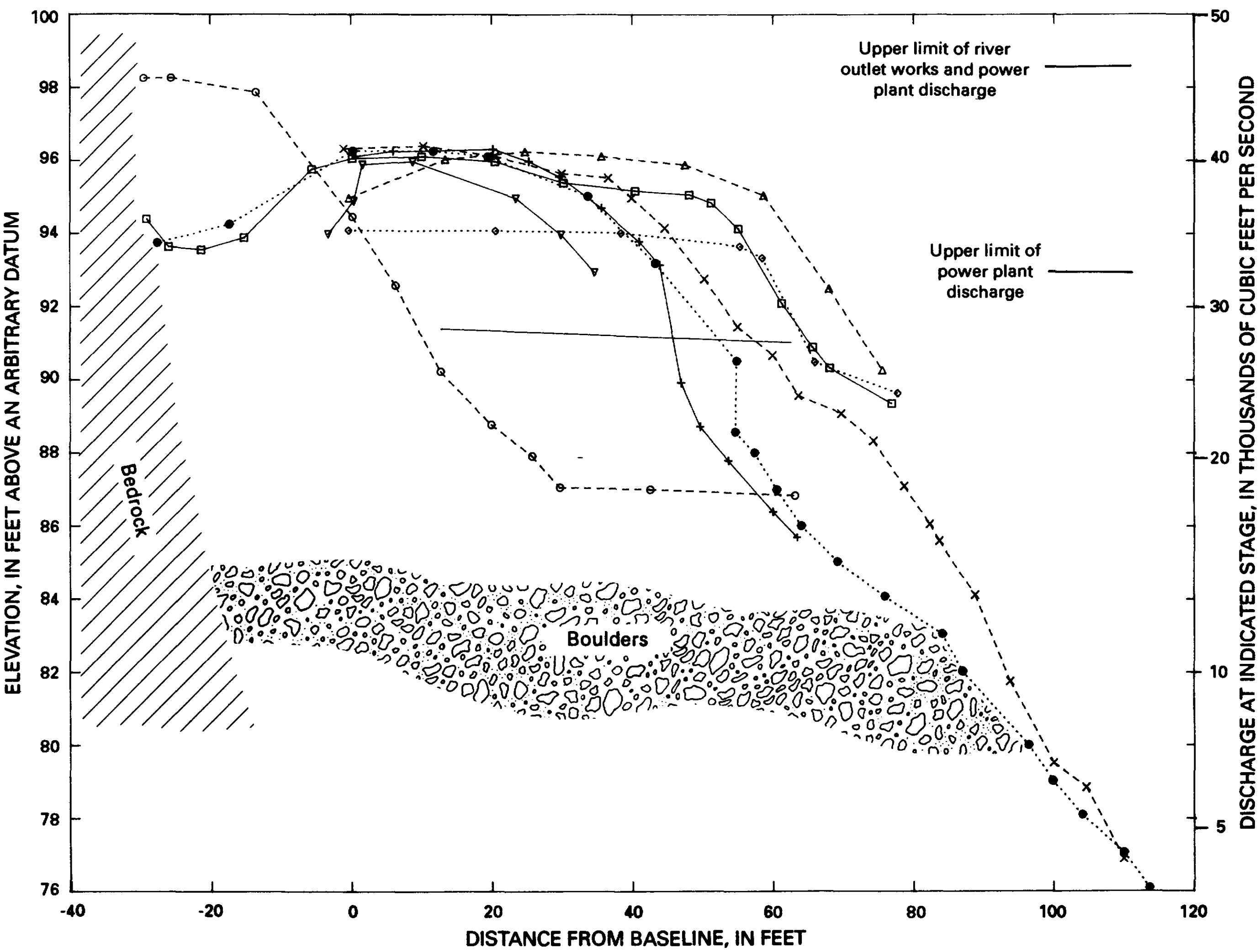


FIGURE 26.—Colorado River near Eighteen Mile Wash. *A*, May 14, 1965, discharge 26,700 ft^3/s. *B*, June 16, 1973, discharge 4,500 ft^3/s. *C*, October 21, 1984, discharge 5,600 ft^3/s (U.S. Bureau of Reclamation photograph). Surficial geology is shown on figure 11.

surface of the deposit, and aggradation of 3–6 ft occurred along the slope into the main channel.

Areas of change along profile lines were used to estimate volume of change over the mapped area by assuming that changes computed at profile lines took place over half the distance between a profile line and the adjacent line. For profiles 1 and 8 at the upstream and downstream ends of the area, only the area on the side of



EXPLANATION

1965—Minimum elevation estimated from aerial photograph
July 7, 1975 (Howard, 1975)
September 13, 1983 (Beus and others, 1985)
August 1, 1984, (Beus and others, 1985)
May 22, 1985
August 2, 1985
October 9, 1985
December 7, 1985
January 13, 1986

FIGURE 27.—Topography along profile 2 (see figure 11 for location) at Eighteen Mile Wash.

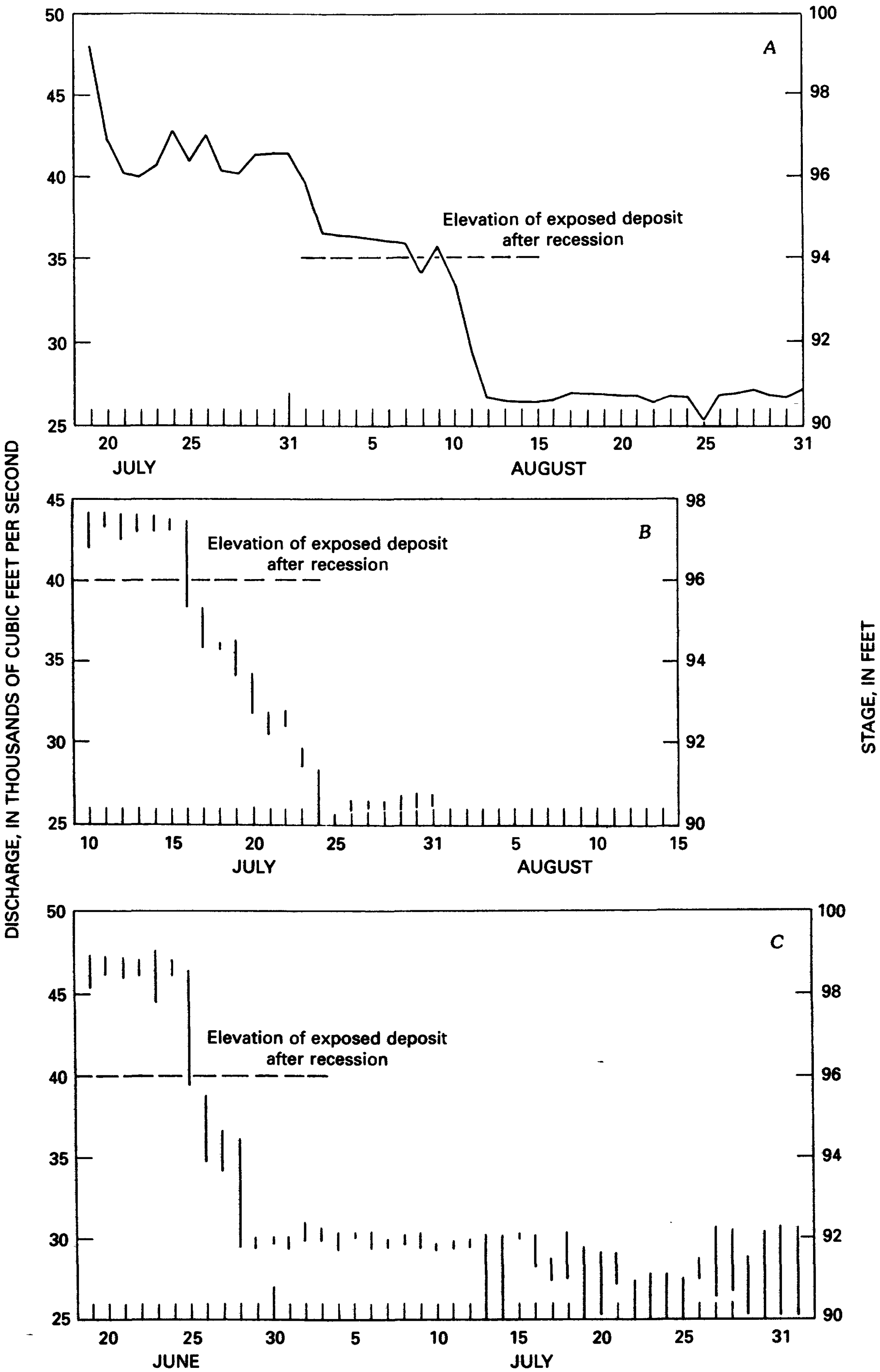


FIGURE 28.—Discharge and stage during recession of high flows at Eighteen Mile Wash. *A*, 1983. *B*, 1984. *C*, 1985.

the profile line toward the recirculation zone was used in the computation. The net volume of change is +122,000 ft^3.

Aggradation of the slope between recirculation zone and thalweg cannot be attributed solely to degradation of the upper surface. Estimates of total volume change on the upper surface and on the slope indicate that four to five times more sediment aggraded on the slope than degraded from the upper surface.

The recirculation zone at Eminence Break Camp, at river mile 44.2, is almost twice as long as it is wide (fig. 14). Bathymetric maps were made from surveys in April 1985, September 1985, and January 1986 using 1,055, 753, and 984 data points, respectively (fig. 15). Only the area of the recirculation zone inundated by a discharge of about 20,000 ft^3/s was surveyed. Less than 5 percent of the reattachment deposit projects above the stage corresponding to 20,000 ft^3/s. A large separation deposit mantles the upstream debris fan (fig. 14) and extends upslope above the area of bathymetric maps. The primary-eddy return-current channel, the reattachment deposit, and the slope into the main channel are similar to those at Blacktail Rapid. The return-current channel, however, is more clearly defined and deeper at this site than at Blacktail Rapid, and the reattachment-deposit crest is more distinct (fig. 18). Data are sparse over the slope into the main channel, and uncertainty in position of the contours defining the slope is much greater than at Blacktail Rapid. Estimates of change on the slope, therefore, have not been made. The position uncertainty is least over the central part of the zone (4.3 ft) and greatest at the upper end (14.5 ft).

Comparison of maps for April and September shows that most of the zone degraded considerably. This period includes 2 months of releases through river outlet works (fig. 9). The upper end of the zone shoreward from the return-current channel aggraded. The slope into the main channel appears to have aggraded, but the amount is unknown because of uncertainty in the contours. Between September and January (fig. 15) during fluctuating flow, the crest of the reattachment deposit aggraded, whereas most of the upper surface of the deposit degraded. Profiles illustrate these changes (fig. 16). Along profile 2, at the upstream end of the zone, little change took place between April and September, but degradation occurred along the profile between September and

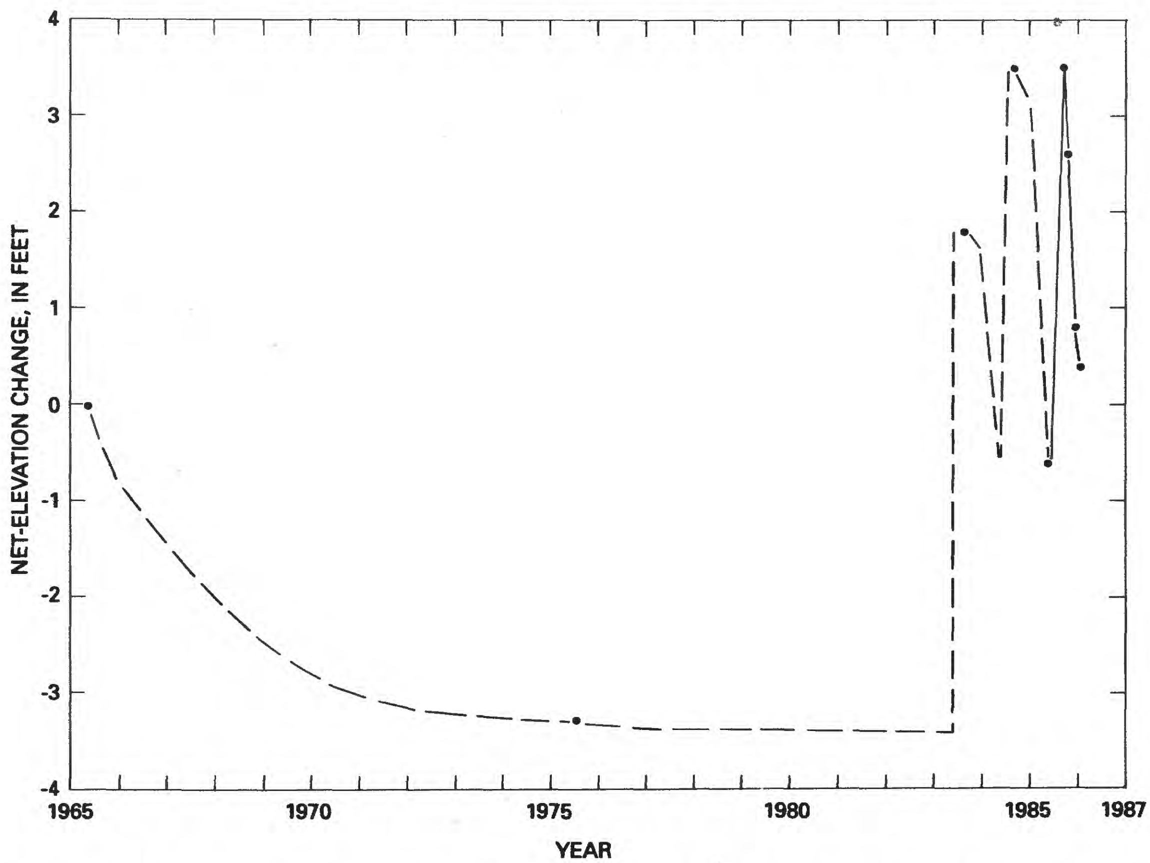
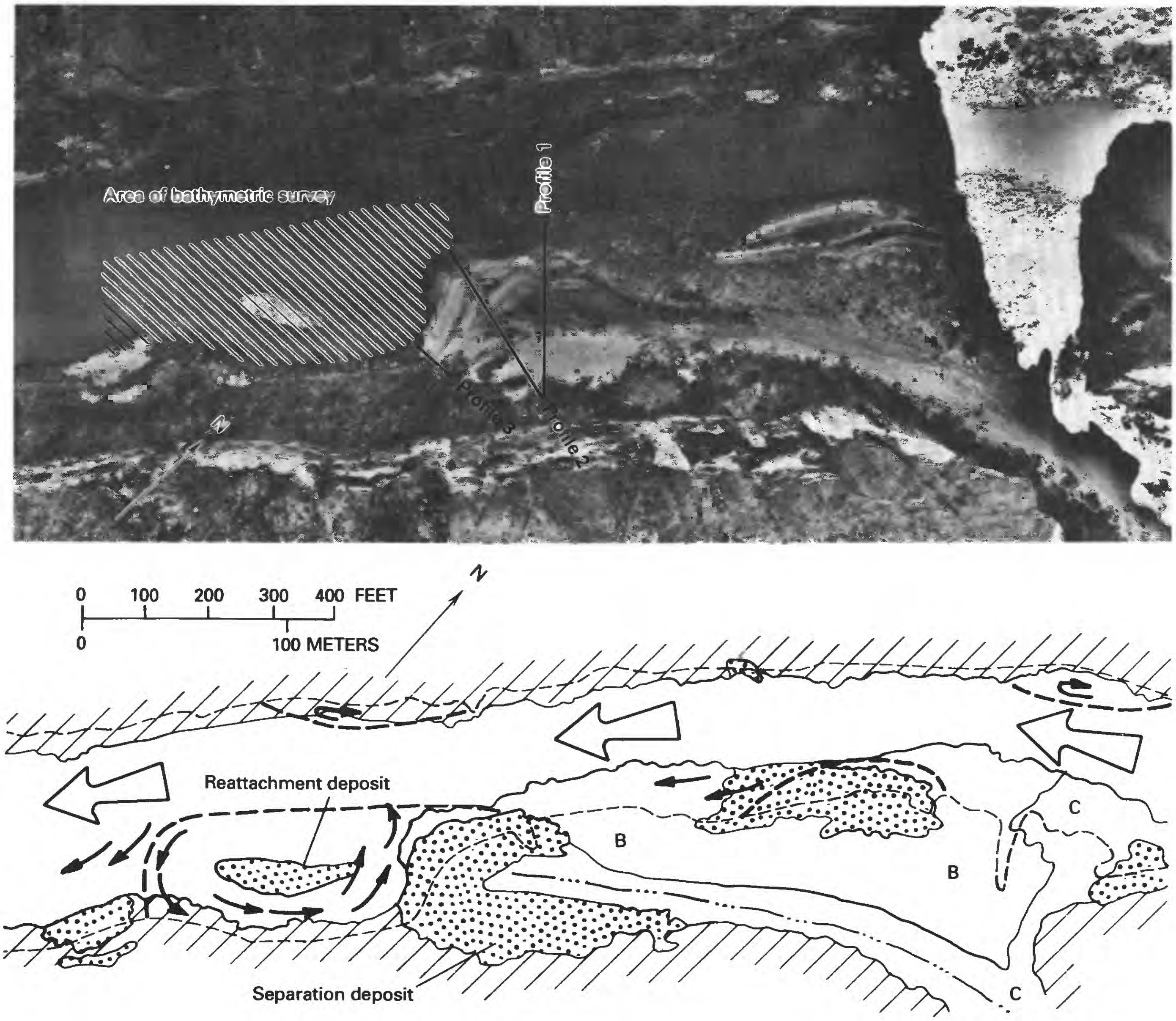


FIGURE 29.—Net-elevation change of a separation deposit at Eighteen Mile Wash, 1965 to January 1986, along profile 2 (see figure 11 for location).



EXPLANATION

RIVER-DEPOSITED OR REWORKED VERY FINE TO MEDIUM SAND (October 21, 1984)

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

EDGE OF WATER

October 21, 1984, discharge about 5,600 cubic feet per second

August 15, 1985, discharge about 22,000 cubic feet per second

SEPARATION SURFACE, 22,000 CUBIC FEET PER SECOND

GENERALIZED SURFACE-FLOW DIRECTION IN RECIRCULATION ZONES, 22,000 CUBIC FEET PER SECOND

SURFACE-FLOW DIRECTION OF MAIN CURRENT

Profile 1— LOCATION OF PROFILE LINES (Numbers refer to table 13)

FIGURE 30.—Area of bathymetric survey, surficial geology, and hydraulic features at National Rapid.

January. Deposition along the end of profile 7 nearest the bank caused the return-current channel to move toward the main channel between April and September (fig. 16). The crest of the reattachment deposit decreased in elevation and moved toward the main channel. The January profile shows that the reattachment deposit aggraded slightly between September and January but was still lower in elevation than in April. The deposit crest and return-current channel had returned to the positions of April. At the lower end of the recirculation zone, degradation occurred between April and September and aggradation occurred between September and January (profile 13, fig. 16). Like profile 7, profile 16 shows that the surface in January was still lower than that in April in spite of aggradation.

Changes in area along profile lines at Eminence Break Camp are summarized in table 8. Because of uncertainty in the position of contours near the main channel, only areas of the upper-deposit surface were measured. Between April and September, total aggradation along profile lines was 1,670 ft^2, total degradation was 3,070 ft^2, and net change was –2,400 ft^2. Average vertical changes along profile lines ranged from +2.6 ft to –4.2 ft for April to September and from +2.3 to –5.4 ft for September to January (table 9). Between September and January, aggradation was 890 ft^2, degradation was 2,030 ft^2, and net change was –1,140 ft^2. The net change for April to January was –3,540 ft^2. Estimated volume change was –148,000 ft^3 for April to September, –79,200 ft^3 for September to January, and –227,000 ft^3 for the entire period.

The recirculation zone just below National Rapid (fig. 30) at river mile 166.6 is similar in shape to that at Eminence Break Camp. Data points for surveys in April 1985, September 1985, and January 1986, which number 768, 432, and 368, respectively, are evenly distributed over the zone. The bottom configuration at National Rapid (fig. 31) is also similar to that at Eminence Break Camp, having a well-defined return-current channel and reattachment-deposit crest. At this site, however, the reattachment-deposit crest is separated from the bank at the lower end of the recirculation zone by the return-current channel. A second recirculation zone was present downstream from the mapped area during all surveys, and the two zones may have joined at some discharges. Position uncertainty at this site varied from trip to trip because remote locations were different for each trip. In April and September, uncertainty was greatest at the upper and lower ends of the zone (10–11 ft) and least over the central part (4.3 ft). For the survey of January 1986, the uncertainty in position ranged from 4.3 ft at the upper edge near the bank to 8 ft at the edge toward the main channel near the center of the zone. A large separation deposit mantles the National Canyon debris fan. Most of this deposit is higher in elevation than the stage during bathymetric surveying. No part of the reattachment deposit lies above the stage at which bathymetric surveys were made.

The shape of the primary-eddy return-current channel and reattachment deposit was similar during all three surveys (fig. 31). Although the elevation of the deposit crest remained about the same for all three surveys (about 1,736 ft), the position of the crest and return-current channel changed considerably. Between April and September, the side of the deposit nearest the bank

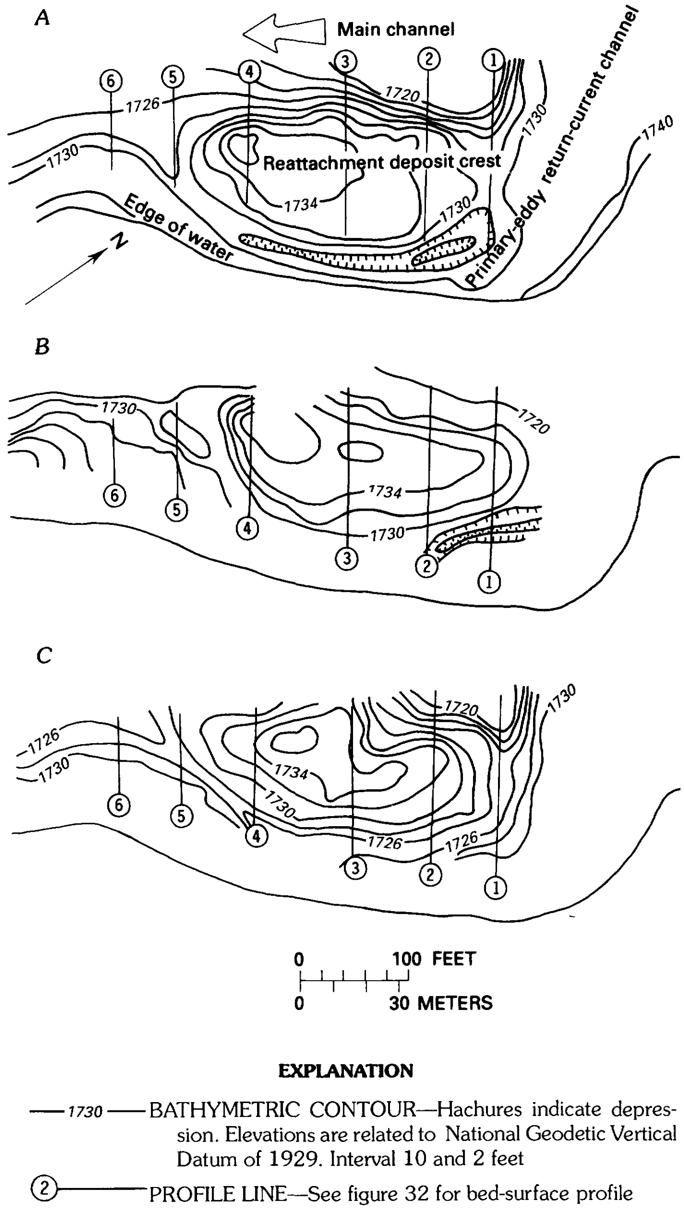


FIGURE 31.—Bathymetric contours within a recirculation zone below National Rapid. *A*, April 25, 1985. *B*, September 10, 1985. *C*, January 28, 1986.

degraded and the side toward the main channel aggraded, resulting in movement of the deposit crest toward the main channel. The upstream end of the deposit aggraded, and the return-current channel moved upstream. By January, the return-current channel had migrated back to the position of April, and the shape and position of the reattachment deposit were also similar to those of April. Most of the slope into the main channel was not mapped at this site because air entrained in the water column at National Rapid interfered with the depth-sounder signal. The slope was mapped at the upper end of the recirculation zone, however, and the maps show that the slope aggraded between April and September and degraded between September and January. Six profiles across the mapped areas illustrate these changes (fig. 32). Profile 6 shows that at the downstream end of the deposit, downstream from the return-current channel, aggradation took place between April and September and degradation between September and January.

Aggradation between April and September was 879 ft^2, degradation was 161 ft^2, and net change was +718 ft^2 (table 8). Between September and January, aggradation was 198 ft^2, degradation was 945 ft^2, and net change was –747 ft^2. Net change for the entire period was –29 ft^2. Average vertical change along profiles ranged from 0 to +1.4 ft from April to December and from –0.2 to –1.8 ft from September to January (table 8). Estimated volume change was +39,400 ft^3 between April and September, –37,900 ft^3 between September and January, and +1,500 ft^3 over the entire period.

A recirculation zone just below Nautiloid Canyon at river mile 34.8 was mapped on January 14, 1986, at discharges of 2,360 and 15,900 ft^3/s to determine the magnitude of short-term changes in the sand deposits. Low-flow and high-flow maps were drawn from 836 and 903 data points, respectively. The recirculation zone is more elongated than at Blacktail Rapid or Eminence Break Camp. The reattachment-deposit crest and return-current channel are the prominent features. A low area is present in the center of the deposit, and the deposit crest rises slightly as did the crest at Eminence Break Camp. The position uncertainty ranged from 4.5 ft at the upper and lower edges and toward the bank to 11.4 ft at the extreme edge toward the main channel. Although slight differences between the maps can be seen, the bottom configurations are almost identical. The differences are probably within the uncertainty caused by position uncertainty and that introduced by drawing contours from point data.

Bathymetric measurements document net degradation of the upper surface of recirculation zones at the three study sites where fluctuating flows were evaluated. Local aggradation of small areas did occur; however, net change at Eminence Break Camp, Blacktail Rapid, and National Rapid was degradational. The slope into the main channel aggraded at Blacktail Rapid. Randle and Pemberton (1987) predicted that a change from high steady flow to fluctuating flow would cause decreased sand transport in the main channel, which would in turn cause main-channel aggradation. Aggradation along the slope at Blacktail Rapid, therefore, may be related to decreased main-channel sediment-transport capacity as well as delivery of sand from the upper surface of the recirculation zone. Behavior of recirculation zones between April and September differed at Eminence Break Camp and National Rapid. Measured changes, however, indicate that sediment was exchanged between the main channel and the recirculation zone during this period of high steady flows.

Sand-storage changes of the upper surface and at edges of recirculation zones are not indicative of those in the nearby main channel. Bathymetric surveys also show that the volume of aggradation and degradation of reattachment deposits far exceeds that of a typical separation deposit such as Eighteen Mile Wash. Bathymetric surveys cover most of the recirculation zones, and measured volume changes indicate that sand is exchanged between recirculation zones and the main channel as well as redistributed within recirculation zones. Although analyses of data from only a few sites (table 1) are presented, preliminary analysis of data from other sites indicates that the changes are representative of changes throughout the study reach.

AGGRADATION AND DEGRADATION OF ALLUVIAL SAND DEPOSITS, 1965–86

CHANGES IN ALLUVIAL SAND DEPOSITS, 1973–84

FLOW CHARACTERISTICS

Between June 1973 and May 1983, daily discharge generally fluctuated to meet hydroelectric needs (fig. 2). During this period, the average daily fluctuation range was 13,000 to 15,000 ft^3/s. The average daily range is defined as the difference between the average monthly maximum and average monthly minimum release from Glen Canyon Dam. Except for 1980, instantaneous peak discharge at Lees Ferry was less than 31,000 ft^3/s. In 1980, mean daily discharge exceeded 30,000 ft^3/s on 8 days and peak discharge was 44,800 ft^3/s. Discharge dramatically increased in June 1983 and then receded in August to steady discharges of about 28,000 ft^3/s. In May 1984, discharge increased to about 45,000 ft^3/s and then decreased to steady discharges of about 28,000 ft^3/s in July (fig. 9). Between October 21 and 23, 1984, flow decreased to about 5,600 ft^3/s.

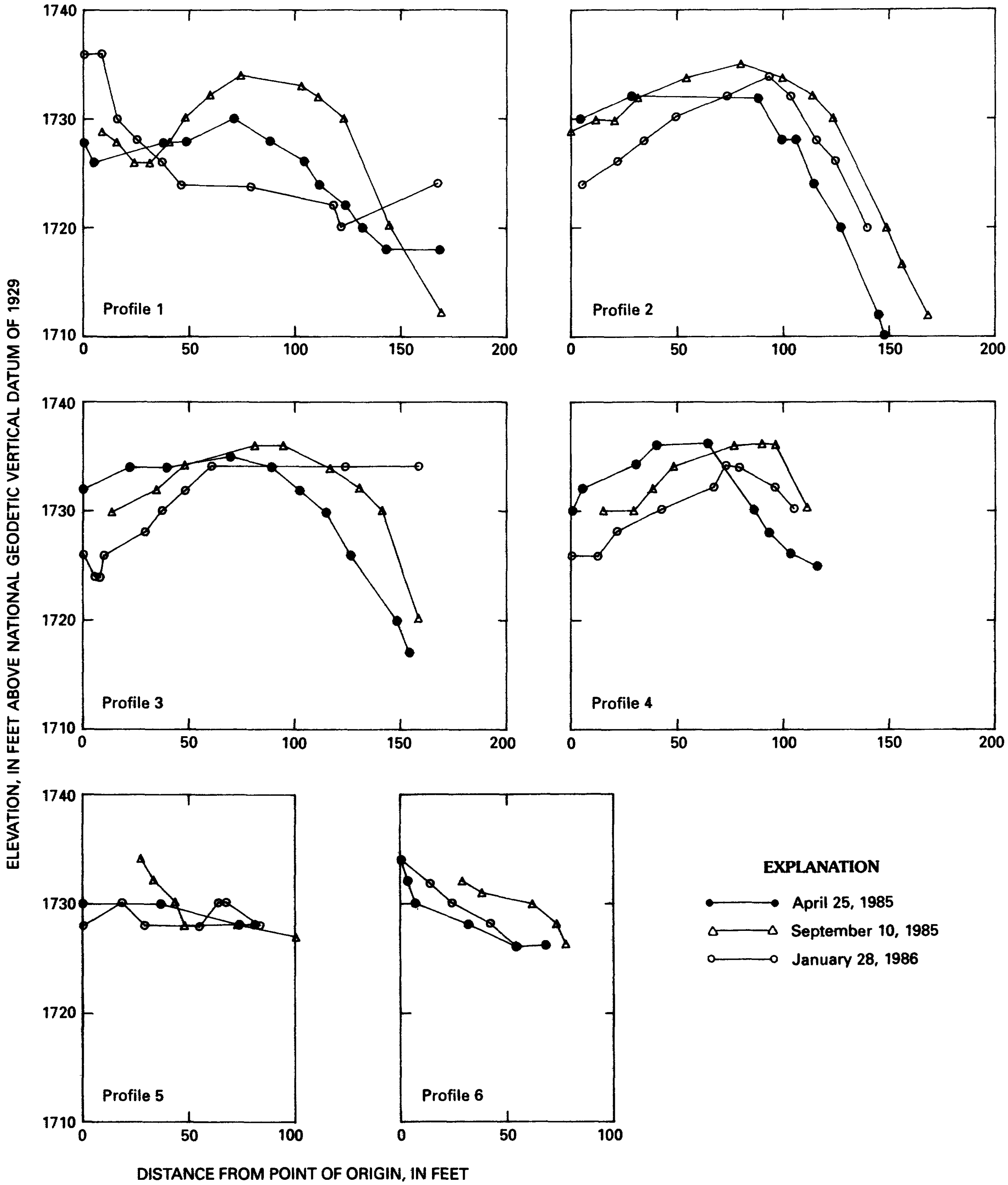


FIGURE 32.—Bed-surface profiles (see figure 31 for locations) of a recirculation zone below National Rapid.

CHANGES IN DEPOSITS

Large-scale changes in storage of sand in recirculation zones were evaluated by comparing inventories of exposed separation and reattachment deposits in 399 recirculation zones between river miles 0 and 118 (table 9). Because stage was very different in the two aerial photograph series in some reaches, only the presence or absence of sand was noted and the area of sand was not measured. Also, high flows scour and redistribute sand within recirculation zones. A decrease in area of sand may be the result of redistribution of sand within a recirculation zone and not represent net change in sand storage (fig. 19). Because comparison of inventories only indicates changes in presence of sand within recirculation zones, differences in inventories represent large-scale volume changes.

On the basis of this inventory, we conclude that sand was eroded from reattachment deposits between river miles 0 and 36 and 77 and 118. These included the narrowest reaches inventoried. The total number of separation deposits in these four reaches changed less than the number of reattachment deposits. Aggradation of reattachment deposits and minor aggradation of separation deposits occurred between river miles 36 and 77.

The most significant changes took place in the narrowest and steepest reaches as well as in those closest to Glen Canyon Dam (table 2). The change in reattachment deposits was slightly greater than the change in separation deposits. None of the deposits involved in these changes, however, had been inventoried as a campsite in 1973 or 1983. The deposits that did increase or decrease in number were at too low an elevation to be considered as campsites.

Changes in area of major alluvial sand deposits during this period were measured for reaches between river miles 0 and 35.9 and river miles 122 and 150, where discharge in the 1973 and 1984 aerial photographs was approximately the same (fig. 4 and table 10). Major alluvial deposits were defined as those inventoried as campsites in 1973 or 1984 (appendix A) and other alluvial deposits in the same recirculation zones. If a separation deposit had been inventoried as a campsite and a reattachment deposit existed in the same zone, its area was also measured. Area changes were measured at less than 45 percent of the total number of recirculation zones where presence or absence of deposits was determined.

Changes in area of reattachment deposits do not necessarily reflect changes in volume of stored sand in recirculation zones, because smaller deposits may be of higher elevation. As illustrated at Eighteen Mile Wash, the volume at a separation deposit changed where the area of deposit exposed at low discharge did not change. However, where area of separation or channel-margin deposits changed, net aggradation or degradation probably also occurred. Changes in area do indicate the extent of reworking of different types of deposits, and area changes are directly related to the size of campsites. Measured areas were those exposed at low discharges, and smaller areas of these deposits are available as campsites at higher discharges, particularly at reattachment deposits.

No significant change in total area of deposits was measured in any reach except between river miles 0 and 11.3. All the change measured in that segment was due to significant erosion of one point-bar deposit at river mile 1.9; the total area of separation or reattachment deposits showed no significant change. Two categories of reach and deposit type, however, significantly decreased in area: separation deposits in Muav Gorge and reattachment deposits in Supai Gorge. Erosion of separation deposits in Muav Gorge is likely due to the low elevation of debris fans in this reach. Low-elevation debris fans were substantially overtopped by the high discharges of 1983. The decrease in area of reattachment deposits in Supai Gorge is consistent with a decrease in number of reattachment deposits in the same segment (table 10). Therefore, a decrease in area in this segment probably reflects degradation of the deposits. The area of channel-margin deposits increased.

Although on an aggregate basis, major alluvial deposits in most reaches did not change significantly in total exposed area, 70 percent of all deposits either increased or decreased in area (table 11). About half of these increased and half decreased in area. More than 40 percent of separation and upper-pool deposits did not change in area. In contrast, about 20 percent of reattachment and channel-margin deposits did not change. The dominant pattern of change of reattachment deposits was toward a decrease in area, and that of channel-margin deposits was toward an increase in area. Decreases in area of reattachment deposits were concentrated in Supai Gorge, and increases in area of channel-margin deposits were concentrated in Muav Gorge (table 11).

These conclusions refine the conclusion of Beus and others (1985) that aggradation of alluvial sand deposits had occurred throughout the river corridor. The sample of alluvial sand deposits studied by Beus and others (1985) included a large proportion of separation and channel-margin deposits, which in this study are shown to be stable or aggrading sites (table 12). Six separation deposits studied by Beus and others (1985) had net vertical aggradation and minor bank erosion. The general pattern of change at Eighteen Mile Wash during this period (fig. 29) was representative of other sites.

Ten study sites of Beus and others (1985) were channel-margin deposits. Erosion of deposits was measured in the narrow reaches of Supai Gorge, Upper

Granite Gorge, and Muav Gorge. Eroded sites were typically small deposits mantling bedrock or talus and were associated with small recirculation zones. Larger channel-margin deposits in all reaches such as Lower Nankoweap Rapid, above Grapevine Rapid, and Granite Park Camp underwent vertical aggradation and some bank erosion. Only two reattachment deposits were surveyed, and aggradation of the upper surface of each deposit was measured.

CHANGES IN ALLUVIAL SAND DEPOSITS, HIGH FLOWS, MAY 1985

FLOW CHARACTERISTICS

On May 17, 1985, discharge at Lees Ferry increased from 26,000 ft^3/s at 9:00 a.m. to 45,800 ft^3/s at 5:30 p.m. Except for a 6-day period when mean daily discharge was about 30,000 ft^3/s, discharges that exceeded 40,000 ft^3/s continued until June 25. Discharge then decreased to less than 30,000 ft^3/s (fig. 28). The resulting hydrograph is similar to those of 1984 and 1986.

CHANGES IN DEPOSITS

Separation deposits were surveyed at Badger Creek Rapid, Eighteen Mile Wash, Twenty Mile Camp, Eminence Break Camp, and National Rapid soon after the onset of high flows in May 1985 (table 1). These sites were also surveyed after recession of high flows in August. In all cases, net aggradation occurred in small areas associated with low-velocity areas upstream from the primary-eddy return current.

Data collected at Eighteen Mile Wash (discussed in the section entitled "Aggradation and Degradation at Eighteen Mile Wash, 1965–86") show that aggradation followed degradation. Aggradation caused the deposit to regain its approximate former shape and size.

At Badger Creek Rapid in May 1985, a wave-cut scarp developed as 0.5-ft-amplitude waves impinged on the deposit face during the increase in discharge. Aggradation of about 0.5 ft, however, was measured between May and August. This aggradation resulted in a beach profile parallel to the slope that was measured below the eroding scarp in May.

The reattachment deposit at Opposite Nineteen Mile Canyon was surveyed during high flows in 1985. Surveys indicated that the deposit was at approximately the same elevation as that of the previous summer, although it was probably smaller in area. The crest of the deposit was within about 1 ft of the water surface. After the recession of the flood of 1985, however, the crest lowered approximately 3 ft, although it retained its general shape. These changes indicate that the shape of the deposit changed with onset of high flows and then readjusted during recession of the high flows. Comparisons of bathymetric surveys at Eminence Break Camp and National Rapid indicate that these reattachment deposits degraded between April and September despite retaining their overall shape. These observations suggest that reattachment deposits were entrained during these high flows.

CHANGES OF ALLUVIAL SAND DEPOSITS DURING STRONGLY FLUCTUATING FLOW, OCTOBER 1985 TO JANUARY 1986

FLOW CHARACTERISTICS

Between October 1, 1985, and January 15, 1986, releases from Glen Canyon Dam fluctuated widely (fig. 2). Average monthly peak release during this time was between 19,300 and 20,300 ft^3/s, and average monthly low release was between 1,800 and 5,500 ft^3/s. Monthly mean discharge decreased from between 23,400 and 28,500 ft^3/s for the period July to September 1985 to less than 12,000 ft^3/s during this special fluctuating-flow study period. The last previous month when monthly mean discharge was less than 12,000 ft^3/s was March 1983. The average daily range of fluctuations was 15,100 ft^3/s in October, 14,000 ft^3/s in November, and 18,500 ft^3/s in December 1985. During the 1976 to 1983 period, 41 percent of all months had average fluctuations less than 14,000 ft^3/s. During this same period, 21 percent of all months had fluctuations between 14,000 and 16,000 ft^3/s. Average fluctuations were 18,000 ft^3/s or more in 9 percent of all months. Therefore, the fluctuation range of October and November 1985 was representative of a median range of fluctuations during the 1976 to 1983 period, and the range in December 1985 was representative of a less frequent operations regime. Except for the period immediately following official closure of Glen Canyon Dam in 1963, however, no precedent existed for the occurrence of widely fluctuating flows preceded by a lengthy period of steady flow.

CHANGES IN DEPOSITS

Although surveys along some profiles documented aggradation between October 1, 1985, and January 1986, most measurements documented degradation (table 13). Of 41 profile lines at the 13 study sites that are separation deposits, about one-quarter of the lines showed net aggradation and about two-thirds showed net degradation (fig. 33). The mean net change along these profile lines was –0.65 ft. A part of every separation deposit degraded, and at seven sites, no areas of aggradation were measured. Erosion in excess of 1 ft was measured at profiles at six widely spaced sites. Erosion associated with the special fluctuating-flow study period, therefore, was typical of sites throughout the Grand Canyon. At the end of the period, cutbanks existed at many sites, which indicated that profiles were not yet stable.

Channel-geometry characteristics of these study sites were compared. Five of the six sites where significant erosion was measured are located in narrow reaches where stage changes during fluctuating discharge are greatest. Significant erosion was not related to slope of the water surface through the constriction or constriction ratio of the site.

Locations of significant erosion were not related to locations of highest velocities in recirculation zones. In some cases, erosion occurred where nearshore currents were less than 1 ft/s, such as at Eighteen Mile Wash. At these sites, saturation of the lower part of a high-elevation separation deposit is sufficient to cause bank failure. Failure occurred even where waves were absent.

At each site, the amount of erosion increased with distance downstream from the separation point. For example, at Twenty-Nine Mile Rapid, the deposit degraded slightly at a profile 100 ft downstream from the separation point (fig. 34, profile 1), but degraded about 2.8 ft along a profile 140 ft farther downstream (fig. 34, profile 2). Also, downstream migration of the separation point at that point exposed low-elevation areas of the upstream part of the separation deposit to downstream-directed currents, as also occurred at Badger Creek Rapid (fig. 5) and at Eighteen Mile Wash. Where underlying debris-fan materials were exposed, degradation in the upstream part was restricted. These trends indicate that erosion tended to eliminate unarmored parts of separation deposits, especially where they project downstream from the debris-fan deposit.

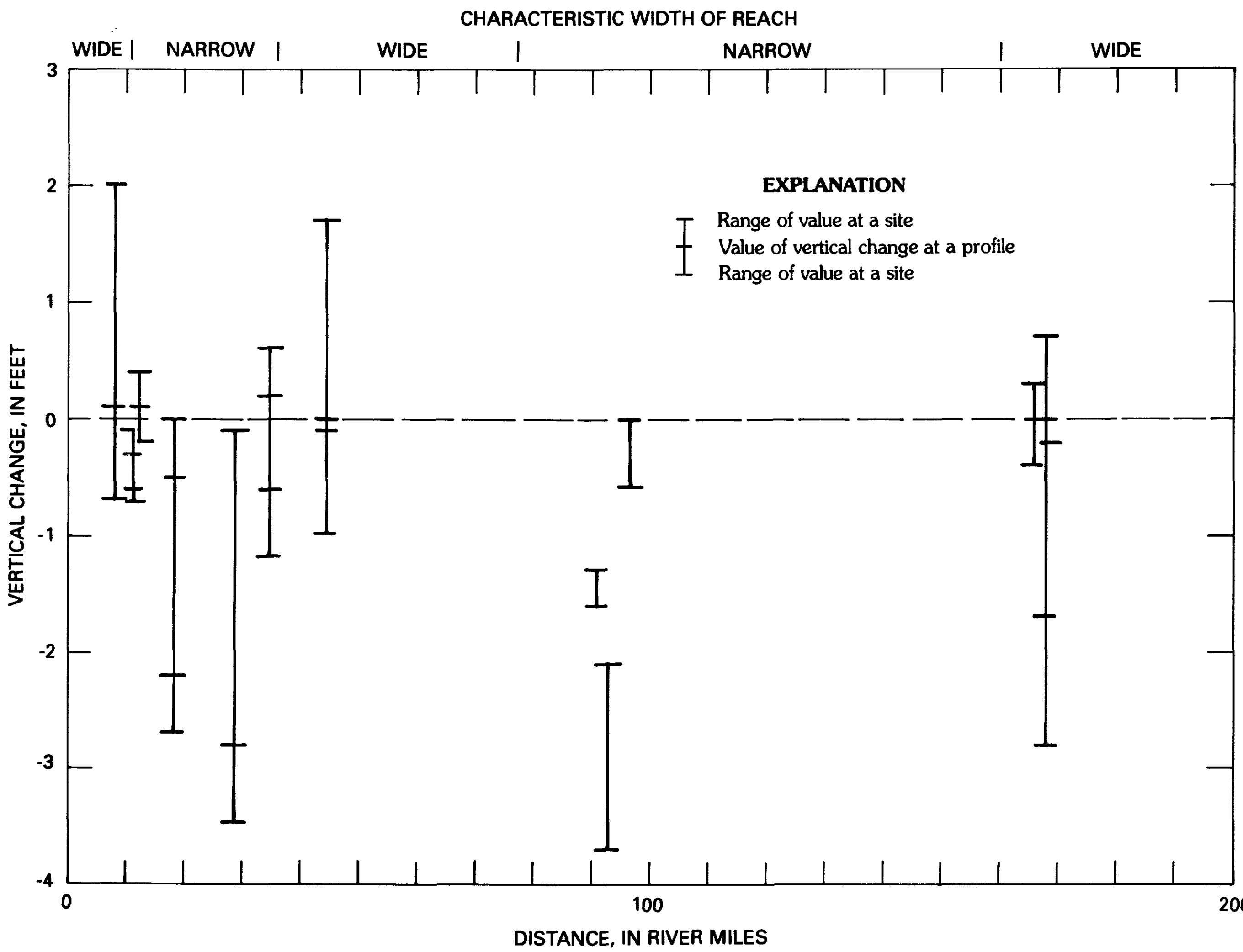


FIGURE 33.—Vertical change along profile lines at 13 separation deposits between October 1985 and January 1986.

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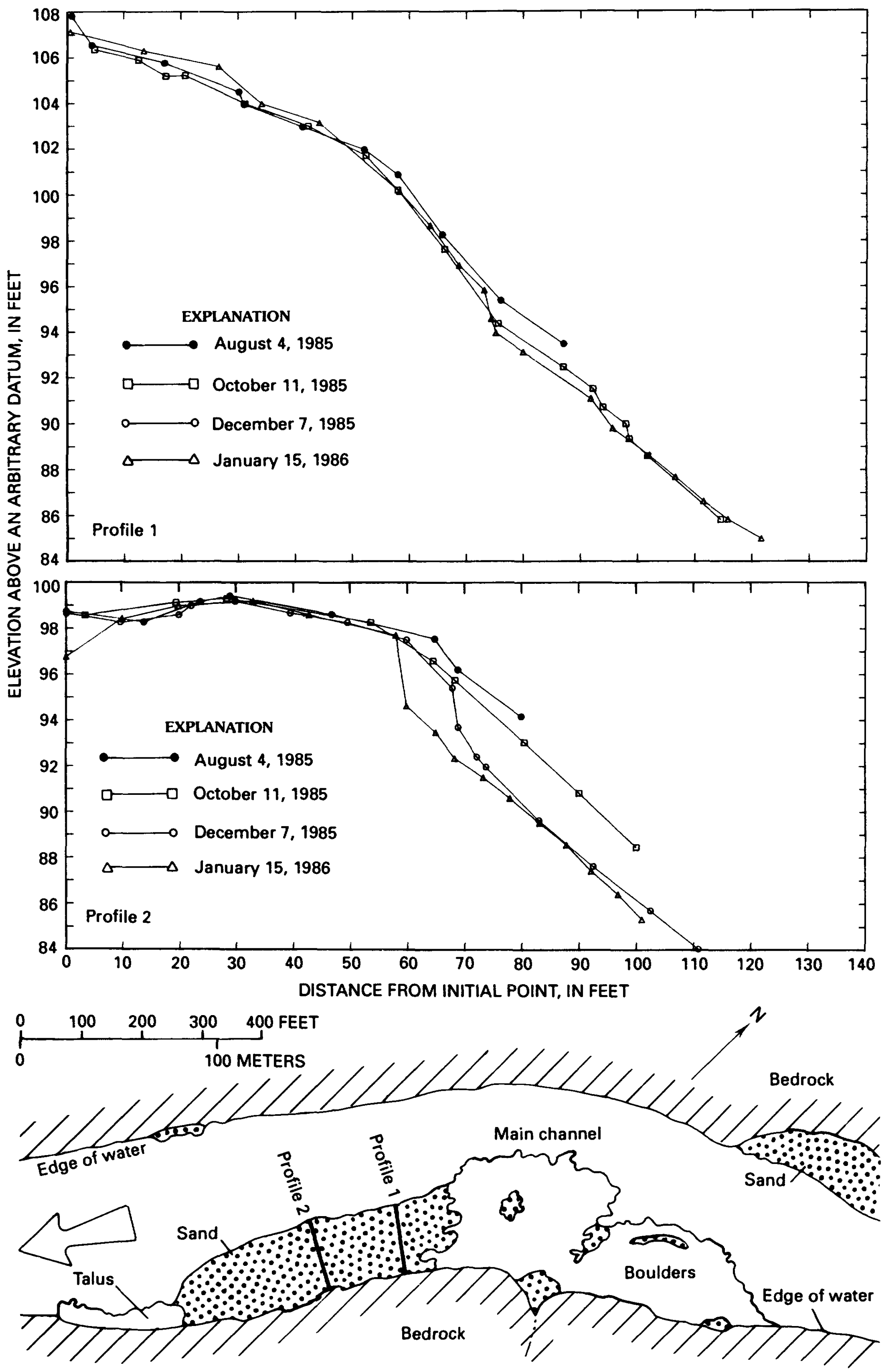

FIGURE 34.—Surficial geology and topography along two profiles at Twenty-Nine Mile Rapid. Mapped on October 21, 1986; discharge, 5,600 ft^3/s.

The upper surface of most surveyed reattachment deposits degraded during fluctuating flow. These changes were documented by bathymetric surveys at Eminence Break Camp, Blacktail Rapid, and National Rapid (table 8) and topographic surveys at Opposite Nineteen Mile Canyon, Saddle Canyon, and Hundred Twenty-Two Mile Creek (table 14). Only the deposit at the site Above Cathedral Wash aggraded. At this site, increase in volume occurred by vertical aggradation of about 0.5 ft as well as by upstream slipface migration of 10–20 ft. Parts of the reattachment-deposit crest aggraded at Eminence Break Camp.

At the site Above Cathedral Wash, constriction-ratio and reach-segment characteristics are similar to other sites, and variations in these parameters do not explain the apparently unique behavior of the site. Proximity to the Paria River, which contributes a large amount of sediment, may be important. Twenty percent of the aggradation at the site was caused by sediment delivered by the Paria River on October 10 and 11. Between river miles 0 and 5, sediment finer than boulders covered 75 percent of the bed, a large amount for the Colorado River in the park, and aggradation may have resulted from greater local availability of sand-size bed material.

As described in the section entitled "Bathymetric Surveys," aggradation occurred on the slope extending from the crest of the reattachment deposit to the thalweg at Blacktail Rapid. Decreased sediment transport was predicted by Randle and Pemberton (1987) throughout the river corridor, and aggradation along this slope probably occurred at other sites.

COMPARISON OF CHANGES IN ALLUVIAL SAND DEPOSITS

Aggradation and degradation occurred throughout the river corridor between 1983 and 1986. At some campsites, vertical aggradation of several feet occurred. Analysis of change in sand storage in all recirculation zones, however, shows that the number of reattachment deposits decreased 10 to 25 percent in the narrow reaches of Supai Gorge, Redwall Gorge, and Upper Granite Gorge (table 9). In Supai Gorge, major reattachment deposits also significantly decreased in area (table 10). In Muav Gorge, separation deposits inventoried as campsites decreased in area. In contrast, the number of deposits possibly increased in the wide reaches of Lower Marble Canyon and Furnace Flats (table 9). Area changes in these same reaches were not determined.

Separation deposits were more stable than other types of deposits. Analysis of volume changes at Eighteen Mile Wash shows that vertical aggradation can occur without change in area exposed at low flow. Erosion of separation deposits in Muav Gorge probably is related to low-elevation debris fans in this reach (table 10). Reattachment deposits are more susceptible to change during high flow, as indicated by the percentage of deposits that have changed in number (table 9) or area (table 11).

The response of channel-margin deposits is uncertain. Only in Muav Gorge was a significant change in total area measured. More than 50 percent of deposits increased in area. Classification of study sites evaluated by Beus and others (1985) suggests that small channel-margin deposits in narrow reaches were eroded, although vertical aggradation occurred at other sites.

These results indicate less change in major deposits due to high discharge in 1983–84 than that reported by Brian and Thomas (1984). Brian and Thomas (1984) inventoried campsites after recession of high flows in 1983 and recognized many new or enlarged alluvial sand deposits. They also reported that about 10 percent of the preexisting campsites had been significantly eroded. Their inventory, however, was made at a discharge of about 25,000 ft^3/s. The difference in results suggests that changes in high-elevation parts of alluvial deposits were more significant than changes in low-elevation parts.

Changes in area of high- and low-elevation parts of alluvial sand deposits were determined to evaluate topographic changes above and below an approximate stage corresponding to a discharge of 25,000 ft^3/s (table 14). At most sites, the area of the high-elevation part of the deposit above this stage increased or did not change between 1973 and 1984, whereas the low-elevation part typically decreased in size or did not change. These results show that although high-elevation parts of deposits aggraded, low-elevation parts either degraded or did not change. Patterns of change determined for high-elevation parts are not necessarily consistent with changes in low-elevation parts.

The onset of strongly fluctuating flows in October 1985 caused widespread erosion, especially in narrow reaches. Erosion of separation deposits occurred at sites as far as 167 mi downstream from Lees Ferry (fig. 33). Erosion was typically of the sand that had been deposited in 1983–85. Comparison of table 14 with figure 33 indicates that sites that eroded significantly between October 1985 and January 1986 also had eroded significantly from 1965 to 1973 and then had aggraded significantly during the 1983 high flows. For example, at Eighteen Mile Wash, Twenty-Nine Mile Rapid, and Fern Glen Rapid, significant erosion was measured between October 1985 and January 1986. These sites had eroded significantly between 1965 and 1973 and aggraded in 1983. Significant aggradation was not followed by significant degradation in narrow reaches where a high separation deposit was armored from further erosion by exposed debris-fan deposits, as at Nautiloid Canyon.

The high flows of 1983 and 1984, therefore, redistributed much sand and removed sand from 10 to 25 percent of recirculation zones in at least those narrow reaches within 160 mi of Lees Ferry. Significant aggradation, however, occurred at many major campsites. Aggradation may have occurred in recirculation zones in wide reaches. Many new alluvial sand deposits eroded rapidly when exposed to strongly fluctuating discharges, which suggests that most of the gain in sand resulting from high flows was of short duration.

SUMMARY

This report has presented a classification of alluvial sand deposits, described some characteristics of these deposits, and described changes that have occurred in these deposits since completion of Glen Canyon Dam. The classification of alluvial sand deposits and the designation of reaches within the Grand Canyon were used to distinguish styles of change in narrow and wide reaches. Measurement of topographic changes in alluvial deposits were based on topographic and bathymetric surveys and analysis of aerial photographs.

The largest and most numerous alluvial sand deposits along the Colorado River in Grand Canyon National Park are formed in zones of recirculating current. Recirculation zones are caused by large debris fans that partially block the channel and by minor bedrock or talus abutments. Alluvial sand deposits can be classified by form and location. Separation deposits are located near the point of flow separation, mantle debris fans, and extend to the edge of the primary-eddy return-current channel. Reattachment deposits are located near the point of flow reattachment and project upstream beneath the primary eddy. Channel-margin deposits are terracelike in form and may fill re-entrants or extend continuously along the channel in wide reaches for lengths of 1 mi. Channel-margin deposits probably are formed in recirculation zones.

The Colorado River corridor in Grand Canyon National Park was divided into 11 reaches. Separation deposits large enough to be used as campsites are common throughout the river corridor in narrow and wide reaches. Reattachment and channel-margin deposits large enough to be used as campsites are common only in wide reaches except in the Muav Gorge, where channel-margin deposits are common.

The form and sedimentology of alluvial sand deposits reflect the hydraulic and sediment-transport conditions existing during reworking and deposition of the deposit. Separation deposits form in lower velocity parts of the river than reattachment deposits and may be composed of slightly finer sand. At sufficiently high discharge, both separation and reattachment deposits are reworked, and sand is redistributed within the recirculation zone and between the recirculation zone and the main channel. This response to high flow is documented by repeated topographic surveys and sedimentologic analysis of study sites Above Cathedral Wash, at Eighteen Mile Wash, and Opposite Nineteen Mile Canyon and by repeated bathymetric mapping at Eminence Break Camp, Blacktail Rapid, and National Rapid.

During recession from high flows, redistribution of sand within recirculation zones may result in degradation of the deposit. The high flows of 1983 and 1984 removed sand from recirculation zones in narrow reaches within 118 mi of Lees Ferry. When the rate of recession is great enough, topographic conditions at some sites cause flow to be directed away from a sand deposit and leave it exposed, such as at Eighteen Mile Wash. At other sites, especially reattachment deposits, redistribution of sand may continue even during a rapid recession. At many reattachment deposits, the result is erosion of downstream areas and loss of sand to the main channel and redistribution of sand in other parts of the deposit within the recirculation zone. Higher rates of recession allow less time for this distribution and therefore may result in exposure of larger areas of alluvial sand deposits after recession at some sites.

Fluctuating flows following high steady flows during the study period resulted in significant erosion. Fluctuating flows typically redistributed sand within recirculation zones and may deposit sand along the slope from the reattachment-deposit crest to the thalweg. Although erosion was significant throughout the park with the onset of fluctuating flow, results of topographic surveys by other investigators in the late 1970's indicate that equilibrium was reached after a few years. Topographic surveys between October 1985 and January 1986 indicate that such stability was not reached within 3–1/2 months of strongly fluctuating flow. Redistribution of sand can affect significant parts of alluvial sand deposits.

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

The high flows of 1983 and 1984 eroded sand from recirculation zones in narrow reaches. The high flows may have resulted in aggradation of all types of alluvial sand deposits in wide reaches. Limited evidence suggests that high flows in 1985 caused further erosion of reattachment deposits in narrow reaches.

Alluvial sand deposits used as campsites, whatever their type, are more stable than the smaller, lower-elevation deposits of the same type not used as campsites. Many campsites aggraded significantly during high flows in 1983. Fluctuating flows in 1985 and 1986 caused rapid erosion of many deposits of all types throughout the Grand Canyon. The greatest erosion typically occurred at sites where significant deposition had occurred in 1983. The increase in sand at campsites from high flow therefore is of limited duration if strongly fluctuating flows follow. During these same high flows, sand was removed from other recirculation zones in narrow reaches. Separation deposits are more stable than reattachment deposits, although erosion can occur in reaches where separation deposits are of low elevation such as Muav Gorge. An inventory of campsites in 1983 showed that narrow reaches generally have few campsites. The high flows of 1983–85 followed by strongly fluctuating flows in 1985 resulted in accentuating the difference between campsite availability in narrow and wide reaches.

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TABLES 1–14; APPENDIX A

TABLE 1.—*Summary of study sites and types of data collected*

[X, indicates data were collected; dashes indicate no data collected; (DSS), detailed study site; N.A., not available. Time of study is that of bathymetric survey. Discharges were estimated during bathymetric surveys or taken from nearest gaging station during day of work. Multiple bathymetric surveys indicated by number in parentheses]

River mile	Site number	Date and time of study	Discharge, in cubic feet per second	Bathymetric survey	Topographic survey	Photographic replications	Surface-flow pattern	Water-surface slope	Scour chains	Sedimentology
(DSS) Above Cathedral Wash (original surveys)										
2.5	1	05-18-85	44,700	---	---	X	X	---	---	---
		07-29-85	26,000–29,000	---	---	X	X	---	---	---
		08-29-85 (1530)	27,100	X	---	X	---	---	---	X
		10-04-85	4,000–19,000	---	X	X	X	---	X	---
		12-07-85	2,600	---	X	---	---	---	---	---
		01-09-86 (1600)	16,300	X	X	X	X	X	X	X
		05-13-86	48,500	---	---	---	X	---	---	---
(DSS) Badger Creek Rapid (original surveys)										
7.9	2	04-13-85 (1400)	17,900	X	---	---	---	---	---	---
		05-19 to 05-21-85	40,000–45,000	---	X	X	X	X	---	---
		07-30 to 07-31-85	25,000–31,000	---	X	X	X	X	---	---
		08-30-85 (1500)	29,800	X	---	---	---	---	---	X
		10-05 to 10-06-85	3,000–17,000	---	X	X	X	X	---	---
		12-07-85	~3,000	---	X	---	---	---	---	---
		01-11-86 (1730)	2,870–21,500	X(2)	X	X	X	X	---	X
(DSS) Soap Creek Rapid (initial survey, Ferrari, 1987)										
11.4	3	05-21 to 05-22-85	44,000–45,000	---	---	X	X	X	---	---
		08-01-85	25,000–31,000	---	X	X	X	X	---	X
		10-07-85	4,000–18,000	---	X	X	X	X	X	---
		01-12-86	2,000–21,000	---	X	X	X	---	X	---
(DSS) Below Salt Water Wash (original survey)										
12.2	4	05-21 to 05-22-85	44,000–45,000	---	---	---	X	---	---	---
		08-01-85	25,000–31,000	---	---	X	X	---	---	X
		10-08-85	4,000–15,000	---	X	X	X	---	X	X
		01-13-86	2,000–21,000	---	X	X	X	---	X	---
(DSS) Eighteen Mile Wash (initial survey, Howard, 1975)										
18.1	5	05-22-85	45,000	---	X	X	X	X	---	---
		08-02-85	28,000–30,000	---	X	X	X	X	---	X
		10-09-85	4,000–20,000	---	X	X	X	X	---	---
		12-07-85	~5,000	---	X	---	---	---	---	---
		01-13-86	2,000–21,000	---	X	X	X	X	---	---
Below Eighteen Mile Wash										
18.2	6	08-02-85	28,000–30,000	---	---	X	X	---	---	---
		10-09-85	4,000–20,000	---	---	X	X	---	---	---
(DSS) Opposite Nineteen Mile Canyon (initial survey, Howard, 1975)										
19.0	7	05-23-85	42,000–45,000	---	X	X	X	---	---	---
		08-03-85	24,000–29,000	---	X	X	X	---	---	X
		10-09 to 10-11-85	4,000–20,000	---	X	X	X	---	X	X
		12-07-85	~5,000	---	X	---	---	---	---	---
		01-14-86	2,000–21,000	---	X	X	X	X	X	---
(DSS) Twenty Mile Camp (initial survey, Ferrari, 1987)										
19.8	8	08-03-85	24,000–29,000	---	X	---	X	---	---	---
		10-11-85	4,000–15,000	---	X	---	---	---	---	---
		01-14-86	2,000–21,000	---	X	X	X	X	---	---
(DSS) Twenty-Nine Mile Rapid (original survey)										
29.2	9	05-24-85	44,000	---	---	X	X	---	---	---
		08-04-85	23,000–29,000	---	X	X	X	---	---	X
		10-11-85	4,000–15,000	---	X	X	X	---	---	---
		12-07-85	~5,000	---	X	---	---	---	---	---
		01-15-86	3,000–22,000	---	X	X	X	X	---	---

TABLE 1.—*Summary of study sites and types of data collected*—Continued

River mile	Site number	Date and time of study	Discharge, in cubic feet per second	Bathymetric survey	Topographic survey	Photographic replications	Surface-flow pattern	Water-surface slope	Scour chains	Sedimentology
		(DSS) Nautiloid Canyon (initial survey, Howard, 1975)								
34.7	10	05-24-85	44,000–48,000	---	X	X	X	X	---	---
		08-04-85	23,000–29,000	---	X	X	X	---	---	---
		09-01-85 (0945)	27,600	X	---	---	---	---	---	---
		10-12-85	3,000–15,000	---	X	X	X	---	---	---
		01-14 to 01-15-86	2,360; 15,900	X(2)	X	X	X	X	---	---
		Tatahatso Wash (initial survey, Ferrari, 1987)								
37.3	11	08-04-85	23,000–29,000	---	X	X	---	---	---	---
		10-12-85	3,000–15,000	---	X	---	---	---	---	---
		(DSS) Eminence Break Camp (original survey)								
44.2	12	04-16-85 (0630)	26,100	X	---	---	---	---	---	---
		04-17-85 (0645)	26,000	X	---	---	X	---	---	---
		05-25-85	40,000–47,000	---	X	X	X	X	---	---
		08-05-85	25,000–31,000	---	X	X	X	X	---	---
		09-02-85 (0910)	27,200	X	---	---	---	---	---	---
		10-12-85	3,000–15,000	---	X	X	X	X	---	---
		01-16-86 (0915)	23,600	X	X	X	X	X	---	X
		(DSS) Saddle Canyon (initial survey, Ferrari, 1987)								
47.2	13	01-18-86	13,000–24,000	---	X	---	X	X	---	---
		05-14-86	48,500	---	---	---	X	---	---	---
		Kwagunt Rapid (initial survey, Ferrari, 1987)								
56.3	14	08-06-86	26,000–30,000	---	X	X	X	---	---	---
		10-13-86	3,000–12,000	---	X	---	---	---	---	---
		Little Colorado River confluence (original survey)								
61.1	15	04-19-85 (1240)	24,000	X	---	---	---	---	---	---
		05-27-85	40,000–47,000	---	---	X	X	X	---	---
		08-06-85	26,000–30,000	---	X	X	X	---	---	---
		09-03-85 (1105)	29,200	X	---	---	---	---	---	---
		09-04-85 (0840)	26,500	X	---	---	---	---	---	---
		01-17-86 (1535)	19,600	X	---	---	---	---	---	---
		01-18-86	13,000–26,000	---	X	X	X	---	---	---
		Below Little Colorado River confluence (initial survey, Howard, 1975)								
61.7	16	01-20-86	12,000–21,000	---	X	---	---	---	---	---
		Above Unkar Rapid (initial survey, Ferrari, 1987)								
72.5	17	01-19-86 (1400)	N.A.	X	---	---	---	---	---	---
		01-20-86	12,000–21,000	---	X	---	---	---	---	---
		Nevills Rapid (original survey)								
75.6	18	08-07-85	17,000–24,000	---	X	X	X	---	---	---
		01-20-86	12,000–21,000	---	X	X	X	X	---	---
		(DSS) Above Grapevine Rapid (initial survey, Howard, 1975)								
81.1	19	05-29-85	44,000–46,000	---	X	X	X	---	---	---
		08-07-85	17,000–24,000	---	X	X	X	---	---	---
		10-15-85	N.A.	---	X	X	X	---	---	---
		01-21-86	12,000–18,000	---	X	X	X	---	---	---
		Cremation Camp (initial survey, Howard, 1975)								
87.1	20	04-21-85	23,800–26,300	X(2)	---	---	---	---	---	---
		05-30-85	45,000–47,000	---	---	---	---	X	---	---
		09-05-85 (1355)	29,300	X	---	---	---	---	---	---
		01-20-86 (1440)	17,800	X	---	---	---	---	---	---
		01-21-86 (1150)	15,300	X	---	---	---	---	---	---

TABLE 1.—*Summary of study sites and types of data collected*—Continued

River mile	Site number	Date and time of study	Discharge, in cubic feet per second	Bathymetric survey	Topographic survey	Photographic replications	Surface-flow pattern	Water-surface slope	Scour chains	Sedimentology
(DSS) Ninety-One Mile Creek (original survey)										
91.0	21	08-08-85	19,000–24,000	---	X	X	---	---	---	---
		10-15-85	N.A.	---	X	X	---	---	---	---
		01-22-86	13,000–22,000	---	X	X	X	X	---	---
Trinity Creek										
91.4	22	08-08-85	19,000–24,000	---	---	X	---	---	---	---
		01-22-86	13,000–22,000	---	---	X	---	---	---	---
(DSS) Granite Rapid (initial survey, Howard, 1975; Ferrari, 1987)										
93.1, 93.4	23	05-31 to 06-01-85	42,000–47,000	---	X	---	X	X	---	---
		08-09-85	18,000–22,000	---	X	---	X	---	---	---
		01-22-86	13,000–22,000	---	X	---	X	---	---	---
Ninety-Six Mile Camp										
96.0	24	06-01-85	42,000–47,000	---	---	X	---	---	---	---
		08-09-85	18,000–22,000	---	---	X	---	---	---	---
		10-16-85	N.A.	---	---	X	---	---	---	---
(DSS) Boucher Rapid (original survey)										
96.6	25	08-09-85	18,000–22,000	---	X	X	X	X	---	---
		10-16-85	N.A.	---	X	X	X	X	---	---
		01-23-86	15,000–22,000	---	X	X	X	---	---	---
Upper Crystal Rapid										
98.0	26	01-22-86 (1610)	N.A.	X	---	---	---	---	---	---
Elves Chasm (original survey)										
116.0	27	10-17-85	N.A.	---	X	X	X	---	---	---
		01-24-86	15,000–23,000	---	X	X	X	X	---	---
(DSS) One Hundred Twenty Mile Camp (initial survey Ferrari, 1987)										
119.7	28	08-11-85	19,000–23,000	---	---	X	---	---	---	X
		10-17-85	N.A.	---	X	X	---	---	---	---
		12-08-85	6,000	---	X	---	---	---	---	---
		01-08-86	N.A.	---	X	---	---	---	---	---
(DSS) Lower Blacktail Rapid (original survey)										
120.1	29	06-02 to 06-03-85	45,000–47,000	---	X	X	X	X	---	---
		08-12-85	16,000–22,000	---	---	X	X	X	---	---
		09-07-85 (0805)	22,600	X	---	---	---	---	---	---
		10-18-85	N.A.	---	X	X	X	X	X	---
		12-08-85	6,000	---	X	---	---	---	---	---
		01-13-86	N.A.	---	X	---	---	---	X	---
		01-24-86 (1435)	20,100	X	---	---	---	---	X	---
One Hundred Twenty-Two Mile Rapid										
121.6	30	06-05-85	44,000–46,000	---	---	X	X	---	---	---
		08-13-85	19,000–23,000	---	---	X	X	---	---	---
		10-18-85	N.A.	---	---	X	X	---	---	---
		01-26-86	21,000–25,000	---	---	X	---	---	---	---
(DSS) One Hundred Twenty-Two Mile Creek (original survey)										
122.0	31	06-05-85	44,000–46,000	---	---	X	X	---	---	X
		08-13-85	19,000–23,000	---	X	X	X	X	---	---
		10-20-85	7,000–13,000	---	X	X	X	X	---	X
		12-08-85	6,000	---	X	---	---	---	---	---
		01-13-86	N.A.	---	X	---	---	---	---	---
		01-25-86	18,000–26,000	---	X	X	X	X	---	X

TABLE 1.—*Summary of study sites and types of data collected*—Continued

River mile	Site number	Date and time of study	Discharge, in cubic feet per second	Bathymetric survey	Topographic survey	Photographic replications	Surface-flow pattern	Water-surface slope	Scour chains	Sedimentology
				The Cutbank						
122.3	32	06-06-85	40,000–42,000	---	---	X	---	---	---	X
		08-14-85	19,000–23,000	---	---	X	---	---	---	---
				Forster Rapid						
122.6	33	06-06-85	40,000–42,000	---	---	---	---	X	---	---
		08-14-85	19,000–23,000	---	---	X	---	---	---	---
				Enfilade Point (initial survey, Ferrari, 1987)						
123.5	34	06-06-85	40,000–42,000	---	---	X	X	---	---	---
		08-14-85	19,000–23,000	---	---	X	X	---	---	---
		10-20-85	7,000–13,000	---	---	X	X	---	---	---
		01-27-86	23,000–26,000	---	X	X	X	---	---	---
				Stone Creek						
131.8	35	06-08-85	30,000–35,000	---	---	X	---	---	---	---
		08-15-85	20,000–24,000	---	---	X	---	---	---	---
		10-20-85	N.A.	---	---	X	---	---	---	---
				Opposite Deer Creek Falls						
136.2	36	08-15-85	20,000–24,000	---	---	X	---	---	---	---
				(DSS) National Rapid (original survey)						
166.5	37	04-25-85	16,800–20,800	X(3)	---	---	X	X	---	---
		06-09 to 06-11-85	30,000	---	X	X	X	X	---	X
		08-15-85	20,000–24,000	---	X	X	X	---	---	---
		09-09-85 (1010)	22,200	X	---	---	---	---	---	---
		09-10-85 (1000)	21,200	X	---	---	---	---	---	---
		10-21 to 10-22-85	8,000–17,000	---	X	X	X	X	---	---
		12-08-85	6,000	---	X	---	---	---	---	---
		01-08-86	N.A.	---	X	---	---	---	---	---
		01-27-86 (1255)	21,100	X	---	---	---	---	---	---
		01-28-86 (1615)	23,100	X(2)	X	X	X	---	---	---
				(DSS) Fern Glen Rapid (Ferrari, 1987)						
168.0	38	01-08-86	N.A.	---	X	---	---	---	---	---
		01-30-86	16,000–23,000	---	X	---	X	X	---	X
				One Hundred Eighty-Six Mile						
185.8	39	04-27-85 (1410)	22,300	X	---	---	---	---	---	---
		06-12-85	30,000	---	---	---	X	X	---	---
		09-11-85 (1040)	26,000	X	---	---	---	---	---	---
		09-12-85 (0825)	26,000	X	---	---	---	---	---	---
		01-29-86 (1545)	19,400	X	---	---	---	---	---	---
				(DSS) Pumpkin Springs (original survey)						
212.9	40	04-29-85 (0835)	26,200	X	---	---	---	---	---	---
		06-13-85	30,000–35,000	---	X	X	X	X	---	X
		08-16-85	20,000–22,000	---	X	X	X	X	---	X
		09-13-85 (0915)	25,200	X	---	---	---	---	---	---
		10-23-85	7,000–16,000	---	X	X	X	---	---	---
		01-30-86 (1545)	25,900	X	---	---	---	---	---	---
		01-31-86 (0915)	21,400	X	X	X	X	X	---	X
				Diamond Creek						
225.2	41	09-14-85 (1100)	25,000	X	---	---	---	---	---	---
		02-02-86 (1005)	23,700	X	---	---	---	---	---	---

TABLE 2.—*Characteristics of the reaches within the study area*

Reach (river miles)	Local name of reach	Major geologic units at river level[1]	Description of reach width	Average ratio of top width to mean depth[2]	Average channel width, in feet[2]	Channel slope[3]	Number of campsites per mile[4]	Type of alluvial sand deposit typically used as campsites
0–11.3	Permian section	Kaibab Limestone Toroweap Formation Coconino Sandstone Hermit Shale	Wide	11.7	280	0.00099	0.4	Separation
11.0–22.5	Supai Gorge	Supai Group	Narrow	7.7	210	.0014	.9	Separation
22.6–35.9	Redwall Gorge	Redwall Limestone	Narrow	9.0	220	.0015	.9	Separation
40.0–61.5	Lower Marble Canyon	Muav Limestone Bright Angel Shale Tapeats Sandstone	Wide	19.1	350	.0010	2.6	Separation; reattachment
61.6–77.4	Furnace Flats	Tapeats Sandstone Unkar Group	Wide	26.6	390	.0021	2.5	Channel margin
77.5–117.8	Upper Granite Gorge	Zoroaster Plutonic Complex Trinity and Elves Chasm Gneisses Vishnu Schist	Narrow	7	190	.0023	.6	Separation; channel margin
117.9–125.5	Aisles	Tapeats Sandstone Vishnu Schist	Narrow	11	230	.0017	3.9	Reattachment; channel margin; separation
125.6–139.9	Middle Granite Gorge	Tapeats Sandstone Unkar Group Vishnu Schist	Narrow	8.2	210	.0020	2.3	Channel margin
140–159.9	Muav Gorge	Muav Limestone	Narrow	7.9	180	.0012	1.1	Channel margin
160–213.8	Lower Canyon	Basalt Muav Limestone Bright Angel Shale	Wide	16.1	310	.0013	2.4	----------------
213.9–225	Lower Granite Gorge	Vishnu Schist	Narrow	8.1	240	.0016	2.3	----------------

[1]Modified from Grand Canyon Natural History Association, 1976.
[2]At 24,000 ft^3/s, average based on cross-section data from Randle and Pemberton (1987); cross sections at about 1-mile intervals.
[3]Based on predicted water-surface elevations at 24,000 ft^3/s (Randle and Pemberton, 1987).
[4]Campsites inventoried by Brian and Thomas (1984).

TABLE 3.—*Channel geometry and hydraulic characteristics for selected sites*

[Dashes indicate no data]

Site number and name	River mile	Water-surface slope			Constriction ratio[3]			Channel top width of constriction, in feet		
		1923[1]	1985–86[2]	Discharge,[2] in cubic feet per second	40,000 cubic feet per second	25,000 cubic feet per second	5,000 cubic feet per second	40,000 cubic feet per second	25,000 cubic feet per second	5,000 cubic feet per second
1 Above Cathedral Wash	2.5	0.0008	0.0003	16,400	0.58	0.57	0.44	290	270	190
2 Badger Creek Rapid	7.9	.0162	.0200	26,500	.65	.63	.49	210	270	210
3 Soap Creek Rapid	11.4	.0096	.0286	26,700	.71	.59	.43	260	200	130
4 Below Salt Water Wash	12.2	.0021	------	------	.55	.48	.35	160	125	80
5 Eighteen Mile Wash	18.1	.0009	.0037	27,900	.93	.70	.45	300	190	90
7 Opposite Nineteen Mile Canyon	19.0	.0004	------	------	1.00	.79	.63	290	210	130
8 Twenty Mile Camp	19.8	.0001	.0004	4,500	.84	.81	.58	230	200	130
9 Twenty-Nine Mile Rapid	29.2	.0106	.0183	5,000	.78	.79	.51	200	180	90
10 Nautiloid Canyon	34.7	.0074	.0011	3,300	.71	.52	.18	220	160	50
12 Eminence Break Camp	44.2	.0012	.0011	3,620	.58	.48	.42	275	230	180
13 Saddle Canyon	47.2	.0007	.0007	22,800	.54	.39	.36	220	160	140
19 Above Grapevine Rapid	81.1	.0009	------	------	.71	.68	.53	170	150	120
21 Ninety-One Mile Creek	91.0	.0009	------	------	----	----	.70	---	---	150
23 Granite Rapid	93.4	.0082	------	------	1.00	.71	.45	290	170	90
25 Boucher Rapid	96.6	.0092	.0017	21,000	----	.64	.81	---	220	160
28 One Hundred Twenty Mile Camp	119.7	.0006	------	------	.78	.79	.85	190	210	160
29 Lower Blacktail Rapid	120.1	.0108	.0012	5,000	.74	.58	.53	270	185	140
31 One Hundred Twenty-Two Mile Creek	122.0	.0007	.0023	5,000	.70	.55	.47	270	190	150
37 National Rapid	166.5	.0066	.0062	29,700	1.00	.70	.40	310	190	130
38 Fern Glen Rapid	168.0	.0088	------	------	.93	.66	.47	330	250	120
40 Pumpkin Springs	212.9	.0008	------	------	.69	.52	.33	250	120	70

TABLE 3.—*Channel geometry and hydraulic characteristics for selected sites*—Continued

Site number and name	River mile	Expansion ratio[4] 40,000 cubic feet per second	Expansion ratio[4] 25,000 cubic feet per second	Expansion ratio[4] 5,000 cubic feet per second	Channel depth, in feet, along thalweg at discharge of ~28,000 cubic feet per second[5] Upstream from rapid	Channel depth Constriction	Channel depth Expansion	Fan shape ratio[6]	Divergence angle[7] 40,000 cubic feet per second	Divergence angle[7] 5,000 cubic feet per second	Constriction length, in feet
1 Above Cathedral Wash	2.5	1.5	1.6	1.8	17	15	40	4.90	65	57	570
2 Badger Creek Rapid	7.9	1.8	1.9	2.1	25	8	21	8.70	29	55	800
3 Soap Creek Rapid	11.4	1.9	2.1	2.1	32	12	32	9.80	12	7	1,000
4 Below Salt Water Wash	12.2	2.1	2.4	2.9	18	16	50	4.10	36	34	400
5 Eighteen Mile Wash	18.1	1.4	2.0	3.9	40	22	50	3.80	100	42	200
7 Opposite Nineteen Mile Canyon	19.0	1.42	1.80	2.3	33	33	69	3.20	---	24	260
8 Twenty Mile Camp	19.8	1.3	1.4	1.9	50	28	50	4.90	33	14	140
9 Twenty-Nine Mile Rapid	29.2	1.6	1.7	2.7	31	14	45	3.50	29	19	290
10 Nautiloid Canyon	34.7	2.0	2.8	8.6	20	16	62	2.70	29	27	170
12 Eminence Break Camp	44.2	1.9	2.1	2.4	30	17	44	4.00	49	56	500
13 Saddle Canyon	47.2	2.6	3.3	1.9	18	12	55	2.80	78	20	1,100
19 Above Grapevine Rapid	81.1	2.0	1.7	2.1	30	12	60	5.00	56	25	120
21 Ninety-One Mile Creek	91.0	---	---	1.9	30	15	49	4.13	---	47	210
23 Granite Rapid	93.4	---	2.7	4.9	32	12	44	3.64	1	24	330
25 Boucher Rapid	96.6	---	1.3	1.4	32	11	48	7.17	---	15	380
28 One Hundred Twenty Mile Camp	119.7	1.8	1.5	1.5	35	25	27	10.00	22	7	160
29 Lower Blacktail Rapid	120.1	2.1	3.0	2.6	20	14	50	3.60	84	11	320
31 One Hundred Twenty-Two Mile Creek	122.0	2.3	3.2	2.3	40	12	46	3.68	90	30	420
37 National Rapid	166.5	1.2	2.0	2.7	23	12	35	6.40	13	90	1,100
38 Fern Glen Rapid	168.0	1.6	2.0	3.6	20	14	44	4.83	43	66	520
40 Pumpkin Springs	212.9	2.2	3.8	6.1	30	22	85	4.14	36	5	410

[1]Birdseye (1923).
[2]Steepest survey measured in 1985-1986, at indicated discharge.
[3]Average channel width at constriction divided by average channel width upstream.
[4]Average channel width in expansion divided by average channel width in constriction.
[5]Depth upstream, in constriction, and in expansion along approximate thalweg at ~28,000 cubic feet per second (Wilson, 1986).
[6]Distance along debris fan parallel to channel at low flow divided by distance perpendicular to channel.
[7]Angle between main-channel flow and channel banks in degrees at expansion for two discharges.

TABLE 4.—*Detailed study sites in relation to reaches*

Reach segment	Types of deposits: Separation	Reattachment	Channel-margin
Permian section	Badger Creek Rapid		
Supai Gorge	Soap Creek Rapid Below Salt Water Wash Eighteen Mile Wash Twenty Mile Camp	Opposite Nineteen Mile Canyon	
Redwall Gorge	Twenty-Nine Mile Rapid Nautiloid Canyon	Nautiloid Canyon	
Lower Marble Canyon	Eminence Break Camp	Eminence Break Camp Saddle Canyon	
Upper Granite Gorge	Ninety-One Mile Creek Granite Rapid Boucher Rapid		Above Grapevine Rapid
Aisles		Lower Blacktail Rapid One Hundred Twenty-Two Mile Creek	One Hundred Twenty Mile Camp
Lower Canyon	National Rapid Fern Glen Rapid	National Rapid	Pumpkin Springs

TABLE 5.—*Particle-size characteristics of alluvial sand deposits between Lees Ferry at river mile 0 and Bright Angel Creek at river mile 87.5*

[mm, millimeter; ϕ, $-\log_2$ (millimeter)]

River mile	Sample number	Time of deposition	Deposit type	Graphic mean size (mm)	Graphic standard deviation (ϕ)	Description[1]
0.0	JCS-03	Pre-dam	Channel margin	0.041	1.7	Poorly sorted silt
0.0	JCS-01	1983	Channel margin	.14	.6	Moderately well sorted fine sand
0.0	JCS-02	1983	Channel margin	.14	.6	Moderately well sorted fine sand
2.0	JBG-06	Pre-dam	Channel margin	.072	.8	Moderately sorted very fine sand
2.0	JBG-07	Pre-dam	Channel margin	.041	.9	Moderately sorted silt
5.7	JBG-08	1983	Separation	.23	.6	Moderately well sorted fine sand
11.4	JBG-09	Pre-dam	Separation	.14	.6	Moderately well sorted fine sand
11.4	JBG-10	Pre-dam	Separation	.16	.7	Moderately well sorted fine sand
18.1	JCS-85-01	1985	Separation	.12	.5	Moderately well sorted very fine sand
18.1	JCS-85-02	1985	Separation	.17	.8	Moderately sorted fine sand
19.0	JCS-04	1984	Reattachment	.39	.4	Well-sorted medium sand
31.5	JBG-13	1983	Separation	.27	.45	Well-sorted medium sand
32.0	JBG-15	1983	Channel margin	.23	.6	Moderately well sorted fine sand
47.2	JCS-13	Pre-dam	Separation	.12	.58	Moderately well sorted very fine sand
47.2	JCS-14	1983	Separation	.13	.5	Well-sorted fine sand
47.2	JCS-15	1984	Separation	.10	.5	Well-sorted very fine sand
47.3	JBG-16	Pre-dam	Reattachment	.074	.85	Moderately sorted very fine sand
47.3	JBG-17	1983	Reattachment	.28	.4	Well-sorted medium sand
47.3	JBG-18	1983	Reattachment	.23	.48	Well-sorted fine sand
47.3	JCS-05	1984	Reattachment	.15	.6	Moderately well sorted fine sand
47.3	JCS-06	1984	Reattachment	.29	.4	Well-sorted medium sand
47.3	JCS-07	1984	Reattachment	.27	.4	Well-sorted medium sand
47.3	JCS-08	1984	Reattachment	.27	.4	Well-sorted medium sand
47.3	JCS-09	1984	Reattachment	.29	.36	Well-sorted medium sand
47.3	JCS-10	1983	Reattachment	.19	.89	Moderately sorted fine sand

TABLE 5.—*Particle-size characteristics of alluvial sand deposits between Lees Ferry at river mile 0 and Bright Angel Creek at river mile 87.5*—Continued

River mile	Sample number	Time of deposition	Deposit type	Graphic mean size (mm)	Graphic standard deviation (ϕ)	Description[1]
47.3	JCS-11	1983	Reattachment	0.15	0.5	Well-sorted fine sand
47.3	JCS-12	Pre-dam	Reattachment	.13	.48	Well-sorted fine sand and very fine sand
52.3	JBG-21	1983	Channel margin	.22	.44	Well-sorted fine sand
53.0	JCS-16	1984	Channel bar	.33	.47	Well-sorted medium sand
53.2	JCS-17	1984	Channel margin	.17	.50	Well-sorted fine sand
56.0	JBG-23	1983	Separation	.20	.27	Very well sorted fine sand
56.0	JBG-24	1983	Separation	.20	.5	Well-sorted fine sand
56.3	JCS-85-03	1985	Recirculation zone bedload	.29	.47	Well-sorted medium sand
56.3	JCS-85-04	1985	Recirculation zone bedload	.29	.41	Well-sorted medium sand
56.3	JCS-85-05	1985	Recirculation zone bedload	.29	.45	Well-sorted medium sand
56.3	JCS-85-10	1985	Recirculation zone bedload	.27	.43	Well-sorted medium sand
56.3	JCS-85-11	1985	Recirculation zone bedload	.27	.38	Well-sorted medium sand
60.6	JCS-85-12	1985	Recirculation zone bedload	.33	.38	Well-sorted medium sand
60.6	JCS-85-13	1985	Recirculation zone bedload	.33	.38	Well-sorted medium sand
60.6	JCS-85-14	1985	Recirculation zone bedload	.32	.4	Well-sorted medium sand
61.1	JCS-18	1983	Channel margin	.15	.52	Moderately well sorted fine sand
61.1	JCS-19	1983	Channel margin	.20	.51	Moderately well sorted fine sand
61.1	JCS-20	1983	Channel margin	.18	.55	Moderately well sorted fine sand
61.1	JBG-25	1983	Channel margin	.18	.50	Well-sorted fine sand
61.7	JCS-21	1984	Separation	.19	.57	Moderately well sorted fine sand
61.7	JCS-22	1983	Separation	.15	.49	Well-sorted fine sand
62.5	JBG-26	1983	Channel margin	.27	.42	Well-sorted fine sand
65.5	JBG-29	1983	Channel margin	.10	.8	Moderately sorted very fine sand
71.3	JBG-31	1983	Channel margin	.15	.5	Well-sorted fine sand
71.3	JBG-32	Pre-dam	Channel margin	.035	1.5	Poorly sorted silt
71.3	JBG-34	1983	Channel margin	.095	.6	Moderately well sorted very fine sand
71.3	JBG-35	1983	Channel margin	.13	.47	Well-sorted very fine sand
71.3	JBG-36	Pre-dam	Channel margin	.095	.5	Well-sorted very fine sand
71.3	JCS-23	1983	Channel margin	.14	.5	Well-sorted fine sand
71.3	JCS-24	Pre-dam	Channel margin	.10	.58	Moderately well sorted very fine sand
71.3	JCS-25	Pre-dam	Channel margin	.09	.58	Moderately well sorted very fine sand
71.3	JCS-26	1983	Channel margin	.13	.45	Well-sorted fine sand
71.3	JCS-27	1983	Channel margin	.19	.5	Well-sorted fine sand
71.3	JCS-28	1983	Channel margin	.17	.4	Well-sorted fine sand
72.9	JBG-37	1983	Channel margin	.15	.5	Well-sorted fine sand
75.6	JBG-38	1983	Separation	.12	.5	Well-sorted very fine sand
75.6	JBG-39	1983	Separation	.10	.6	Moderately well sorted very fine sand
81.1	JCS-29	1983	Channel margin	.29	.5	Moderately well sorted medium sand
81.1	JCS-30	1983	Channel margin	.13	.6	Moderately well sorted fine sand
81.1	JBG-40	1983	Channel margin	.23	.9	Moderately well sorted fine sand
81.1	JBG-41	1983	Channel margin	.15	.6	Moderately well sorted fine sand
81.1	JBG-42	1983	Channel margin	.13	.6	Moderately well sorted fine sand

[1]Based on Wentworth size classes and sorting classification (Folk, 1968, p.46).

TABLE 6.—*Summary statistics of particle-size characteristics*

Time of deposition	Deposit type	Number of samples[1]	Mean graphic means value, in millimeters	Standard deviation of graphic means, in millimeters	Ninety-five percent confidence interval, in millimeters
Pre-dam	Separation	3	0.140	0.020	0.117–0.162
Post 1983	Separation	12	.165	.054	.134–.196
Pre-dam	Reattachment	2	.102	.040	.047–.157
Post 1983	Reattachment	10	.251	.073	.206–.296
Pre-dam	Channel margin	7	.068	.028	.057–.079
Post 1983	Channel margin	24	.169	.050	.149–.189
1985	Recirculation zone bedload	8	.299	.025	.282–.316

[1]Small sample sizes restrict statistical significance of data in some categories. Statistics are reported for descriptive purposes.

TABLE 7.—*Areas of alluvial sand deposits at low discharge in selected reaches, October 1984*

[All deposit values are in thousands of square feet]

Reach segment	Description of reach width	All deposit types			Area by type of deposit									
					Sepsration		Reattachment		Channel margin		Point bar		Upper pool	
		Total	Average	Area per mile	Total	Average	Total	Average	Total	Average	Total	Average	Total	Average
0–11.3	Wide	410	51	36	230	57	93	31	0	0	92	92	0	0
11.4–22.5	Narrow	510	23	46	390	30	96	16	0	0	0	0	23	7.6
22.6–35.9	Narrow	540	25	41	290	21	190	47	0	0	0	0	54	18
40.9–61.5	Wide	4,700	60	180	1,200	49	1,900	87	1,300	73	37	37	270	21
117.9–125.5	Narrow	920	25	120	130	26	350	35	330	22	0	0	0	0
125.6–139.9	Narrow	900	22	63	240	17	140	34	410	20	0	0	97	32
140–159.9	Narrow	240	8.2	12	100	14.5	2.3	2.3	130	7.5	0	0	5.7	5.7

TABLE 8.—*Summary of changes between bathymetric surveys*

[Aggradation and degradation were computed as the difference in area between profile lines for successive surveys. Average vertical change was computed by dividing the area of net vertical change along profile lines by the length of the line. Dashes, no data]

Profile	April–September 1985				September 1985–January 1986				
								Average vertical change	
	Aggradation, in square feet	Degradation, in square feet	Net change in area, in square feet	Average vertical change in upper surface of deposit, in feet	Aggradation, in square feet	Degradation, in square feet	Net change in area, in square feet	Upper surface of deposit, in feet	Slope into main channel, in feet
Eminence Break Camp									
1	164	0	+164	+2.6	0	341	-341	-5.4	----
2	41	2	+39	+0.6	0	235	-235	-3.5	----
3	197	0	+197	-1.7	11	260	-249	-2.2	----
4	37	418	-381	-2.9	142	67	+75	+0.6	----
5	4	386	-382	-3.1	100	45	+55	+0.4	----
6	142	401	-259	-1.6	96	321	-225	-1.4	----
7	62	202	-140	-0.9	99	101	-2	0.0	----
8	0	246	-246	-1.6	113	122	-9	-0.1	----
9	0	421	-421	-2.6	102	112	-10	-0.1	----
10	0	282	-282	-1.8	0	276	-276	-1.7	----
11	0	132	-132	-1.1	0	78	-78	-0.7	----
12	14	270	-256	-1.9	54	68	-14	-0.1	----
13	15	305	-290	-4.2	169	6	+163	+2.3	----
Lower Blacktail Rapid									
1	----	----	----	----	0	186	-186	-1.6	----
2	----	----	----	----	537	8	+529	0.0	+3.8
3	----	----	----	----	444	105	+339	-0.8	+4.6
4	----	----	----	----	721	223	+498	-1.3	+5.9
5	----	----	----	----	574	220	+354	-1.3	+4.7
6	----	----	----	----	173	228	-55	-1.4	+2.8
7	----	----	----	----	428	125	+303	-0.2	+3.6
8	----	----	----	----	83	0	+83	+0.7	----
National Rapid									
1	268	37	+231	+1.4	116	414	-298	-1.8	----
2	230	10	+220	+1.6	0	219	-219	-1.6	----
3	189	36	+153	+0.9	66	95	-29	-0.2	----
4	103	69	+34	+0.3	0	122	-122	-1.2	----
5	13	9	+4	0	16	29	-13	-0.2	----
6	76	0	+76	+1.1	0	66	-66	-0.9	----

TABLE 9.—*Number of separation and reattachment deposits in recirculation zones between river miles 0 and 118, 1973 and 1984*

Reach segment	Total number of recirculation zones surveyed	Width of reach	Bias of analysis[1]	Deposit type[1]			
				Reattachment		Separation	
				1973	1984	1973	1984
0–11.3	36	Wide	Decrease	31	28	18.5	19.5
11.4–22.5	40	Narrow	Decrease	27	20.5	26	26
22.6–35.9	60	Narrow	No bias	37.5	34	38.5	29.5
40–61.5	115	Wide	Increase	96.5	100.5	49.5	50
61.6–77.4	37	Wide	Increase	28	32	23.5	25
77.5–117.8	111	Narrow	Increase	78.5	68.5	28.5	27.5
Total	399			298.5	283.5	184.5	177.5

[1]Change in number of deposits from 1973 to 1984 caused by difference in stage.

TABLE 10.—*Areas of major alluvial sand deposits in selected reaches, 1973 and 1984*

[Values are in thousands of square feet]

Reach segment	Types of deposits											
	Total			Separation			Reattachment			Channel margin		
	1973	1984	Change	1973	1984	Change	1973	1984	Change	1973	1984	Change
0–11.3	460–610	370–450	([1])	210–270	210–250	([2])	100–130	84–100	([2])	-------	-------	---
11.4–22.5	540–670	460–560	([2])	350–430	350–430	([2])	170–200	86–110	([1])	-------	-------	---
22.6–35.9	480–620	490–590	([2])	280–360	260–320	([2])	150–200	170–210	([2])	-------	-------	---
122–125.5	300–380	320–400	([2])	-------	-------	---	57–67	59–72	([2])	112–140	140–180	([2])
125.6–139.9	840–920	810–990	([2])	200–220	220–260	([2])	120–130	130–150	([2])	410–440	370–450	([2])
140–150	128–150	120–150	([2])	73–86	55–67	([1])	0	2	---	50–59	64–78	([2])

[1]Erosion.
[2]No change.

TABLE 11.—*Number of deposits that underwent change, 1973–84*

Reach segment	Separation			Reattachment			Channel margin			Upper pool		
	Gain	Loss	No change	Gain	Loss	No change	Gain	Loss	No change	Gain	Loss	No change
0–11.3	1	0	3	2	2	1	0	0	0	0	0	0
11.4–22.5	4	3	6	0	6	1	0	0	0	0	2	1
22.5–35.9	2	6	6	1	1	2	0	0	0	0	1	2
122–125.5	1	1	0	2	0	1	7	2	0	1	0	1
125.6–139.9	6	3	5	2	2	0	7	9	4	0	1	2
140–150	0	2	1	1	0	0	7	0	2	0	0	0
Total	14	15	21	8	11	5	21	11	6	1	4	6
Percent	28	30	42	33	46	21	55	29	16	9	36	55

TABLE 12.—*Classification of deposits studied by Howard (1975) and Beus and others (1985)*

[Study site names are those of Beus and others (1985). River mile in brackets is river mile used in appendix A of this report. L, left side of river; R, right side of river]

Separation	Reattachment	Channel margin	Upper pool
Eighteen Mile Wash (18.2) [18.1L]	Nineteen Mile Wash[1] (19.3) [19.0L]	Nineteen Mile Wash[1] (19.3) [19.0L]	Upper Granite Rapid (93.2)[93.1L]
Nautiloid Canyon (34.7) [34.7L]	One Hundred Ninety Mile (190.2)	Lower Nankoweap (53) [53.2R]	Blacktail Canyon (120.1) [120.0R]
Below Little Colorado River confluence (61.8) [61.7R]		Grapevine (81.1) [81.1L]	
Tanner Mine (65.5) [65.6L]		One Hundred Nine Mile (109.4)	
Unkar Indian Village (72.2) [72.5R]		Walthenberg Canyon (112.2)	
Bedrock Rapids (131) [131.0R]		Upper 124.5 Mile Canyon (124.3)	
		The Ledges (151.6) [151.6R]	
		National Canyon (165.5) [166.4L]	
		Lower Lava (180.9)	
		Granite Park (208.8)	

[1]Nineteen Mile Wash had one profile line across reattachment deposit and one profile line across channel-margin deposit.

TABLE 13.—*Summary of measured changes at 20 sites during fluctuating flow, October 1985 to mid-January 1986*

River mile	Deposit type	Date	Profile	Length of section, in feet[1]	Average vertical change[2]	Description
			Above Cathedral Wash			
2.5	Reattachment	10-04-85	1	57	+0.6	Profile 1 across crest; profile 2
		to	2	45	-0.1	downstream of reattachment point
		01-09-86				
			Badger Creek Rapid			
7.9	Separation	10-05-85	1	54	+0.1	Figure 5
		to	2	85	-0.7	
		01-11-86	3	90	+2.0	
			Soap Creek Rapid			
11.4	Separation	09-21-85	1	87	-0.1	Separation point migrates
		to	2	83	-0.3	downstream through
		01-12-86	3	53	-0.6	all cross sections
			4	35	-0.7	
			5	39	-0.7	
			6	37	-0.3	
			Below Salt Water Wash			
12.2	Separation	10-08-85	1	16	+0.4	Low-velocity area
		to	2	57	-0.2	
		01-13-86	3	45	+0.1	
			Eighteen Mile Wash			
18.1	Separation	10-09-85	1	20	-0.0	Figure 12
		to	2	90	-2.2	
		01-13-86	3	10	-2.72	
			Opposite Nineteen Mile Canyon			
19.0	Reattachment	10-10-85	1	57	-0.3	Profile 1 across bar crest; profile
		to	2	30	-0.3	2 downstream from reattachment
		01-14-86				point
			Twenty Mile Camp			
19.8	Separation	10-11-85	1	17	-0.5	About 120 feet downstream from
		to				separation point
		01-14-86				
			Twenty-Nine Mile Rapid			
29.2	Separation	10-11-85	1	43	-0.1	Figure 34
		to	2	42	-2.8	
		01-15-86	3	47	-3.5	
			Nautiloid Canyon			
34.7	Separation	10-12-85	1	9	-0.6	Profiles located progressively
		to	2	17	+0.2	farther downstream
		01-14-86	3	20	+0.6	
			4	20	-1.2	
			Eminence Break Camp			
44.2	Separation	10-12-85	1	18	-0.1	Figure 14
		to	2	70	+0.0	
		01-16-86	3	29	-1.0	
			4	26	+1.7	

TABLE 13.—*Summary of measured changes at 20 sites during fluctuating flow, October 1985 to mid-January 1986*—Continued

River mile	Deposit type	Date	Profile	Length of section in feet[1]	Average vertical change[2]	Description
			Saddle Canyon[3]			
47.2	Reattachment	09-24-85	1	60	-0.2	Figure 17
		to	2	89	-0.1	
		01-18-86	3	68	-0.2	
			4	20	-1.2	
			5	25	-1.2	
			6	16	-1.4	
			Above Grapevine Rapid[3]			
81.1	Channel	10-15-85	1	21	-1.0	Profile 1 between separation and
		to	2	22	-1.1	reattachment points; profile 2 near
		01-21-86				reattachment point
			Ninety-One Mile Creek[3]			
91.0	Separation	10-15-85	1	15	-1.3	Profile 1 near separation point;
		to	2	3	-1.1	profile 2 primary-eddy current
		01-22-86				
			National Rapid			
166.5	Separation	10-21-85	1	66	-0.4	Figure 30
		to	2	32	+0.3	
		01-08-86	3	-	0.0	
			Fern Glen Rapid			
168.0	Separation	10-01-85	1	3	+0.7	Profiles located progressively
		to	2	15	+2.8	farther downstream
		01-08-86	3	72	+1.7	
		USBR	4	-	-0.0	
			5	10	-0.2	
			Pumpkin Springs[3]			
212.9	Channel margin;	10-23-85	1	18	-7.2	Profile 1 near reattachment point;
	reattachment	to	2	25	-1.8	profile 2 downstream from
		01-31-86				reattachment point

[1]Length of section is that portion of cross section over which survey comparisons could be made and which were both affected by fluctuating flows; actual cross sections are longer.

[2]Average vertical change equals cross-section area divided by horizontal length of cross section.

[3]Surveys in January 1986 after conclusion of special fluctuating-flow study period; some change may be due to resumption of higher flows beginning January 17, 1986.

TABLE 14.—*Areas of exposed sand at detailed study sites, 1965, 1973, and 1984*

[Area is in thousands of square feet]

Site[2]	Deposit[3]	Site name	Area of exposed sand					Change[1]		
			High elevation[4]			Low elevation[5]		High elevation		Low elevation
			1965	1973	1984	1973	1984	1965–73	1973–84	1973–85
2.5L	R	Above Cathedral Wash	35	18	17	64	59	-	NC	NC
7.9L	S	Badger Creek Rapid	43	35	29	42	55	-	-	+
	R	Badger Creek Rapid	7.9	0	0	17	0	-	NC	-
11.4R	S	Soap Creek Rapid	85	86	90	110	99	NC	NC	NC
12.2L	S	Below Salt Water Wash	17	10	17	31	35	-	+	-
18.1L	S	Eighteen Mile Wash	11	4.0	6.9	15	15	-	+	NC
19.0L	R	Opposite Nineteen Mile Canyon	29	16	14	57	25	-	NC	-
19.8L	S	Twenty Mile Camp	21	20	21	33	30	NC	NC	NC
29.2L	S	Twenty-Nine Mile Rapid	23	19	25	51	53	-	+	NC
34.7L	S	Nautiloid Canyon	34	30	18	41	33	-	+	-
	R	Nautiloid Canyon	0	0	0	32	66	NC	NC	+
44.2L	S	Eminence Break Camp	62	81	76	100	92	+	NC	NC
	R	Eminence Break Camp	17	13	3.5	63	43	-	-	-
93.4L	S	Granite Rapid	5	0	6.1	NA	NA	-	+	NA
96.6L	S	Boucher Rapid	22	23	27	NA	NA	NC	+	NA
168.0R	S	Fern Glen Rapid	97	54	70	95	100	-	+	NC
	R	Fern Glen Rapid	5.0	0	0	19	12	-	NC	-

[1]NC, no change; minus sign, loss of area; plus sign, gain in area; NA, not applicable.
[2]River mile. L, left side of river; R, right side of river.
[3]R, reattachment; S, separation.
[4]Area exposed at discharge of about 25,000 cubic feet per second.
[5]Area exposed at discharge of about 6,000 cubic feet per second.

APPENDIX A

Comparison of river mile inventories of 1973 and 1983 from Lees Ferry to Stone Creek

River mile inventory 1923[1]	Side of river	Site	Aerial photograph number[2]	River mile inventory 1973	River mile inventory 1983	Deposit type[3]
0.0	-----	Lees Ferry	-----	-----	-----	--------------
1.9	Left	Unnamed site	1-141	1.9	2.0	Point bar
2.5	Left	Above Cathedral Wash	1-144	-----	-----	Reattachment
2.7	Right	Cathedral Wash	1-145	2.7	3.0	Separation
5.7	Right	Six Mile Wash	1-173	5.8	-----	Separation
7.9	Right	Badger Creek Rapid	1-193	7.9	8.0	Separation
7.9	Left	Badger Creek Rapid	1-193	7.9	8.0	Separation
10.3	Left	Below Ten Mile Rock	1-211	-----	10.2	Reattachment
11.4	Right	Soap Creek Rapid	1-219	-----	11.5	Separation
12.0	Left	Salt Water Wash	1-223	-----	12.0	Separation
12.2	Left	Below Salt Water Wash	1-226	12.2	12.4	Separation
16.5	Left	Hot Na Na Wash	2-3	16.5	16.5	Separation
17.0	Right	House Rock Rapid	2-6	17.1	-----	Separation
18.1	Left	Eighteen Mile Wash	2-15	18.2	18.2	Separation
18.9	Right	Nineteen Mile Canyon	2-21	-----	19.0	Upper pool
19.0	Left	Opposite Nineteen Mile Canyon	2-22	19.3	19.2	Reattachment
19.8	Left	Twenty Mile Camp	2-28	20.0	20.0	Separation
20.2	Left	Unnamed site	2-29	20.2	-----	Separation
20.3	Right	Above North Canyon Rapid	2-32	-----	20.5	Upper pool
20.4	Right	North Canyon Rapid	2-32	-----	20.5	Separation
21.3	Left	Twenty-Two Mile Wash	2-38	21.5	21.5	Separation
21.6	Left	Unnamed site	2-40	21.5	21.5	Separation
21.7	Right	Unnamed site	2-41	21.8	-----	Reattachment
22.5	Left	Unnamed site	2-45	22.3	22.8	Separation
22.7	Right	Above Indian Dick Rapid	2-47	22.6	22.7	Separation
23.4	Left	Twenty-Three and One-Half Mile Rapid	2-50	23.2	-----	Separation
24.5	Left	Above Twenty-Four and One-Half Mile Rapid	2-57	-----	24.5	Upper pool
24.8	Left	Twenty-Four and One-Half Mile Rapid	2-58	-----	24.7	Separation
25.0	Left	Twenty-Five Mile Rapid	2-60	24.9	-----	Reattachment; upper pool
26.2	Left	Unnamed site	2-68	26.2	-----	Separation
26.4	Left	Above Tiger Wash Rapid	2-70	-----	26.5	Separation
26.7	Left	Tiger Wash Rapid	2-72	26.7	-----	Separation
28.7	Right	Unnamed site	2-86	28.8	-----	Separation
28.9	Right	Unnamed site	2-86	29.0	-----	Separation; reattachment
29.2	Left	Twenty-Nine Mile Rapid	2-87	29.2	29.3	Separation
30.3	Right	Unnamed site	2-94	30.3	30.3	Reattachment; upper pool
30.4	Right	Unnamed	2-95	-----	30.4	Reattachment
31.5	Right	South Canyon	2-102	31.5	31.5	Separation
33.5	Left	Little Redwall Camp	2-114	33.5	33.7	Separation
33.7	Left	Unnamed site	2-116	33.9	33.8	Separation
34.7	Left	Nautiloid Canyon	2-123	34.7	34.8	Separation
35.1	Left	Unnamed site	2-132	35.1	-----	Separation
36.0	Left	Thirty-Six Mile Rapid	2-138	36.0	-----	Separation
37.2	Right	Unnamed site	2-147	37.2	-----	Reattachment;
37.3	Left	Tatahatso Wash	2-148	37.3	-----	Upper pool
37.6	Left	Below Tatahatso Wash	2-150	37.6	37.5	Upper pool
38.0	Left	Unnamed site	2-154	-----	38.4	Separation; reattachment

See footnotes at end of table.

Comparison of river mile inventories of 1973 and 1983 from Lees Ferry to Stone Creek—*Continued*

River mile inventory 1923[1]	Side of river	Site	Aerial photograph number[2]	River mile inventory 1973	River mile inventory 1983	Deposit type[3]
38.5	Left	Unnamed site	2-157	38.6	38.8	Channel margin; reattachment
39.9	Left	Unnamed site	2-166	39.8	-----	Separation
40.2	Left	Unnamed site	2-168	40.1	-----	Channel margin;
40.9	Right	Upper Buckfarm Canyon	2-173	40.9	40.9	Reattachment; upper pool
41.0	Right	Lower Buckfarm Canyon	2-173	41.0	41.0	Separation
41.3	Right	Bert Loper Canyon	2-205	41.3	-----	Separation
41.5	Right	Royal Arches	2-206	41.5	-----	Reattachment
42.0	Left	Unnamed site	2-177	41.9	-----	Channel margin
42.2	Left	Unnamed site	2-178	42.1	42.3	Channel margin
42.8	Left	Unnamed site	2-181	-----	42.9	Channel margin
43.1	Left	Unnamed site	2-183	43.2	-----	Separation;
43.5	Left	President Harding Rapid	2-184	43.4	43.3	Separation
44.2	Left	Eminence Break Camp	2-187	44.2	-----	Separation
44.6	Left	Unnamed site	2-191	44.5	44.6	Separation
44.8	Left	Unnamed site	2-192	44.7	44.8	Reattachment; upper pool
44.9	Left	Unnamed site	2-193	45.0	-----	Separation
45.3	Right	Above Triple Alcoves Camp	2-195	-----	45.3	Channel margin; reattachment
45.9	Left	Unnamed site	2-198	45.8	46.0	Upper pool
46.7	Right	Triple Alcoves	2-203	46.8	46.5	Reattachment; upper pool
46.8	Right	Unnamed site	2-204	Marsh	Marsh	Reattachment
47.0	Right	Lower Triple Alcoves Camp	2-211	-----	46.6	Separation
47.2	Right	Saddle Canyon	2-213	47.1	47.2	Separation
47.3	Right	Below Saddle Canyon	2-214	-----	47.3	Reattachment
47.5	Left	Unnamed site	2-215	-----	47.5	Separation
47.5	Right	Unnamed site	2-215	-----	47.8	Separation; reattachment
47.7	Left	Unnamed site	2-216	-----	47.8	Reattachment
48.0	Left	Unnamed site	2-217	-----	48.0	Reattachment
48.3	Right	Unnamed site	2-219	48.3	-----	Reattachment; upper pool
49.5	Left	Unnamed site	2-225	-----	49.7	Reattachment; upper pool
49.8	Left	Unnamed site	2-226	49.5	49.9	Reattachment; separation
49.8	Right	Fifty Mile Camp	2-227	-----	49.9	Upper pool
49.9	Right	Dinosaur Camp	2-227	50.0	50.0	Separation
50.3	Left	Unnamed site	2-229	-----	50.2	Channel margin; reattachment
50.7	Left	Unnamed site	2-232	50.6	50.6	Reattachmet
51.1	Right	Unnamed site	2-235	-----	51.0	Separation
51.2	Left	Unnamed site	2-236	Marsh	51.5	Reattachment
51.3	Right	Unnamed site	2-236	-----	51.4	Reattachment
51.5	Left	Unnamed site	2-237	Marsh	-----	Reattachment
51.9	Right	Little Nankoweap Creek	3-1	51.9	51.8	Reattachment; upper pool
52.1	Right	Unnamed site	3-2	52.0	-----	Separation
52.3	Right	Above Nankoweap Rapid	3-3	-----	52.3	Channel margin
52.5	Right	Nankoweap Rapid	3-4	52.5	52.5	Channel margin
53.0	Right	Nankoweap Rapid	3-7	-----	52.7	Channel margin; reattachment

See footnotes at end of table.

Comparison of river mile inventories of 1973 and 1983 from Lees Ferry to Stone Creek—Continued

River mile inventory 1923[1]	Side of river	Site	Aerial photograph number[2]	River mile inventory 1973	1983	Deposit type[3]
53.2	Right	Below Nankoweap Rapid	3-9	53.0	53.0	Channel margin; reattachment
53.2	Left	Unnamed site	3-9,10	53.1	53.0	Point bar
53.4	Right	Below Nankoweap Rapid	3-10	-----	53.2	Separation
53.7	Left	Unnamed site	3-12	53.3	53.4	Channel margin; reattachment
53.7	Right	Unnamed site	3-12	53.6	53.4	Separation
53.8	Right	Unnamed site	3-13	53.7	-----	Channel margin; reattachment
53.8	Left	Unnamed site	3-13	53.8	53.8	Channel margin
54.1	Left	Unnamed site	3-14	-----	54.0	Separation
54.2	Right	Unnamed site	3-15	-----	54.0	Separation
54.3	Right	Unnamed site	3-16	54.2	54.2	Reattachment; upper pool
54.4	Right	Unnamed site	3-17	54.5	-----	Reattachment
54.5	Left	Unnamed site	3-17	Marsh	54.4	Upper pool
54.6	Left	Unnamed site	3-18	-----	54.6	Channel margin
54.7	Left	Unnamed site	3-19	-----	54.7	Reattachment
55.0	Left	Unnamed site	3-21	-----	55.0	Upper pool; reattachment
55.1	Left	Unnamed site	3-21	-----	55.2	Separation
55.3	Left	Unnamed site	3-22	Marsh	55.4	Reattachment
55.6	Right	Unnamed site	3-24	Marsh	-----	Reattachment
56.3	Right	Kwagunt Rapid	-----	-----	56.2	Reattachment
56.4	Right	Below Kwagunt Rapid	-----	-----	56.4	Channel margin
56.5	Right	Unnamed site	3-28	56.6	56.5	Channel margin; reattachment
56.8	Left	Unnamed site	3-29	56.8	56.8	Channel margin
57.0	Left	Unnamed site	3-30	-----	57.0	Separation
57.5	Right	Malagosa Canyon	3-33	57.4	57.5	Separation
57.6	Left	Unnamed site	3-34	57.7	57.5	Reattachment
58.2	Right	Awatubi Canyon	3-37	-----	58.2	Separation
58.6	Left	Unnamed site	3-39	58.5	58.7	Separation
58.9	Right	Unnamed site	3-40	-----	58.5	Upper pool
59.0	Left	Unnamed site	3-41	59.0	59.0	Reattachment;
59.5	Right	Unnamed site	3-44	-----	59.5	Channel margin
59.8	Right	Sixty Mile Rapid	3-45	-----	59.8	Separation
60.2	Left	Unnamed site	3-48	-----	60.0	Reattachment; upper pool
60.6	Right	Unnamed site	3-51	-----	60.5	Separation
61.1	Right	Unnamed site	3-53	-----	61.2	Reattachment; upper pool
61.4	Left	Island Camp	3-56	-----	61.8	Separation; reattachment
61.7	Right	Below Little Colorado River confluence	3-58	-----	61.9	Separation
62.3	Right	Unnamed site	3-61	62.4	62.3	Upper pool
63.3	Right	Unnamed site	3-68	63.3	-----	Separation
64.0	Left	Unnamed site	3-71	63.9	-----	Reattachament
64.7	Right	Carbon Creek	3-75	64.5	64.5	Separation
65.4	Right	Lava Canyon Rapid	3-79	65.5	65.5	Reattachment; upper pool
65.6	Left	Palisades Creek	3-82	65.5	65.6	Separation
66.0	Left	Unnamed site	3-84	66.1	-----	Channel margin
66.4	Left	Unnamed site	3-86	66.4	66.5	Reattachment; channel margin

See footnotes at end of table.

Comparison of river mile inventories of 1973 and 1983 from Lees Ferry to Stone Creek—*Continued*

River mile inventory 1923[1]	Side of river	Site	Aerial photograph number[2]	River mile inventory 1973	River mile inventory 1983	Deposit type[3]
66.8	Left	Espejo Creek	3-90	66.9	66.8	Channel margin; separation
67.3	Left	Comanche Creek	3-92	67.3	-----	Channel margin
67.7	Left	Unnamed site	3-94	67.7	-----	Channel margin
67.8	Right	Unnamed site	3-94	-----	67.8	Channel margin
68.0	Right	Upper Tanner	3-96	68.0	68.0	Point bar
68.2	Right	Unnamed site	3-97	68.1	68.2	Point bar
68.6	Left	Tanner	3-101	68.7	68.6	Channel margin
68.7	Left	Tanner	3-101	68.8	-----	Point bar
69.3	Left	Below Tanner	3-111	69.5	69.0	Point bar
69.4	Right	Upper Basalt Rapid	3-112	69.5	69.6	Channel margin
69.8	Right	Lower Basalt Rapid	3-113	-----	69.8	Channel margin
69.9	Left	Unnamed site	3-114	69.9	-----	Channel margin
70.2	Left	Unnamed site	3-116	70.2	-----	Channel margin
70.3	Right	Unnamed site	3-117	-----	70.3	Channel margin
70.5	Right	Unnamed site	3-117	-----	70.5	Channel margin
70.9	Left	Unnamed site	3-120	Marsh	-----	Channel margin; reattachment
71.3	Left	Cardenas Creek	3-121	-----	71.3	Separation
71.4	Left	Unnamed site	3-121	Marsh	-----	Reattachment
71.7	Left	Unnamed site	3-124	-----	71.7	Channel margin
71.9	Right	Unnamed site	3-126	-----	-----	Separation
72.1	Left	Unnamed site	3-128	72.1	72.1	Point bar
72.5	Right	Above Unkar Rapid	3-129	-----	72.5	Channel margin
72.6	Right	Middle Unkar Rapid	3-130	-----	72.6	Channel margin
72.7	Left	Unnamed site	3-132	-----	72.7	Channel margin
73.1	Right	Lower Unkar Rapid	3-133	-----	73.1	Channel margin
73.4	Left	Unnamed site	3-135	73.4	73.3	Channel margin
73.7	Left	Unnamed site	3-137	73.7	-----	Channel margin
73.7	Right	Granary Camp	3-137	-----	73.7	Channel margin
73.9	Right	Unnamed site	3-138	73.9	-----	Channel margin
74.0	Right	Unnamed site	3-138	74.0	-----	Separation
74.2	Left	Unnamed site	3-140	74.2	-----	Channel margin
74.3	Left	Unnamed site	3-142	74.3	74.4	Channel margin
74.3	Right	Unnamed site	3-142	74.3	-----	Separation
74.7	Left	Unnamed site	3-144	74.7	74.7	Channel margin
74.7	Right	Unnamed site	3-144	-----	74.6	Channel margin
74.9	Left	Escalante Creek	3-145	74.9	74.8	Upper pool
75.0	Right	Unnamed site	3-145	-----	75.0	Channel margin
75.6	Left	Nevills Rapid	3-148	75.5	75.5	Separation
75.8	Right	Opposite Papago Creek	3-152	-----	75.8	Reattachment
76.5	Right	Unnamed site	3-156	76.4	-----	Channel margin
76.6	Left	Above Hance Rapid	3-156	76.5	76.4	Reattachment; upper pool
77.2	Left	Unnamed site	3-161	77.1	-----	Channel margin
78.8	Left	Sockdolager Rapid	3-168	78.8	-----	Upper pool
81.1	Left	Above Grapevine Rapid	3-181	81.1	81.3	Channel margin; reattachment
82.6	Right	Eighty-Two and One-Half Mile	3-189	82.6	-----	Channel margin
84.0	Right	Clear Creek	3-197	84.0	-----	Separation; reattachment
84.4	Left	Above Zoroaster Rapid	3-201	84.4	-----	Separation
85.7	Left	Cremation Creek	3-207	85.7	-----	Channel margin
87.1	Left	Cremation Camp	3-215	87.1	87.1	Separation
87.2	Right	Roys Beach Camp	3-216	-----	87.1	Channel margin
88.0	Left	Unnamed site	3-220	88.0	-----	Channel margin

See footnotes at end of table.

Comparison of river mile inventories of 1973 and 1983 from Lees Ferry to Stone Creek—*Continued*

River mile inventory 1923[1]	Side of river	Site	Aerial photograph number[2]	River mile inventory 1973	1983	Deposit type[3]
89.3	Right	Below Pipe Springs Rapid	3-228	89.3	89.5	Channel margin
90.9	Left	Unnamed site	3-239	91.1	90.8	Separation
91.0	Right	Ninety-One Mile Creek	2-240	91.2	91.2	Separation
91.4	Right	Trinity Creek	3-242	91.5	-----	Separation
92.2	Left	Unnamed site	3-246	92.2	92.1	Channel margin
93.1	Left	Upper Granite Rapid	4-7	93.2	93.4	Reattachment; upper pool
93.4	Left	Granite Rapid	4-7	93.3	93.6	Separation
94.2	Left	Unnamed site	4-12	-----	-----	Separation
94.2	Right	Ninety-Four Mile Creek	4-12	93.9	94.3	Separation
94.9	Left	Hermit Rapid	4-15	-----	94.7	Upper pool
95.8	Left	Old Dune Camp	4-22	95.8	-----	Channel margin; reattachment
96.0	Left	Ninety-Six Mile Camp	4-23	95.9	95.6	Channel margin
96.6	Left	Boucher Rapid	4-27	96.5	96.7	Separation
98.0	Right	Upper Crystal Rapid	4-36	-----	98.1	Upper pool
98.2	Right	Crystal Rapid	4-37	-----	98.3	Separation
99.0	Left	Tuna Creek Above Rapid	4-41	99.1	-----	Channel margin; reattachment
99.1	Right	Tuna Creek Rapid	4-42	99.1	-----	Upper pool
99.5	Left	Unnamed site	4-43	99.5	-----	Point Bar
102.7	Right	Below Turquoise Rapid	4-67	102.9	-----	Channel margin
103.1	Right	Shady Grove; One Hundred-Three Mile	4-68	103.1	-----	Channel margin
		One Hundred-Four Mile Rapid	-73	103.8	103.8	Upper pool; reattachment
105.6	Right	One Hundred-Five and One-Half Mile	4-83	105.6	-----	Upper pool; reattachment
106.8	Right	One Hundred-Seven Mile	4-93	106.8	-----	Channel margin
107.0	Right	Above Bass Rapid	4-95	107.5	107.7	Channel margin
107.3	Left	Bass Canyon	4-96	107.7	-----	Channel margin
107.4	Right	Bass Rapid	4-97	107.9	108.0	Channel margin
107.6	Right	Unnamed site	4-99	108.2	-----	Reattachment
107.8	Right	Lower Bass Camp	4-101	108.3	108.2	Channel margin
108.1	Right	Shinumo Rapid	4-103	-----	108.6	Channel margin
112.6	Right	Unnamed site	4-132	112.5	-----	Separation
114.0	Right	Unnamed site	4-141	-----	114.0	Channel margin
114.4	Right	Upper Garnet Canyon	4-144	114.3	114.5	Separation
114.6	Right	Lower Garnet Camp	4-145	114.5	-----	Channel margin
115.6	Left	Royal Arch Trail Camp	4-153	115.4	115.4	Channel margin
115.7	Right	Unnamed site	4-154	-----	115.5	Separation
115.8	Right	Monument Fold Camp	4-155	115.7	115.6	Reattachment; separation
117.0	Left	Below Elves Chasm	4-161	117.0	116.8	Separation
117.3	Left	Unnamed site	4-163	117.4	117.2	Channel margin
117.7	Left	Stephen Aisle	4-165	117.7	-----	Channel margin
118.0	Right	Unnamed site	4-167	-----	118.1	Upper pool
118.3	Right	Unnamed site	4-169	-----	118.6	Reattachment
118.5	Left	Apache Terrace	4-170	118.5	188.6	Channel margin
118.7	Right	Unnamed site	4-171	118.7	118.8	Reattachment
118.9	Left	Unnamed site	4-172	118.8	-----	Channel margin
119.1	Right	One Hundred Nineteen Mile Camp	4-173	119.2	119.0	Reattachment
119.2	Left	Unnamed site	4-174	119.2	119.1	Separation

See footnotes at end of table.

Comparison of river mile inventories of 1973 and 1983 from Lees Ferry to Stone Creek—*Continued*

River mile inventory 1923[1]	Side of river	Site	Aerial photograph number[2]	River mile inventory 1973	River mile inventory 1983	Deposit type[3]
119.4	Right	Unnamed site	4-175	-----	119.3	Channel margin
119.4	Left	Unnamed site	4-175	-----	119.4	Reattachment
119.7	Left	One Hundred Twenty Mile Camp	4-176	119.7	119.8	Channel margin; reattachment
119.8	Right	Unnamed site	4-177	-----	119.8	Reattachment
120.0	Left	Unnamed site	4-178	119.9	-----	Channel margin
120.0	Right	Upper Blacktail Rapid	4-178	120.1	120.0	Upper pool
120.1	Right	Lower Blacktail Rapid	4-178	-----	120.2	Separation
120.2	Left	Opposite Blacktail Rapid	4-179	120.5	120.5	Channel margin
120.5	Left	Below Blacktail Rapid	4-181	120.5	120.5	Separation
121.5	Left	Unnamed site	4-186	121.6	-----	Upper pool
121.6	Left	One Hundred-Twenty-Two Mile Rapid	4-187	121.7	121.8	Separation
121.8	Left	Unnamed site	4-188	121.9	-----	Channel margin
122.0	Right	One Hundred Twenty-Two Mile Creek	4-189	122.0	122.2	Reattachment; upper pool
122.2	Left	Unnamed site	4-190	122.2	-----	Channel margin
122.3	Left	The Cutbank	4-191	-----	122.2	Reattachment
122.6	Left	Forster Rapid	4-192	122.7	122.6	Reattachment; upper pool
122.7	Left	Unnamed site	4-193	122.8	-----	Channel margin
122.9	Left	Unnamed site	4-194	-----	123.0	Reattachment
123.2	Left	Upper Enfilade Point Camp	4-197	-----	-----	Channel margin
123.5	Left	Enfilade Point	4-198	123.5	123.2	Separation
123.8	Right	Unnamed site	4-200	-----	124.0	Channel margin
124.2	Left	Unnamed site	4-202	-----	124.6	Channel margin
124.3	Left	Unnamed site	4-202	124.4	124.8	Separation
124.6	Left	Fossil Rapid	4-205	-----	124.9	Channel margin
125.2	Left	Below Fossil Rapid	4-207	125.2	-----	Channel margin
125.2	Right	Unnamed site	4-207	-----	125.2	Channel margin
125.4	Left	One Hundred Twenty-Six Mile Camp	4-208	125.4	125.8	Channel margin; reattachment
125.5	Left	Unnamed site	4-209	125.5	125.8	Channel margin reattachment
126.1	Left	Unnamed site	4-213	126.2	126.0	Separation
126.3	Right	Randy's Rock	4-215	126.3	126.5	Upper pool
127.7	Left	Below bedrock	4-224	127.7	----	Separation
131.0	Right	Above Dubby	4-244	131.0	131.0	Separagion
131.1	Right	Unnamed site	4-246	-----	131.3	Channel margin
131.4	Right	Just above Dubby	4-247	131.6	131.8	Upper pool; channel margin
131.8	Right	Stone Creek	4-249	131.9	132.0	Separation; reattachment
132.0	Left	Unnamed site	5-4	132.1	-----	Channel margin
133.0	Left	Opposite One Hundred Thirty-Three Mile Creek	5-11	133.1	133.0	Separation
133.1	Left	Racetrack	5-11	-----	133.1	Reattachment
133.4	Right	Upper Tapeats	5-13	-----	133.7	Channel margin
133.7	Right	Tapeats Creek Mouth	5-14	-----	133.8	Channel margin
133.8	Right	Unnamed site	5-15	-----	133.9	Channel margin
133.8	Right	Lower Tapeats Rapid	5-15	133.9	133.9	Channel margin
134.1	Left	Unnamed site	5-17	134.2	134.1	Channel margin
134.5	Left	Unnamed site	5-20	134.5	134.5	Separation; reattachment

See footnotes at end of table.

Comparison of river mile inventories of 1973 and 1983 from Lees Ferry to Stone Creek—*Continued*

River mile inventory 1923[1]	Side of river	Site	Aerial photograph number[2]	River mile inventory 1973	River mile inventory 1983	Deposit type[3]
134.8	Left	Owl Eyes Camp	5-22	-----	134.8	Channel margin
134.7	Right	One Hundred Thirty-Five Mile Rapid	5-21	-----	134.8	Channel margin
134.8	Right	Above Granite Narrows Camp	5-21	-----	134.9	Channel margin
136.1	Left	Granite Narrows Camp	5-29	136.0	-----	Channel margin
136.2	Left	Opposite Deer Creek Falls	5-31	136.2	136.2	Channel margin
136.4	Left	Lower Deer Creek Camp	5-32	136.4	136.5	Separation
136.5	Left	Unnamed site	5-32	136.5	136.6	Channel margin; reattachment
136.6	Left	Unnamed site	5-33	-----	136.7	Channel margin; reattachment
136.7	Left	Above Poncho's Kitchen Camp	5-34	-----	136.8	Separation;
137.0	Left	Poncho's Kitchen Camp	5-36	137.0	-----	Separation
137.0	Left	Lower Poncho's Camp	5-36	137.1	-----	Reattachment;
137.1	Left	Below Poncho's Camp	5-37	-----	-----	Separation
137.4	Left	Unnamed site	5-39	-----	137.3	Channel margin
137.3	Right	Unnamed site	5-39	-----	-----	Separation; reattachment
137.5	Right	Unnamed site	5-39	-----	137.3	Channel margin
137.6	Left	One Hundred Thirty-Seven and One-Half Mile Rapid	5-40	137.7	137.5	Channel margin
137.9	Left	Unnamed site	5-42	137.9	137.8	Separation
138.2	Left	Unnamed site	5-44	138.3	138.0	Separation
138.4	Left	Unnamed site	5-45	138.5	-----	Channel margin
138.6	Right	Unnamed site	5-46	-----	138.7	Reattachment
138.9	Right	Fishtail Rapid	5-48	138.9	139.0	Upper pool
139.3	Left	Unnamed site	5-51	139.4	139.5	Channel margin
139.3	Right	Unnamed site	5-51	139.4	-----	Channel margin
139.7	Left	One Hundred Forty Mile Canyon	5-53	139.7	139.8	Reattachment; upper pool
139.9	Left	Unnamed site	5-54	139.9	-----	Separation
140.2	Left	Unnamed site	5-56	-----	140.3	Channel margin
141.0	Left	Unnamed site	5-60	-----	141.0	Separation; Reattachment
141.4	Left	Unnamed site	5-62	-----	141.4	Channel margin
142.4	Right	Unnamed site	5-69	-----	142.5	Channel margin
143.4	Left	Above Kanab Rapid	5-74	143.3	143.4	Channel margin
143.1	Right	Unnamed site	5-74	-----	143.0	Channel margin
143.5	Right	Mouth of Kanab Creek	5-75	-----	143.5	Channel margin
145.0	Left	Unnamed site	5-84	-----	145.1	Channel margin
145.6	Left	Olo Canyon	5-88	145.4	145.5	Separation
147.7	Right	Spring Above Matkatamiba Rapid	5-102	-----	147.7	Channel margin
147.9	Right	Matkatamiba Rapid	5-103	-----	147.8	Channel margin
148.5	Left	Lower Matkatamiba Rapid	5-106	148.3	148.4	Channel margin
149.7	Right	Upset Rapids	5-114	149.8	149.7	Separation
151.6	Right	Ledges Camp	5-122	151.6	151.8	Rock
152.3	Left	Unnamed site	5-128	152.3	-----	Separation
153.6	Right	Sinyala Rapid	5-133	-----	153.5	Separation
153.8	Left	Sinyala Ledges Camp	5-135	153.8	-----	Rock
154.9	Right	Rockfall Lower Ledges	5-140	-----	155.0	Channel margin reattachment
155.7	Right	Last Chance Camp	5-146	155.6	155.7	Upper pool

See footnotes at end of table.

Comparison of river mile inventories of 1973 and 1983 from Lees Ferry to Stone Creek—*Continued*

River mile inventory 1923[1]	Side of river	Site	Aerial photograph number[2]	River mile inventory 1973	River mile inventory 1983	Deposit type[3]
155.8	Right	Unnamed site	5-146	-----	-----	Separation
156.3	Right	Unnamed site	5-150	-----	156.2	Channel margin
156.6	Left	Unnamed site	5-151	-----	156.5	Channel margin
157.8	Right	Unnamed site	5-158	-----	157.7	Channel margin
158.0	Left	Unnamed site	5-159	-----	157.8	Channel margin
158.3	Right	Unnamed site	5-159	158.1	-----	Channel margin
158.7	Right	Unnamed site	5-161	158.6	158.5	Channel margin
159.4	RIght	Unnamed site	5-167	-----	159.3	Separation
159.9	Left	Unnamed site	5-170	159.8	-----	Channel margin
160.4	Left	Unnamed site	5-172	-----	160.4	Channel margin
160.7	Right	Unnamed site	5-175	160.7	-----	Separation
161.6	Right	Unnamed site	5-180	-----	161.6	Channel margin
162.0	Left	Unnamed site	5-182	-----	162.0	Separation
162.1	Left	Unnamed site	5-182	-----	-----	Channel margin
162.4	Left	Unnamed site	5-184	-----	162.5	Channel margin
162.8		Unnamed site	5-187	-----	163.0	Upper pool; Reattachment
163.1	Right	Unnamed site	5-189	-----	163.2	Separation; Reattachment
163.3	Left	Unnamed site	5-190	-----	163.5	Channel margin
163.9	Left	Unnamed site	5-193	163.9	163.9	Channel margin
164.5	Right	One Hundred Sixty-Four Mile Rapid	5-199	164.5	164.5	Separation
164.9	Right	Unnamed site	5-202	-----	165.0	Channel margin
165.0	Left	Unnamed site	5-202	-----	165.0	Reattachment
165.1	Right	Unnamed site	5-203	-----	165.2	Reattachment
165.7	Left	Unnamed site	5-206	-----	165.7	Reattachment
165.8	Left	Unnamed site	5-207	-----	165.8	Channel margin
165.9	Left	Unnamed site	5-207	-----	166.0	Separation
165.9	Left	Unnamed site	5-208	-----	-----	Channel margin
166.3	Left	Above Upper National Rapid	5-210	-----	-----	Channel margin
166.4	Left	Upper National Rapid	5-211	166.5	166.5	Channel margin Reattachment
166.5	Left	National Rapid	5-211	166.6	166.6	Separation

[1]River mile located to nearest 0.1 mile based on 1923 survey (Birdseye, 1923) as plotted on 1984 aerial photographs.
[2]Number of aerial photographs on which site is located (U.S. Bureau of Reclamation, 1984 series).
[3]Largest deposit type listed first.

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