Regulated Streamflow, Fine-Grained Deposits, and Effective Discharge in Canyons with Abundant Debris Fans

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The fundamental channel unit of rivers that flow through canyons that have abundant debris fans is a channel complex composed of (1) a backwater upstream from the debris fan, (2) a debris fan and channel constriction, (3) an eddy or eddies and associated bars in the expansion downstream from the fan, and (4) a downstream gravel bar. These fan-eddy complexes exist at the mouths of nearly all debris-flow-generating tributaries. Such tributaries exist along many, but not all, of the narrow canyons of the Green and Colorado Rivers. Reaches affected by debris fans are steeper, have higher stream power per unit bed area, and have coarser beds than other narrow canyons of the same river system. A large proportion of fine-grained sediment in these canyons is deposited in eddies; this proportion is as large as 75 percent in Grand Canyon. Before construction of Glen Canyon Dam, many eddy bars along the Colorado River in Grand Canyon were more extensive than they are today, and separation and reattachment bars merged. Fine-grained deposits can be classified as (1) low-elevation eddy bars and channel-margin deposits formed by discharges less than or equal to the primary mode of the calculated product of streamflow frequency and sediment transport, and (2) high-elevation eddy bars and channel-margin deposits formed by floods that produce subsidiary modes of the streamflow-frequency-sediment-transport product.

1. INTRODUCTION

The relative channel-forming role of rare catastrophic floods and of frequent moderate-magnitude floods has been the subject of longstanding debate. Frequent events determine the shape of relatively unconstrained meandering streams whose floodplains are formed by lateral accretion [*Wolman and Leopold*, 1957; *Wolman and Miller*, 1960], but the role of catastrophic floods is more important in narrow canyons because flood flows are of higher stage, velocity, and turbulence [*Baker*, 1984]. Narrow canyons often have coarse bed material that can only be transported by high magnitude discharges [*Baker*, 1977]. Even where coarse bed material is absent, the tendency for streams in narrow canyons to build floodplains by vertical accretion increases the role of catastrophic floods in determining channel shape [*Nanson*, 1986]. The elevation of the active floodplain and of bankfull stage become more variable where there is a large range in flood magnitude and where recovery time is long [*Baker*, 1977; *Wolman and Gerson*, 1978; *Andrews*, 1980].

The role of catastrophic floods has been stressed in those narrow canyons of the Colorado Plateau where debris flows deliver large amounts of coarse sediment to the channel and valley floor. *Graf* [1979] and *Kieffer* [1985] showed that only rare floods significantly rework coarse bed material within rapids of the Green and Colorado Rivers. Numerous studies have described high-elevation slackwater deposits that contain the preserved evidence of rare high-magnitude discharges [*Baker et al.*, 1983; *O'Conner et al.*, 1994].

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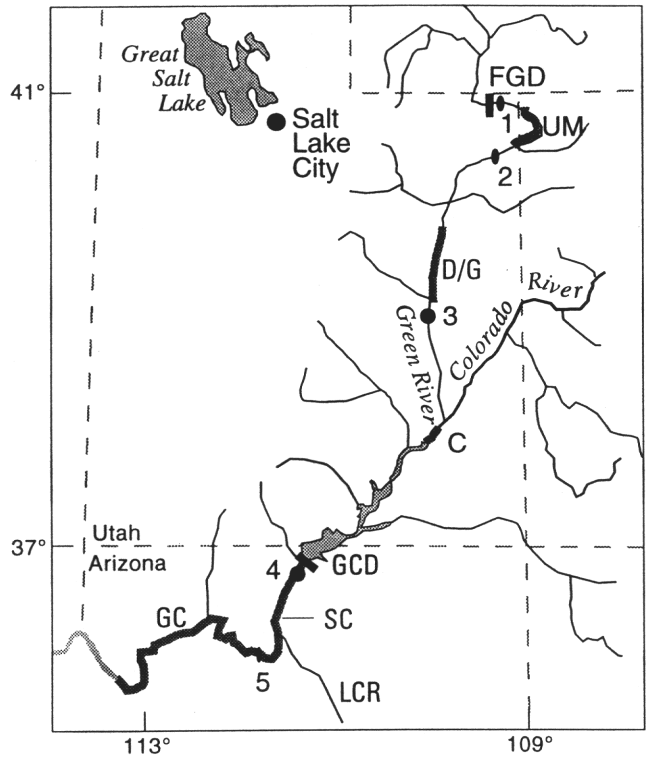


Fig. 1. Map showing major rivers of the Colorado Plateau. Canyons with abundant debris fans are shown as thick grey lines and are labelled as (GC) Grand Canyon, (C) Cataract Canyon, (D/G) Desolation/Gray Canyons, and (UM) Canyon of Lodore and Split Mountain Canyon in the Uinta Mountains. U.S. Geological Survey stream gaging stations used in flood-frequency analyses are located with black circles and labelled as: (1) Green River near Greendale, UT, (2) Green River near Jensen, UT, (3) Green River at Green River, UT, (4) Colorado River at Lees Ferry, AZ, and (5) Colorado River near Grand Canyon, AZ. FGD is the location of Flaming Gorge Dam and GCD is the location of Glen Canyon Dam. LCR is Little Colorado River and SC is Saddle Canyon.

Less attention has been given to fine-grained alluvial deposits that occur at lower elevations in these canyons, but environmental management considerations have recently redirected the attention of geomorphologists. These discontinuous deposits are important environmental resources along the Colorado Plateau's large rivers because recreational boating depends, in part, on the availability of these deposits for campsites [*Kearsley et al.,* 1994]. These deposits are also substrate for riparian vegetation that may support an abundant and diverse ecosystem [*Stevens et al.,* 1995]. These canyons are managed for their intrinsic environmental values because they are within the U.S. National Park Service system or are designated as Wild and Scenic Rivers.

Low-elevation alluvial deposits are affected by an extensive network of dams. These dams have greatly decreased the magnitude of floods and the volume of mainstem sediment transport of the Colorado River and its tributaries [*Andrews,* 1986, 1990]. The long-term fate of these deposits is the subject of substantial public concern, and management agencies wish to know if reservoir operations can be revised so as to provide more favorable downstream conditions (e.g. U.S. Bureau of Reclamation, 1993]. Thus, the attention of environmental managers has been drawn to the role of frequent moderate-magnitude hydrologic events in shaping attributes of the downstream channel because these are the hydrologic events that can be controlled by dam operations. Even though much of the river-corridor geomorphology may have been determined by rare catastrophic floods, low-elevation fine-grained alluvial deposits are an environmental resource that can be manipulated by normal dam operations. These management considerations led us to reevaluate the concepts of effective discharge and bankfull stage for those rivers where these concepts might otherwise be expected to have the least application.

The purposes of this paper are to (1) describe the large-scale geomorphic attributes of canyons that have abundant debris fans, (2) describe the reach-scale geomorphic organization of these rivers, (3) describe the processes and patterns of fine-grained sediment deposition, and (4) demonstrate that the concept of geomorphic effectiveness, defined as the product of streamflow frequency and sediment transport, provides useful geomorphic and management insights concerning the depositional regimes responsible for these fine-grained deposits.

2. METHODS

Reach-scale attributes of the Green River (Figure 1) were determined from 1:24000 scale topographic maps (Flaming Gorge Dam to the Colorado River confluence, 650 km) and by photogeologic interpretation of large scale (approx. scale 1:5000) air photography taken at low discharge in 1963 (16 reaches comprising 40 percent of the river between the downstream end of the Uinta Mountains and the Colorado River confluence, 520 km). Width of the alluvial valley floor and channel gradient were determined from topographic maps and published geologic maps. Reaches with abundant debris fans were identified, and meandering reaches were classified by channel pattern: restricted meanders occur where the outer limits of the meander belt impinge on confining valley walls, and incised meanders occur where the wavelength of the channel and the valley are similar. Active sand bars, gravel bars, vegetated terraces, and debris fans of the Green River were mapped. The different components of fan-eddy complexes, as described below, were also mapped. Average channel width for each mapped reach was determined by dividing the total area of low-flow channel and unvegetated bars by the length of each reach.

In Grand Canyon, mapping at a scale of 1:2400 was conducted in 2 reaches, each about 15 km long. These reaches were located between the stream gaging stations at Lees Ferry, Arizona, and near Grand Canyon, Arizona (Figure 1). The purpose of this mapping was to evaluate the adequacy of previously proposed classifications of eddy bars and to determine the discharges that form most of the alluvial deposits of the river corridor. Mapping in these reaches has included extensive field work as well as photogeologic interpretation; methods have been described by *Schmidt et al.* [1994a, b]. The methods used in sedimentologic analyses of many of these alluvial deposits in Grand Canyon are summarized by *Rubin et al.* [1990, 1994]. All mapping data for the Green and Colorado Rivers have been entered into a geographic information system, and area measurements for mapping units have been determined from these data.

Flood recurrence for 5 gaging stations on the Green and Colorado Rivers was determined for the period 1923 to 1962 using *U.S. Water Resources Council* [1981] methods. This period was prior to widespread completion of dams. The Green River stream gage near Jensen, Utah, was installed in 1947, and the flood record was extended by correlation with records of stations with longer periods of measurement [*Schmidt,* 1994].

The product of streamflow frequency and sediment transport for the Colorado River in Grand Canyon was determined from (1) flow duration data for hourly releases from Glen Canyon Dam [*U. S. Bureau of Reclamation,* 1990, written commun.], and (2) sand-transport relations for the Colorado River near Grand Canyon, Arizona [*Pemberton,* 1987]. The duration of hourly flow for each discharge increment of 5 m^3s^{-1} was determined and multiplied by the corresponding suspended sand-transport rate and summed by 25 m^3s^{-1} increments. Sand-transport data were determined from sampling conducted in 1983 and between 1985 and 1986 [*Garrett et al.,* 1993]. Transport data for discharges greater than 890 m^3s^{-1} were only collected in 1983. It is not known whether the same transport rates occurred during the high discharges that occurred between 1984 and 1986. As described later in this paper, deposits formed by high discharges that occurred between 1984 and 1986 are thin, suggesting that the 1983 transport rates may over-estimate transport conditions of 1984 to 1986. Daily flood waves caused by hydroelectric peak power production attenuate downstream (J. D. Smith and S. M. Wiele, U.S. Geological Survey, Boulder, written commun., 1994), but only hourly data at the dam were used in our analysis. Attenuation does not affect the general characteristics of the calculations described below, but it may affect the precision of the determination of the modal discharge increment.

3. REGIONAL SETTING

The earliest geomorphic investigations of the Colorado River system [*Powell,* 1875; *Dutton,* 1882; *Hunt,* 1969] recognized the disparity between present stream courses and trends of the dominant geologic structures. The Green and Colorado Rivers cross many geologic structures that expose formations of differing erosional resistance. The resulting width of the alluvial valley and the channel gradient of different segments of the Green and Colorado Rivers vary by an order of magnitude, and these differences partly control the characteristics of incised valley meanders [*Hardin,* 1990].

Many of the narrow canyons are affected by debris flows from tributaries. Although the ratio of width of the alluvial valley to width of the channel is similar to that of incised meander reaches, stream power per unit bed area in debris flow-affected reaches is much greater because the channel is narrower and because channel gradient is steeper (Figure 2). Stream power per unit bed area, ω, was calculated as

$$\omega = \rho g Q_{2yr} s w^{-1},$$

where ρ is the density of water, g is the acceleration of gravity, Q_{2yr} is the 2-yr recurrence flood at the nearest gaging station for the period 1923 to 1962, s is the channel slope determined from 1:24000 scale topographic maps, and w is the reach average channel width (Table 1).

In reaches with abundant debris fans, large parts of the river bed are composed of gravel and coarser material. On the Green River, the proportion of all alluvial deposits composed of gravel was calculated from surficial geologic maps (Table 1). Between 35 and 64 percent of all alluvial bars include gravel on Green River reaches with abundant debris fans. In Grand Canyon, *Wilson*'s [1986] side-scan sonar surveys showed that the percentage of the bed of the Colorado River composed of bedrock or boulders varied between 30 and 81 percent during three surveys in 1984.

Although the stream bed includes significant amounts of coarse material in reaches with abundant debris fans, large loads of sand are transported as suspended load and as bed load in the form of ripples and dunes. Some of the

Table 1. -- Geomorphic Characteristics of the Green and Colorado Rivers

Location	Length of mapping, in meters	Pre-dam 2-yr flood, in cubic meters per second	Channel slope, in meters per meter	Channel width, in meters	Stream power per unit length, in watts per meter	Stream power per unit area, in watts per square meter	Average valley width, in meters	Ratio of valley to channel width, in meters per meter	Post-dam proportion of fine sediment deposited within eddies	Post-dam proportion of alluvial deposits that are gravel
Grand Canyon										
Little Colorado confluence	4020	2127	0.0016	105	33000	310	125	1.2	0.75	0.41
middle Marble Canyon	10500	2148	0.00067	115	14000	120	225	2.0	0.44	0.03
Green River										
Lower Stillwater Canyon	15540	789	0.00037	125	2900	23	600	4.8	0	0
Upper Stillwater Canyon	17490	789	0.00028	150	2200	15	1200	8.0	0	0
Lower Labyrinth Canyon	16990	789	0.00018	135	1400	10	1200	8.9	0	0
Middle Labyrinth Canyon	12730	789	0.00019	140	1500	11	700	5.0	0	0
Upper Labyrinth Canyon	16090	789	0.0002	135	1500	11	800	5.9	0	0
below Gunnison Valley	16490	789	0.00057	155	4400	28	1000	6.5	0	0.14
Green River Valley	14090	789	0.0008	180	6200	34	4700	26.1	0	0.15
Grey Canyon	14930	789	0.0013	110	10000	91	500	4.5	0.29	0.36
Lower Desolation Canyon	16090	789	0.002	110	15000	140	500	4.5	0.19	0.64
Middle Desolation Canyon	16120	789	0.0011	125	8500	68	700	5.6	0.12	0.35
Upper Desolation Canyon	16860	789	0.00025	165	1900	12	1400	8.5	0.01	0.03
southern Uinta Basin	16020	789	0.00019	215	1500	7	1800	8.4	0	0
central Uinta Basin (south)	16490	789	0.00019	205	1500	7	5000	24.4	0	0
central Uinta Basin (north)	15330	621	0.00024	140	1500	11	7000	50.0	0	0
northern Uinta Basin	13670	621	0.00024	185	1500	8	5000	27.0	0	0.02
downstream from Split Mountain	16090	621	0.00099	130	6000	46	800	6.2	0	0.87

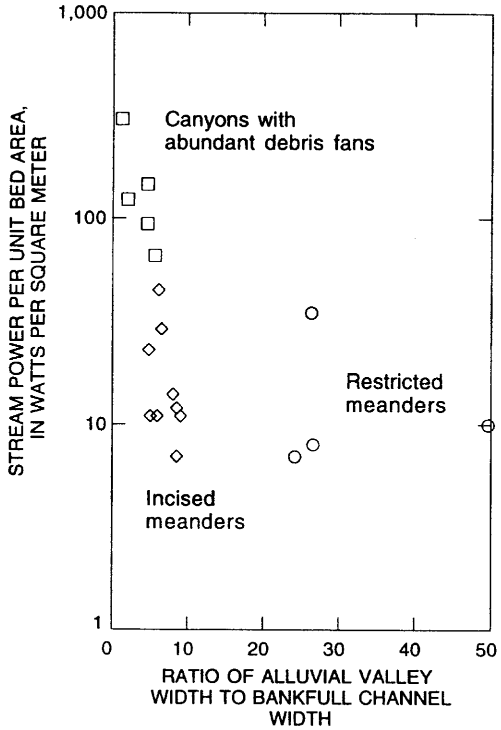


Fig. 2. Graph showing geomorphic characteristics of the Green and Colorado Rivers, and distinguishing restricted meanders, incised meanders, and canyons with abundant debris fans. Data are listed in Table 1.

suspended load, which also includes silt and clay, is deposited as bars and along the channel banks. The suspended load diffuses and is advected into eddies where it is deposited [*Andrews,* 1991; *Nelson et al.,* 1994]; thus, the size distribution of eddy bar sediments and measured sediment loads are similar [*Howard and Dolan,* 1981; *Schmidt,* 1990; *Schmidt et al.,* 1993]. *Andrews* [1986, 1990] has shown that the average annual sediment load has decreased by an order of magnitude since construction of Flaming Gorge and Glen Canyon Dams in 1962 and 1963, respectively.

4. THE FAN-EDDY COMPLEX

Although the meandering pattern of reaches with abundant debris fans may be similar to that of incised meanders, the characteristics of alluvial sedimentation are very different. Debris fans not only affect reach-scale channel attributes such as bed-material size and channel gradient, but fans also control the location and diversity of gravel and fine-grained deposits. Fine-grained deposits in narrow canyons unaffected by debris flows are less diverse and form long benches on alternating banks of the channel. Alluvium is comprised of large proportions of vertical accretion deposits, and levees are common [*Nanson,* 1986].

The frequency of tributary junctions determines the number of debris fans that affect the channel [*Dolan et al.,* 1978]. In Grand Canyon, reaches may have many impinging debris fans (Figure 3). Upstream from each debris fan, a backwater of low-velocity flow may extend several kilometers [*Leopold,* 1969; *Kieffer,* 1985; *Miller,* 1995], and fine-grained alluvium may line these banks. Eddies exist in the lee of most constricting debris fans, and these eddies vary greatly in length. At high discharge, the downstream termination of these eddies (1) is caused by acceleration due to flow over or around a cobble/gravel bar, (2) is caused by narrowing of the bedrock or talus banks, or (3) occurs where the main channel flow impinges on curving channel banks. At low flow, many eddies terminate at exposed reattachment bars formed at higher discharges (Figure 4a and 4c). These channel irregularities cause eddies to be shorter than those predicted from laboratory experiments with similarly scaled constriction geometries [*Schmidt et al.,* 1993].

Eddy bars have distinctive topography and locations relative to the geometry of recirculating flow. *Schmidt* [1990] classified eddy bars based on observations of the Colorado River in Grand Canyon. Separation bars form near the flow-separation point and mantle the downstream parts of debris fans. Reattachment bars form under the primary eddy cell. Deposits not formed in eddies occur as channel-margin deposits that discontinuously line the banks.

Gravel bars are common (1) upstream from constrictions within backwaters of debris fans, and (2) downstream from large eddies. These bars either exist as mid-channel bars, or they may be attached to one bank. Attachment typically occurs on the bank opposite from the side where the debris fan enters the canyon. We refer to the geomorphic assemblage of backwater, constricting debris fan, eddy and eddy bars, and gravel bar as a fan-eddy complex (Figure 5). This assemblage is the fundamental geomorphic channel unit of canyons with abundant debris fans, and occurs at nearly every tributary mouth where debris fans constrict the river. The size of each channel element varies from site to site and is probably related to the size and characteristics of the associated debris fan, the frequency and magnitude of debris flows that replenish the fan, and the frequency and magnitude of main channel floods.

4.1. *Sedimentology of Fine-grained Deposits*

Separation and reattachment bars often have multiple topographic levels (Figure 4b and 4d). Typically, separation bars are of higher elevation and record evidence of

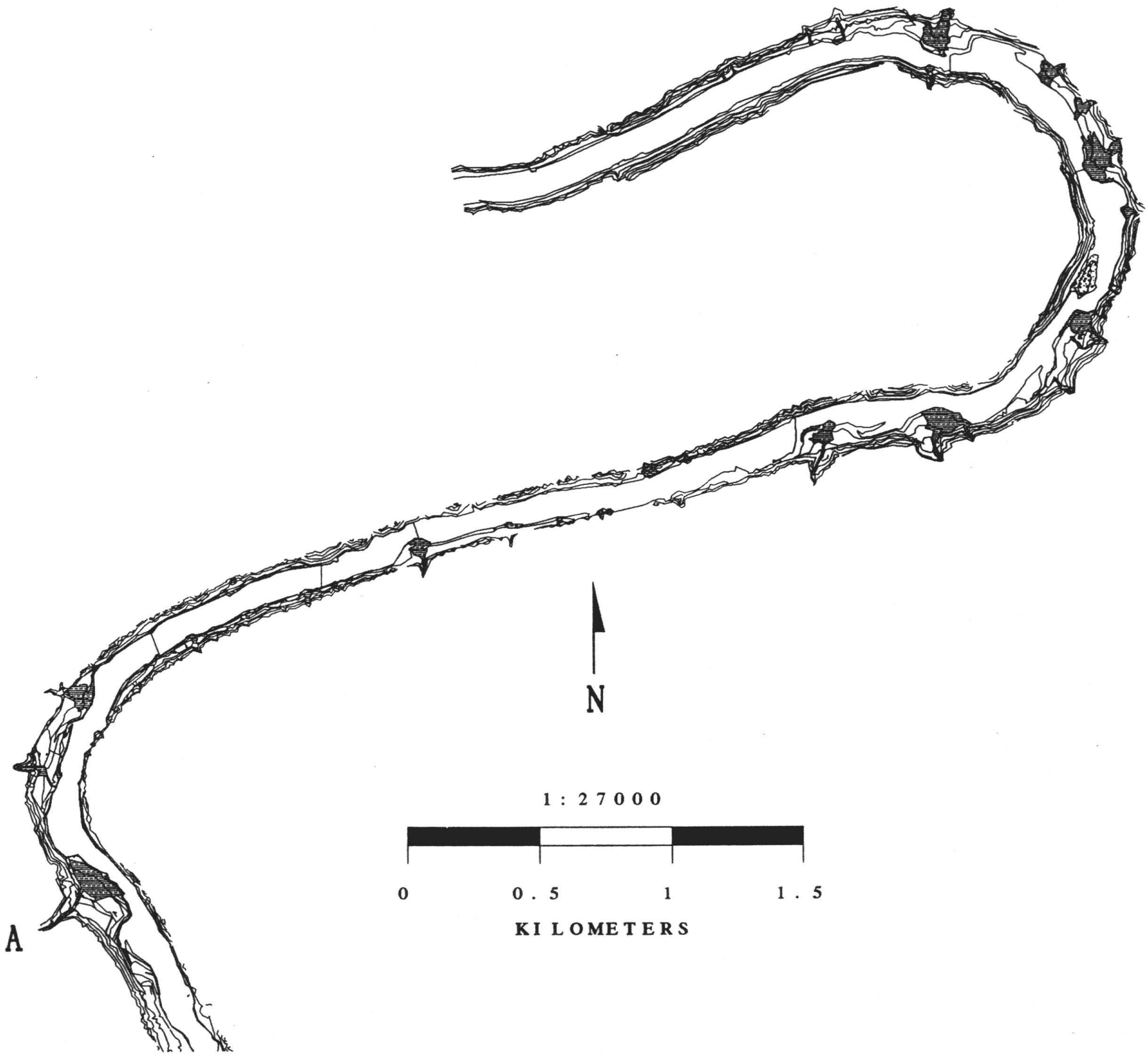
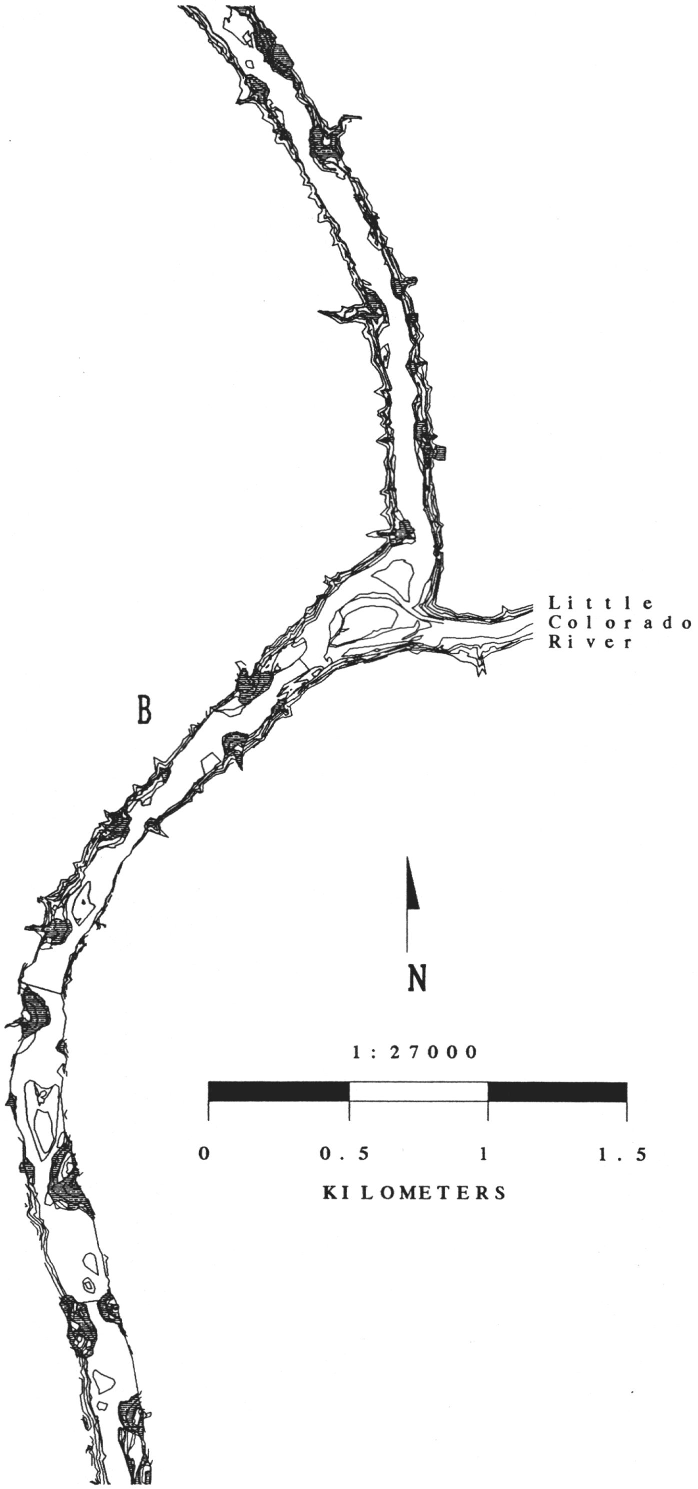


Fig. 3. Maps showing topography along two reaches of the Colorado River in June 1990. Debris fans are shown in dark shading. Contour interval is 2.5 m. (a) 9-km reach near Point Hansbrough and Saddle Canyon that begins 70 km downstream from Lees Ferry. Location A is shown in detail in Figures 4a and 4c. (b) 7-km reach near Little Colorado River confluence that begins 100 km downstream from Lees Ferry. Location B is shown in detail in Figures 4b and 4d.

higher formative discharges than do reattachment bars. Excavations of these deposits have been made at more than 20 sites throughout Grand Canyon [*Schmidt and Graf,* 1990; *Rubin et al.,* 1990, 1994]. In all cases, reattachment bars are composed of sedimentary structures indicative of rotary flow, similar to the pattern described by *Rubin et al.* [1990], or are composed of wave structures formed by processes described by *Bauer and Schmidt* [1993]. Separation bars are composed of a mixture of (1) fluvial structures consistent with secondary eddy cells and deposition in stagnating flow and (2) wave structures such as beach swash, wave ripples, and berms. Wave structures are more common in separation bars because these sites are closer to the wave source in the rapids.

Where debris fans are small or of low relief, alluvial deposits occur as continuous banks that extend downstream for several channel widths. These deposits may have ridges parallel or divergent to the orientation of main channel flow. Channel-parallel ridges are interpreted as levees formed by the same processes as on alluvial streams (Figure 6). Excavations indicate that these levees are composed of foresets indicating transport onshore and



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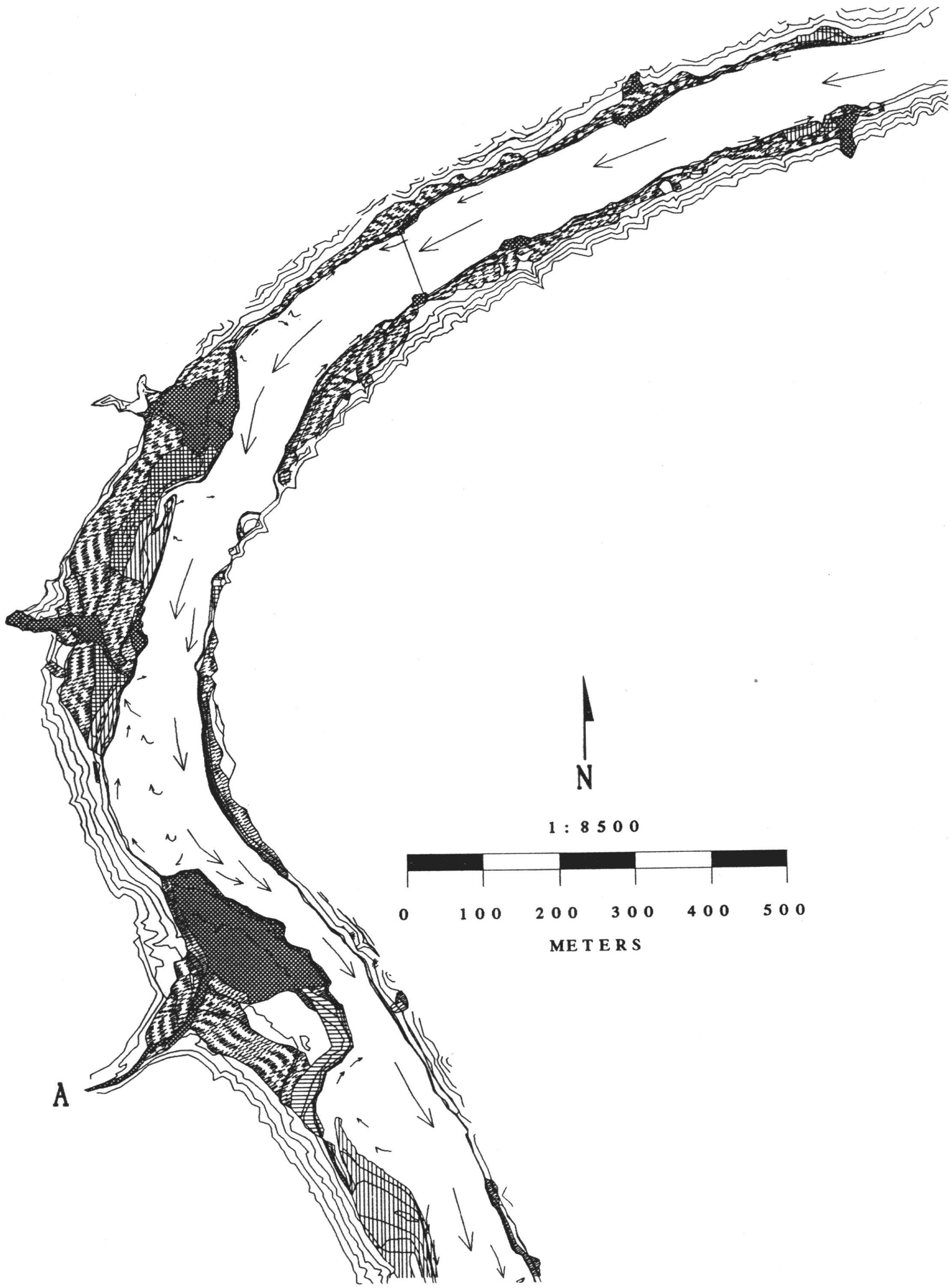
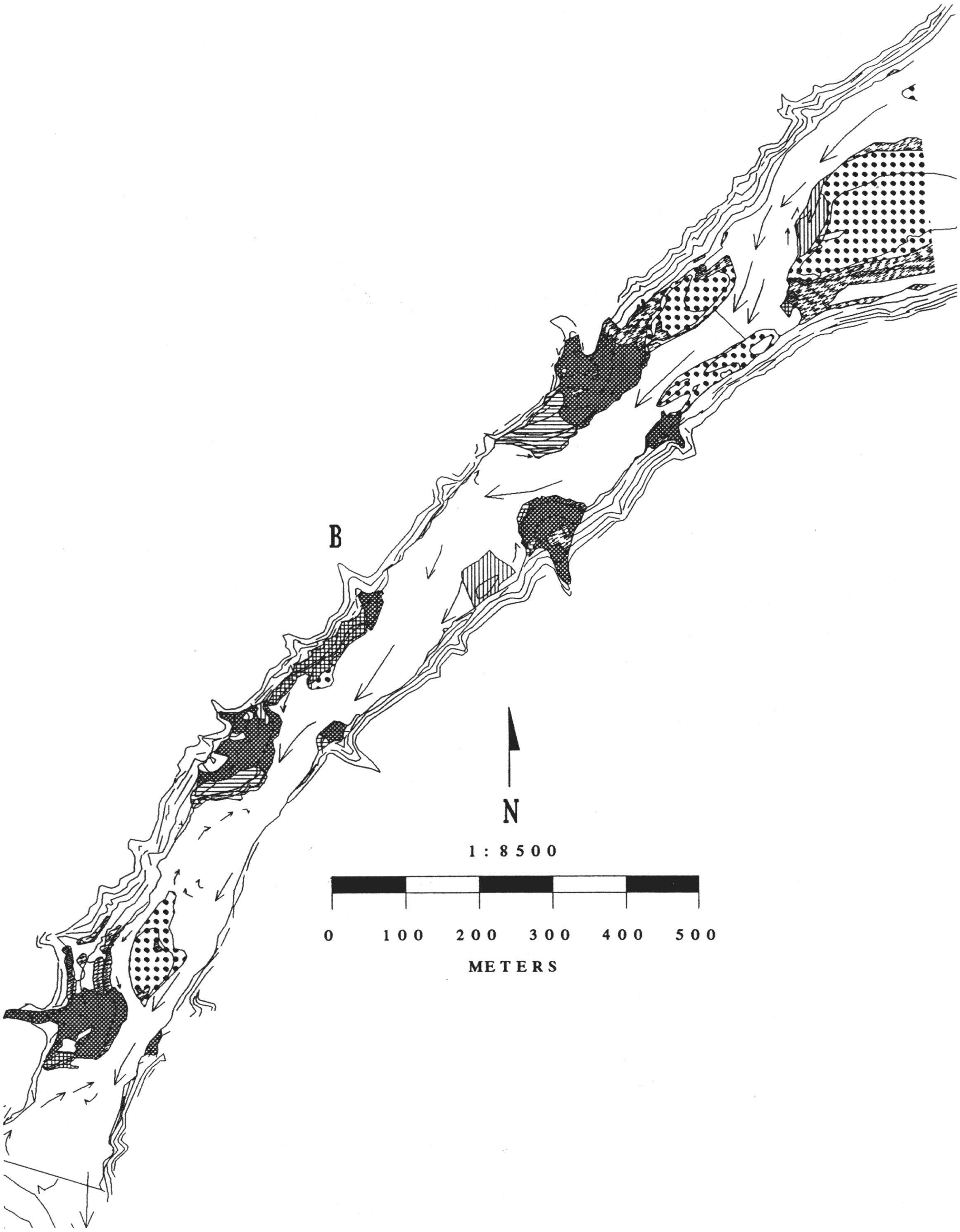
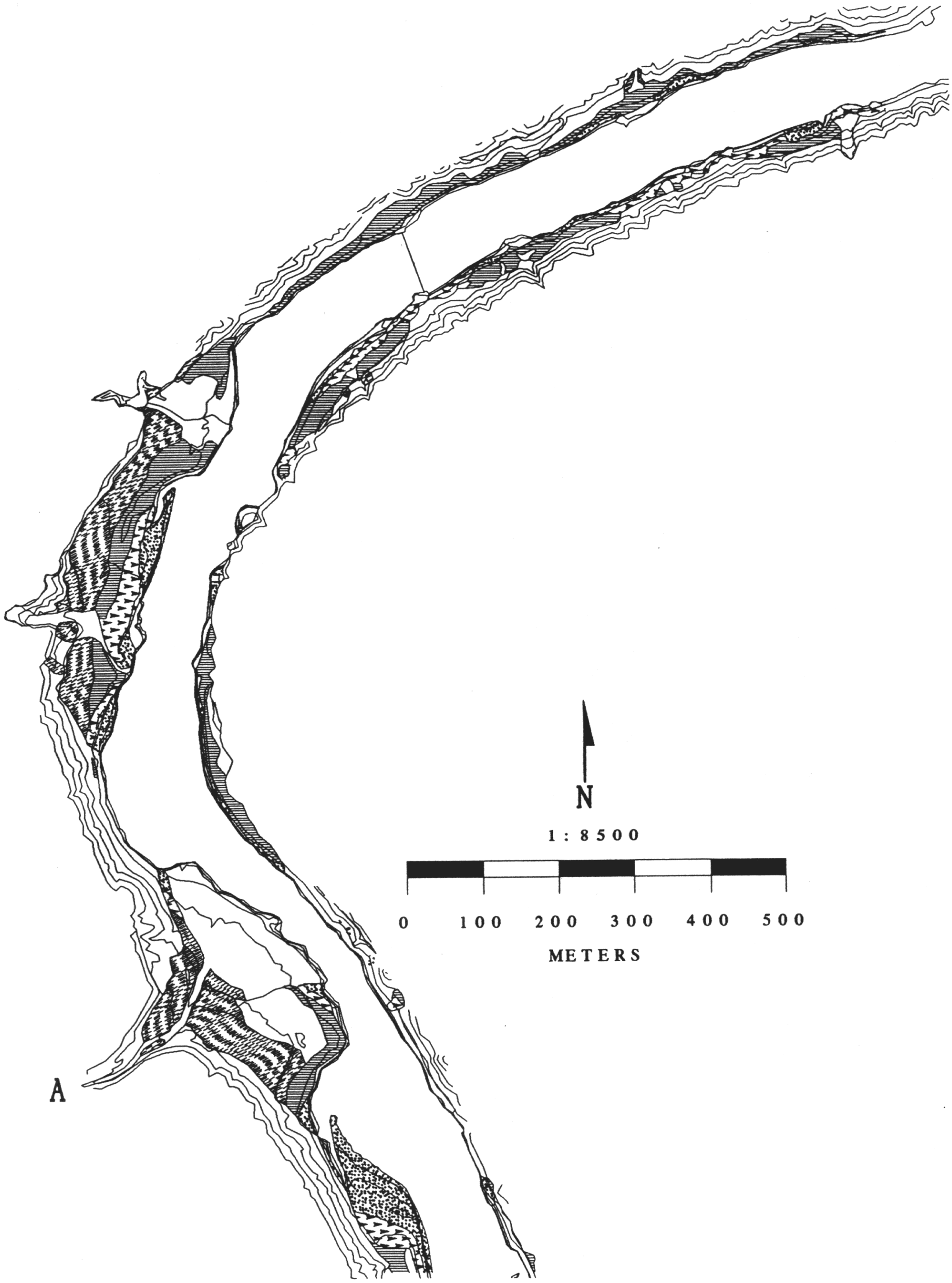


Fig. 4. Maps showing surface flow patterns at about 425 m^3s^{-1}, major classes of river corridor deposits in June 1990, and topographic levels of fine-grained deposits in two reaches of the Colorado River in Grand Canyon. Surface flow patterns and major classes of deposits are shown in (a) and (b) where dark-shaded areas are debris fans, horizontal hatchures are separation bars, vertical hatchures are reattachment bars, cross-hatchures are undifferentiated eddy deposits, areas with broad lines are channel-margin deposits, and areas with large dots are gravel bars. Topographic levels of fine-grained deposits are shown in (c) and (d) where stippled areas are fluctuating flow sands deposited by



powerplant flows, arrowheads are high flow sands of 1984 to 1986, horizontal hatchures are flood sands of 1983, and areas with dashed lines are pre-dam deposits higher than those of 1983. (a) Major classes of river corridor deposits near Saddle Canyon. See Figure 3a for location. (b) Major classes of river corridor deposits downstream from the Little Colorado River. See Figure 3b for location. (c) Topographic levels of fine-grained alluvium near Saddle Canyon. See Figure 3b for location. (d) Topographic levels of fine-grained alluvium downstream from the Little Colorado River. See Figure 3b for location.



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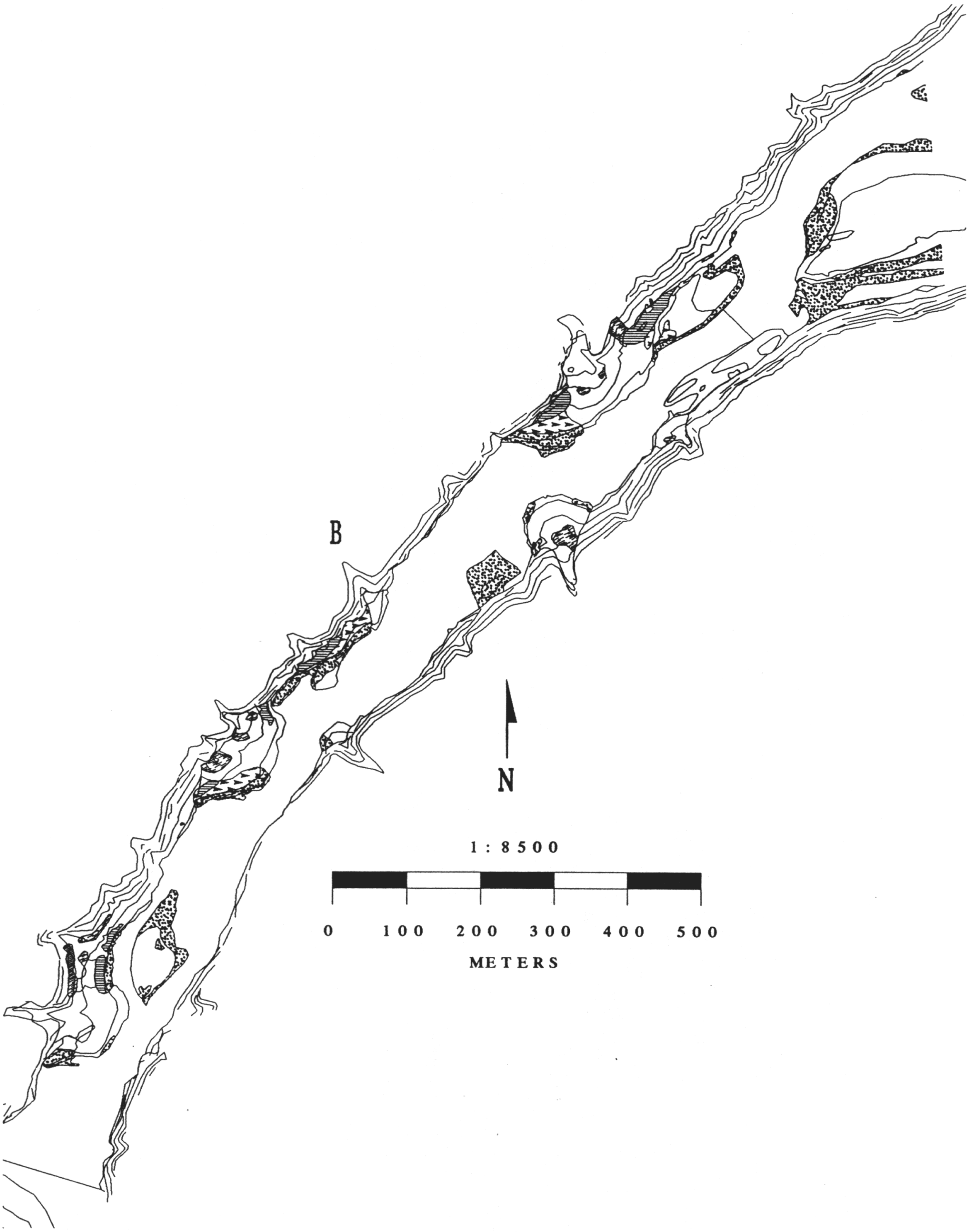

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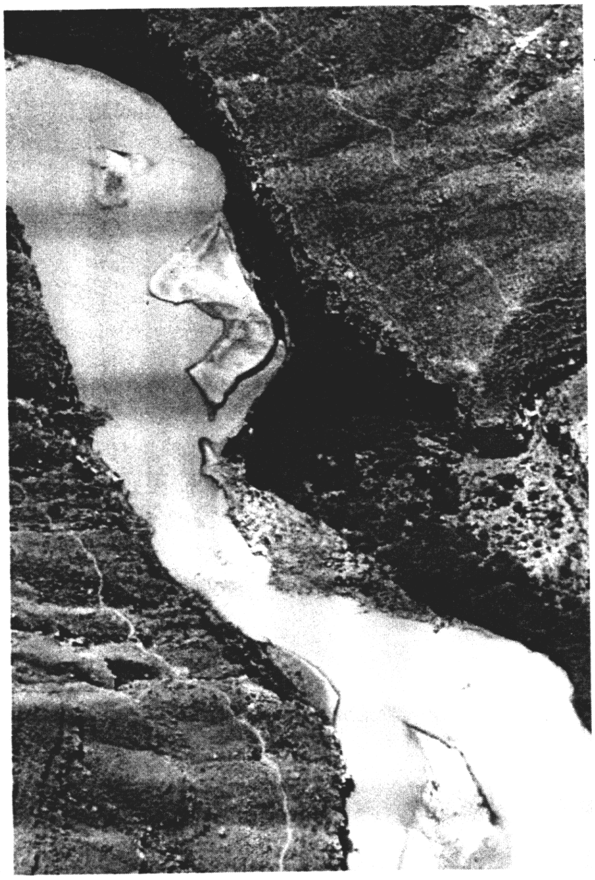

Fig. 5. Photograph of a fan-eddy complex in Desolation Canyon, Green River, at low discharge, August 1992. Flow is towards the left side of photograph, and a 4.5 m long raft is shown in the lower part of the photo. Upstream from the debris fan is a central gravel bar, and fine-grained sediment lines the channel banks. Downstream from the debris fan is a reattachment bar, bounded on its upstream side by an eddy-return channel. The fine-grained sediment that mantles the downstream side of the fan is a separation bar. Further downstream is a gravel bar in the center of the channel.

downstream. Levees are typically composed of a single set of foresets that record the onshore migration and construction of the ridge. Divergent ridges occurring in series and that do not merge into higher downstream surfaces are also interpreted as levees. Channel-divergent ridges with sedimentary structures indicating rotary flow or where the crest of the ridge merges downstream with onshore alluvial surfaces are interpreted as narrow reattachment bars.

Alluvial deposits occur as distinct topographic surfaces throughout Grand Canyon, although the thickness of the associated deposits varies greatly (Figure 7). There are

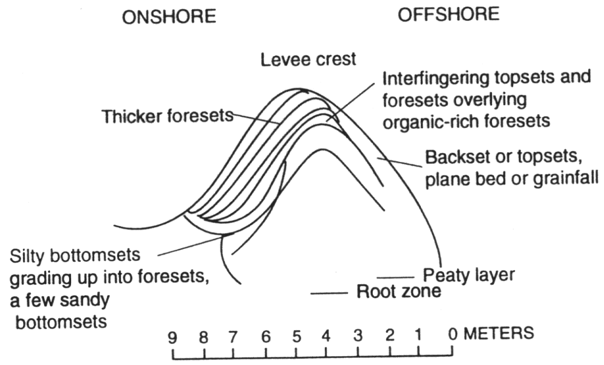

Fig. 6. Stratigraphy of a levee upstream from Little Nankoweap Creek, Grand Canyon. View is downstream, the river channel is to the right side of the levee, and vertical exaggeration is 3 times. This levee was formed in 1983.

extensive topographic surfaces created by (1) the largest post-dam discharge, 2820 m^3s^{-1}, which occurred in June 1983, (2) high annual floods of about 1410 m^3s^{-1}, which occurred between 1984 and 1986, and (3) fluctuating flows within the capacity of the Glen Canyon Dam powerplant that are less than 890 m^3s^{-1} (Figure 8). The thickest deposits within eddy bars were formed by the 1983 flood, and contain large thicknesses of fluctuating-flow sands inset within their flanks. Deposits of the 1984 to 1986 floods are thin, despite the extensive area of the associated topographic surfaces.

High-elevation terraces composed of silty to very fine sand are common in some wider reaches of the Colorado River in Grand Canyon [*McKee,* 1938], and range in age from 50 yrs BP to at least 2000 yrs BP [*Hereford,* 1993; Hereford et al, 1993]. Our mapping did not focus on these deposits, and few excavations were made to establish sediment transport directions. Our estimates of the total proportion of fine-grained alluvium deposited within eddies is an underestimate because we classified all high terrace deposits as channel-margin deposits despite the fact that we observed rotary flow structures at some sites.

4.2. *Distribution of Fine-Grained Deposits*

Eddy processes are responsible for a large proportion of the fine-sediment deposition in canyons with abundant debris fans. In Grand Canyon, detailed mapping and sedimentologic analyses show that the proportion of fine-grained alluvium deposited within eddies is as large as 75 percent (Table 1). Along the Green River, reconnaissance photogeologic interpretation indicates that eddy deposits only occur in reaches with abundant debris fans, where they comprise between 1 and 29 percent of all fine sediment deposits (Table 1).

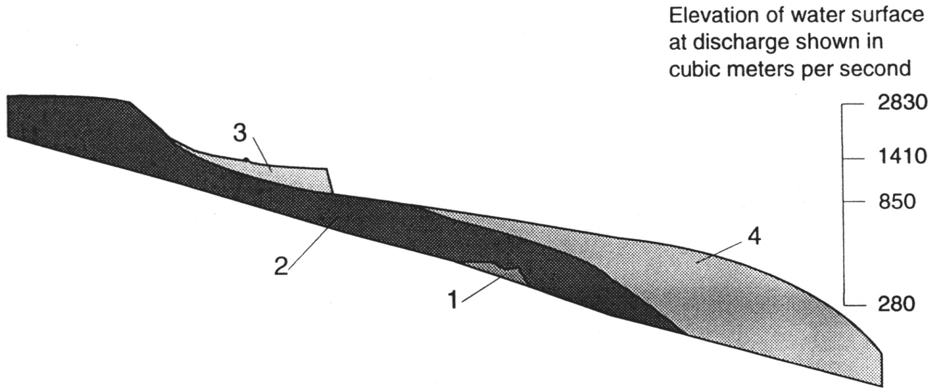

Fig. 7. Schematic diagram, not to scale, showing generalized internal structure and history of Grand Canyon reattachment bars. (1) Pre-dam deposits, eroded by high discharges of 1983. (2) Flood sands of 1983. This deposit truncates underlying pre-dam deposits and is truncated offshore by overlying deposits. Sedimentary structures are mainly fluvial dunes and climbing ripples. (3) Thin deposits of high flow (1984-1986) sands. These deposits truncate underlying 1983 flood sands and are of limited extent. They are typically bounded onshore by the 1983 deposits and are truncated offshore by younger deposits. Sedimentary structures are primarily climbing ripples, but are commonly trampled by humans or have been reworked by wind. (4) Deposits of recent (post-1986) discharges less than powerplant capacity. Sedimentary structures are primarily climbing ripples. Figure adapted from *Rubin et al.* [1994].

4.3 *Depositional Patterns Prior to Reservoir Construction*

The distinctions between separation and reattachment bars are not clear when large volumes of sediment are stored in eddies, such as occurred before dam construction. Aerial photographs of the Colorado River taken in 1935 show that the total amount of fine-grained sediments exposed at low discharge greatly exceeds the condition that has existed at any time since closure of Glen Canyon Dam. The channel bed within eddies typically was entirely covered with sand of sufficient thickness such that many eddy beds were entirely exposed at low discharge.

5. EFFECTIVE DISCHARGE

One of the goals of evaluating geomorphic effectiveness is to develop an understanding of the magnitude and frequency of discharges that determine the distribution and form of alluvial deposits. The comparison between effective discharge and modern alluvial deposits along Colorado Plateau rivers may also help define which dam-controlled discharges are of most importance in managing the downstream environment.

The effective discharge is defined as the modal value of the product of streamflow frequency and sediment transport. In the case of alluvial rivers, the suspended load or total load transport rate is used [*Andrews,* 1980, 1986; *Ashmore and Day,* 1988] because floodplain sediments are composed of the same sizes. In canyons with abundant debris fans, effective discharge calculations using suspended-sand transport rates apply to fine-grained alluvial deposits, and do not necessarily apply to coarse-grained alluvial deposits.

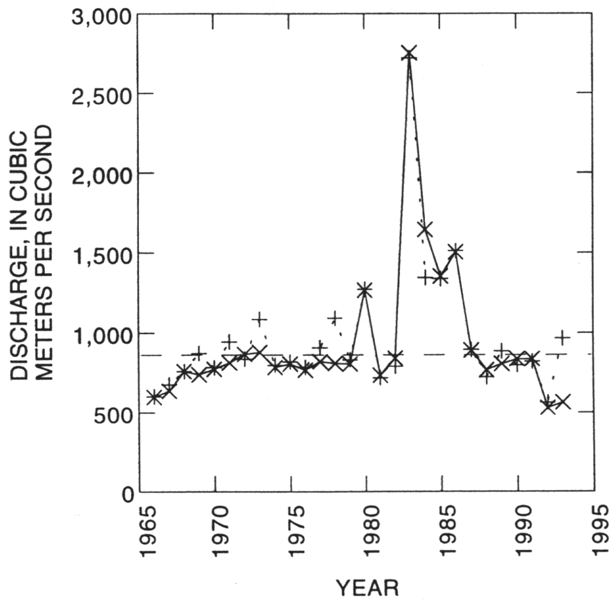

Fig. 8. Annual maximum discharge of the Colorado River at Lees Ferry, Arizona (stream gaging station 09380000), and near Grand Canyon, Arizona (09402500). Horizontal dashed line is maximum powerplant capacity of Glen Canyon Dam. Lees Ferry data are depicted with x's and Grand Canyon data with +'s. Until 1980, flood flows were entirely controlled because the upstream reservoir had not filled.

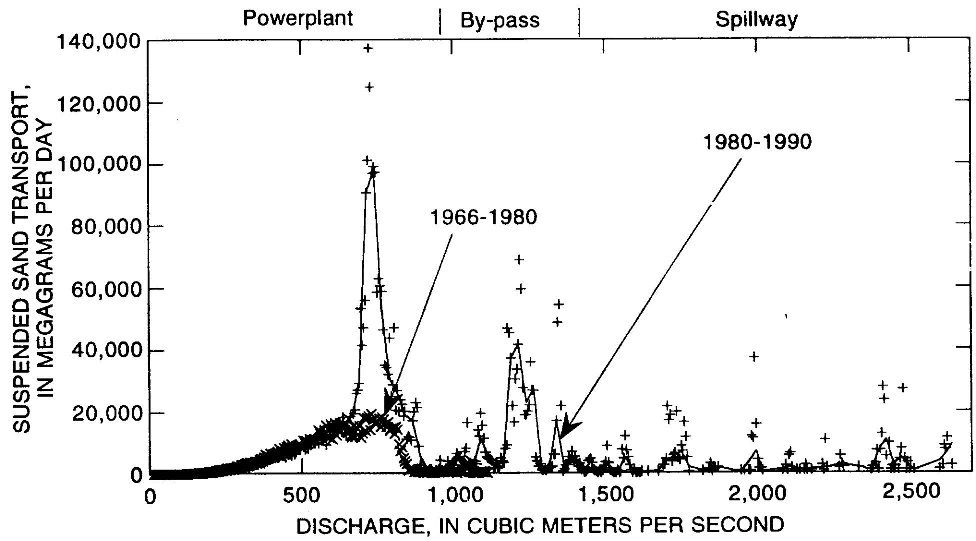

Fig. 9. Effective discharge curves for Colorado River near Grand Canyon, Arizona. Each symbol is calculated for a 25 m^3s^{-1} increment of discharge centered on the plotted point. X's are for 1965-1980 and +'s are for 1980-1990. Best fit smooth curves were calculated for each data set using the locally weighted least squared error method with a smoothing factor of 10 percent.

To accurately determine effective discharge, the evaluated time interval must be representative of the system in terms of the distribution of floods and the degree of sediment storage. On unregulated rivers, the time period over which these calculations are made must be sufficiently long so that rare floods are not given statistical importance beyond that associated with their expected recurrence. On regulated rivers where streamflow frequency is determined by basin hydrology as modified by reservoir operating rules, evaluations of geomorphic effectiveness should be consistent with the time period of a prevailing operating rule. If the operating rule changes, then the statistical distribution of downstream flow will change, and the effective discharge will change.

Between 1965 and 1980, the operating rule for Glen Canyon Dam was to completely control floods so as to fill its reservoir as quickly as possible; subsequently, the rule was to maintain a relatively full reservoir, and some floods were passed downstream [*U.S. Bureau of Reclamation,* 1993]. Between 1966 and 1979, annual maximum discharge of the Colorado River at Lees Ferry, Arizona, located 25 km downstream from Glen Canyon Dam, did not exceed powerplant capacity; annual maximum discharge near Grand Canyon, Arizona, exceeded powerplant capacity only in years when there was significant tributary flooding of the Little Colorado River (Figure 8). The cumulative duration of hourly releases from Glen Canyon Dam that exceeded powerplant capacity was 0.2 percent between 1966 and 1980. For this period prior to filling of the reservoir, the effective discharge curve of the Colorado River in Grand Canyon has a single mode (Figure 9). However, the curve is skewed with little transport at high discharges because of the operational restriction imposed by powerplant capacity. The effective discharge is about 700 to 750 m^3s^{-1}, but significant amounts of sand were transported by discharges as low as about 500 m^3s^{-1}. Because they are so infrequent, discharges greater than 850 m^3s^{-1} transported very little sand. The shape of this curve is similar to the post-dam effective discharge curve calculated by *Andrews* [1986] for the Green River.

Effective discharge for the period 1980 to 1990 was also about 725 m^3s^{-1}, but the dominant mode was more narrowly confined to discharges between about 650 and 825 m^3s^{-1}. The effective discharge curve for this period also shows that (1) high peak discharges between 1983 and 1986 transported large amounts of sand and (2) many increments of discharge transported little or no sand. Thus, the effective discharge curve has subsidiary modes. The existence of subsidiary modes is related to characteristics of dam operations at times when reservoir inflow was high and there was little available flood control capacity. In those circumstances, flows were maintained at maximum powerplant capacity. However, when overflow occurred, discharge was increased to the maximum capacity of the available overflow facilities. In the case of Glen Canyon Dam, when flows exceed powerplant capacity, discharge was increased to the full capacity of two by-pass tubes. Maximum discharge of the powerplant in combination with discharge from these tubes is about 1410 m^3s^{-1}, depending on reservoir elevation. Thus, the Colorado River rarely has had flows at discharges between 875 and 1150 m^3s^{-1}. In 1983, releases exceeded the capacity of the powerplant and by-pass tubes, and the emergency spillways were used. Dam releases in 1983 were held at approximately three dominant rates, and there are many increments of discharge greater than 1410 m^3s^{-1} that did not occur.

6. LONGITUDINAL CORRELATION OF GEOMORPHIC SURFACES AND RELATION TO EFFECTIVE DISCHARGE

The water surface elevation of the calculated effective discharge is typically compared with the elevation of the active floodplain of alluvial rivers in order to determine their formative flow [*Andrews,* 1980]. In the case of streams in canyons with abundant debris fans, the active floodplain and the bankfull channel are not obvious because channel migration does not provide an opportunity for development of lateral accretion deposits that are typical of many floodplains. Also, other parts of the channel, such as rapids, may be adjusted to extreme events [*Baker,* 1977; *Kieffer,* 1985]. Nevertheless, we can determine if any of the discontinuous fine-grained alluvial deposits are longitudinally correlative and have similar elevations to modes of the effective discharge calculation for sand transport. If such correlations exist, then the modal discharge increment may be considered to have produced these deposits even if other parts of the channel are shaped by other discharges.

In the case of Grand Canyon, discontinuous fine-grained deposits known to have formed by the same discharge can be identified, based on direct observation, repeated topographic surveys, and sedimentologic analysis [*Rubin et al.,* 1990; *Schmidt and Graf,* 1990]. Although these deposits have considerable relief, deposition approaches the water surface near stagnation points. Bars typically build to within about 0.3 m of the water surface [*Schmidt and Graf,* 1990; *Schmidt and Andrews,* unpubl. data]. Longitudinal correlation of the elevation of deposits formed near the reattachment point provides a consistent estimation of the water surface because the elevation of the water surface at the reattachment point is approximately the same as that of the adjacent main flow. Where internal stratification is visible, deposits formed near the reattachment point can be recognized by ripple structures produced by flow that reverses in an upstream-downstream direction [*Rubin et al.,* 1990]. Without visible internal stratification, the

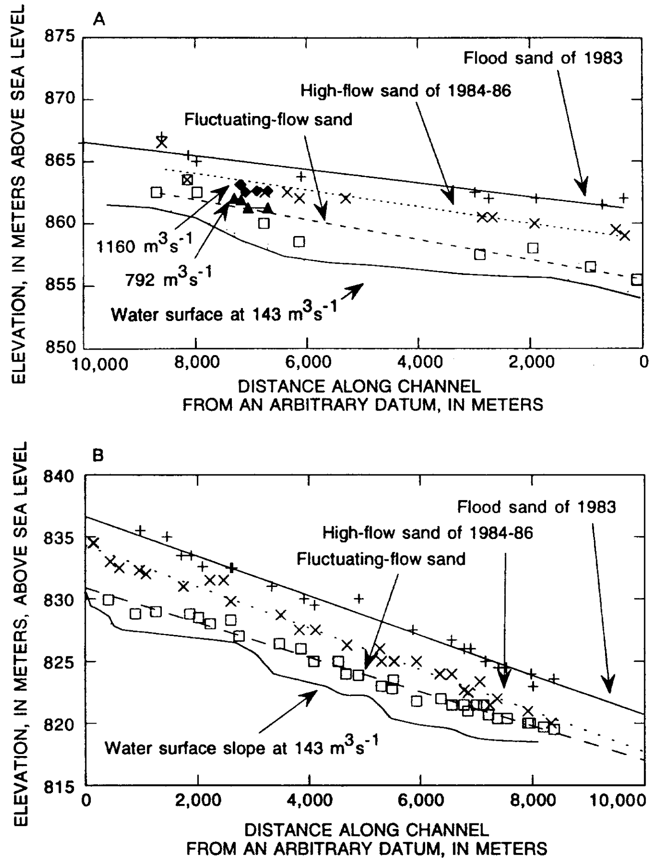

Fig. 10. Graphs showing longitudinal correlation of flood sand, high flow sands, and fluctuating-flow sands in two study reaches. (a) Reach near Saddle Canyon that is shown on Figure 3a. Dark circles and dark triangles are surveyed water surface elevations in 1985 at indicated discharges. (b) Reach near Little Colorado River that is shown on Figure 3b.

highest elevation part of reattachment bars can be used to approximate the water surface elevation.

The elevation of separation bars is not included in longitudinal correlations because the water surface of the upstream part of eddies, near the separation point, is considerably less than that of the adjacent main channel flow. Measurements of water surface in Grand Canyon at 1200 m^3s^{-1} show that the elevation of the water surface within an eddy near the separation point may be as much as 0.2 m lower that the elevation of the adjacent downstream-flowing water surface.

The elevation of reattachment point deposits known to have formed in 1983 and between 1984 and 1986 correlate well over long distances, and the average longitudinal slope of these deposits parallels that of the average low flow slope (Figure 10). The correlation of these deposits thus can be an useful tool for estimating formative discharges.

In the Colorado River in Grand Canyon, elevations of three longitudinally correlative surfaces are associated with different modes of the effective discharge calculation for the period 1980 to 1990. When averaged over a 10-yr period, discharges greater than powerplant capacity yield subsidiary modes and geomorphically recognizable deposits, and surfaces associated with these flows are widely exposed. In many reaches, deposits associated with the primary mode are less extensive than are these higher flood deposits. Deposits formed by floods in 1983 and between 1984 and 1986 do not constitute floodplains in the sense that they were not incrementally constructed, are not laterally continuous, and are not formed by channel migration. The 1983 deposits were constructed by one geomorphically effective event that has several subsidiary modes of the streamflow-frequency-sediment-transport product, and the 1984 to 1986 deposits were shaped by three successive years of similar peak discharges that have one mode. Each of these suites of high-flow deposits is now being modified by subaerial erosion, which subdues, but does not completely destroy, the fluvial attributes of the landforms.

Despite the correlative nature of these distinct high-elevation topographic surfaces, the thickness of the underlying deposits differs greatly. Bars and levees formed in 1983 commonly approach or exceed 1 m in thickness, whereas deposits formed between 1984 and 1986 are rarely more than 0.3 m thick. Thus, there is a significant disparity between the calculated effectiveness of these discharges, and the effectiveness as evaluated by the characteristics of the deposits themselves. The likely explanations for this disparity are that (1) main channel sediment transport was relatively low in 1984 to 1986 due to depletion of sediment by the 1983 flood, or (2) deposition rates in eddies were lower in 1984 to 1986 than in 1983 because the eddies were already partly filled with sediment. Thus, in fluvial systems where sediment supply and deposition rates may vary, the modes of the product of streamflow frequency and sediment transport may not successfully predict the thickness of associated deposits, despite the fact that extensive topographic surfaces are created.

The lower-elevation depositional surfaces along the Colorado River in Grand Canyon that formed by discharges within the range of powerplant capacity correlate with the modal discharge increment of about 725 m^3s^{-1}. These deposits are incrementally constructed by the river by discharges that occur nearly every year (Figure 8). The mechanisms of deposition are (1) the same eddy processes that occur at higher discharges, and (2) colonization by riparian plants and vertical accretion of silt and clay on top of flood-formed sand bars. The former process was documented by *Rubin et al.* [1990] who demonstrated that a wedge of fluctuating-flow fine sand was deposited as an inset fill against the flood-formed main platform of the reattachment bar. The latter process is illustrated in Figure 11. This reattachment bar has alternated between an exposed sand condition, as existed in 1984 (Figure 11A) during the period of high discharges, and nearly complete vegetative overgrowth, as existed during the period of reservoir filling (Figure 11b). *Stevens et al.* [1995] described the succession of riparian plants on reattachment bars and show that such plants preferentially colonize silts and clays.

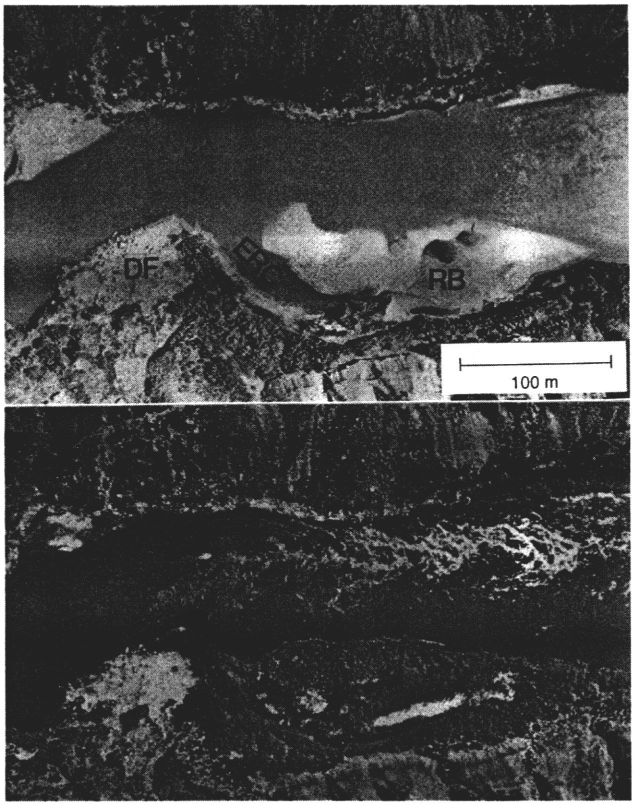

Fig. 11. Reattachment bar in lower Marble Canyon showing unvegetated and vegetated condition of the same site. DF is location of debris fan, RB is reattachment bar, and ERC is eddy return channel formed by upstream-directed eddy currents. (a) Unvegetated condition in October 1984. (b) Vegetated condition in May 1980.

7. DISCUSSION

Alluvial deposits in canyons with abundant debris fans have numerous surfaces constructed by several discharges.

In the case of Grand Canyon, deposits formed by rare post-dam floods, and lower-elevation deposits constructed by powerplant discharges, both occur extensively. During periods of significant flood control, such as the period of initial filling of large reservoirs, reattachment bars may become vegetated, but subsequent floods that occur after reservoir filling can reactivate these surfaces in a process similar to the disequilibrium floodplain model of *Nanson* [1986].

Eddy bars persist in specific zones of recirculation because the coarse-grained debris fans that obstruct the river channel give rise to flow separation, and these fans are rarely modified. Although bars change shape with discharge, they remain within specific lateral separation eddies and do not migrate from eddy to eddy. Measurements and observations of the Colorado River in Grand Canyon based on aerial photography (dating to 1935) and oblique photography (dating to the 1880's) [*Webb,* 1995] show that the locations of eddy sand bars have been stable for long periods. Observations of relations between flow geometry and sand-bar location suggest that bars should be persistent over periods consistent with the frequency of events that reshape flow-separation-inducing debris fans. In Grand Canyon, that time scale is on the order of 10 to 100 yrs [*Melis et al.,* 1994].

Large floods that overtop low-relief debris fans may cause recirculation zones to diminish in size or disappear [e.g. *Kieffer and others,* 1989, fig. 3.5]. *Melis et al.* [1994] have shown that most debris fans in Grand Canyon are overtopped by discharges at or greater than the pre-dam mean annual flood, and photographs of the river at discharges greater than 2830 m^3s^{-1} show that many eddies are thin or non-existent at such discharges. Because eddy deposits contain sedimentary structures indicative of recirculation, eddy bars therefore must form in flows less than those that completely inundate the controlling constriction. Thus, most fine-grained alluvial deposits form at discharges less than those that overtop debris fans or during the descending limb of fan-overtopping floods after eddies have been reestablished.

Eddy bars are subject to scour and fill over various time scales. Interpretation of sedimentary structures shows that eddy bars are dynamic features, subject to erosion and deposition during floods and erosion after flood recession. The topographic form and internal stratigraphy of bars results from the range of eddy geometries that occur at each site, which are dependent on site-specific channel geometry-discharge relations. Eddy bars associated with low debris fans that are overtopped frequently by mainstem flooding are likely to have different scour-and-fill histories than eddy bars formed in the lee of high-elevation debris fans that are overtopped less frequently.

8. CONCLUSIONS

In canyons with abundant debris fans, the fundamental geomorphic unit is a complex of fan-related features: (1) a low-velocity backwater upstream from the fan, (2) a debris fan that constricts the channel, (3) eddies and eddy bars in the expansion downstream from the fan, and (4) a downstream gravel bar. Mapping of alluvial deposits in Grand Canyon demonstrates that eddies are the dominant environment for deposition of fine-grained sediment.

Previous work on alluvial rivers has shown that channel morphology is controlled by the effective discharge, which is calculated to be the modal value of the product of streamflow frequency and sediment transport rate. The present study indicates that the concept of effective discharge can also be applied to fine-grained deposits in narrow canyons with abundant debris fans.

Pre-dam effective discharge for the Green River had a single dominant mode [*Andrews,* 1986]; the Colorado River was probably similar in this regard. Post-dam effective discharge, however, is very different. *Hirsch et al.* [1990] have shown that the Colorado River basin has the highest proportion of reservoir volume to mean annual flow of any large drainage basin in the United States or Canada. Because the discharge in these rivers follows technological rules that are related to dam operations, streamflow frequency and the calculated effective discharge curve have multiple modes. Calculations of post-dam effective discharge that only use streamflow data for the period prior to filling of large reservoirs do not show subsidiary modes and do not anticipate the resulting geomorphic adjustment once large reservoirs fill.

Mapping of alluvial suspended-load deposits in Grand Canyon demonstrates that each of the longitudinally extensive post-dam geomorphic surfaces corresponds with one of the multiple modes in calculated effective discharge. Volume of these deposits, however, is not proportional to the area of the corresponding mode in the calculated effective discharge curve.

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REFERENCES

Andrews, E. D., Effective and bankfull discharge of streams in the Yampa River basin, Colorado and Wyoming, *J. Hydrol., 46*, 311-330, 1980.

Andrews, E. D., Downstream effects of Flaming Gorge Reservoir on the Green River, Colorado and Utah, *Geol. Soc. Amer. Bull., 97,* 1012-1023, 1986.

Andrews, E. D., The Colorado River: a perspective from Lees Ferry, Arizona, in *Surface Water Hydrology,* edited by M. G. Wolman and H. C. Riggs, pp. 304-310, The Geological Society of America, The Geology of North America vol. O-1, 1990.

Andrews, E. D., Deposition rate of sand in lateral separation zones, Colorado River, abst., Eos, 72, 219, 1991.

Ashmore, P. E. and T. J. Day, Effective discharge for suspended sediment transport in streams of the Saskatchewan River basin, *Water Resour. Res., 24,* 864-870, 1988.

Baker, V. R., Stream-channel response to floods, with examples from central Texas, *Geol. Soc. Amer. Bull., 88*, 1057-1071, 1977.

Baker, V. R., Flood sedimentation in bedrock fluvial systems, in *Sedimentology of Gravels and Conglomerates,* edited by E. H. Koster and R. J. Steel, pp. 87-98, The Canadian Society of Petroleum Geologists, Calgary, 1984.

Baker, V. R., R. C. Kochel, P. C. Patton, and G. Pickup, Paleohydrologic analysis of Holocene flood slack-water sediments, *Spec. Publs Int. Assoc. Sediment., 6,* 229-239, 1983.

Bauer, B. O. and J. C. Schmidt, Waves and sandbar erosion in the Grand Canyon: Applying coastal theory to a fluvial system, *Annals Assoc. Amer. Geogr., 83,* 475-497, 1993.

Dolan, R., A. D. Howard, and D. Trimble, Structural control of the rapids and pools of the Colorado River in the Grand Canyon, *Science, 202*, 629-631, 1978.

Dutton, C. E., The Tertiary history of the Grand Canyon district, 264 p., *Monograph 2,* U.S. Geol. Survey, 1882.

Garrett, W. B., E. K. VanDeVanter, and J. B. Graf, Streamflow and sediment-transport data, Colorado River and three tributaries in Grand Canyon, Arizona, 1983 and 1985-86, 624 p., *Open-File Rep. 93-174,* U.S. Geol. Surv., 1993.

Graf, W. L., Rapids in canyon rivers, *J. Geol., 87,* 533-551, 1979.

Hardin, D. R., Controlling factors in the distribution and development of incised meanders in the central Colorado Plateau, *Geol. Soc. Amer. Bull., 102,* 233-242, 1990.

Hereford, R., Map showing surficial geology and geomorphology of the Palisades Creek archaeologic area, Grand Canyon, Arizona, *Open-File Rep. 93-553,* U.S. Geol. Surv., 1993.

Hereford, R., H. C. Fairley, K. S. Thompson, and J. R. Balsom, Surficial geology, geomorphology, and erosion of archaeologic sites along the Colorado River, eastern Grand Canyon, Grand Canyon National Park, Arizona, 46 p., *Open-File Rep. 93-517,* U. S. Geol. Surv., 1993.

Hirsch, R. M., J. F. Walker, J. C. Day, and R. Kallio, The influence of man on hydrologic systems, in *Surface Water Hydrology,* edited by M. G. Wolman and H. C. Riggs, pp. 329-359, Geol. Soc. Am., The Geology of North America vol. O-1, 1990.

Howard, A. D. and R. Dolan, Geomorphology of the Colorado River in the Grand Canyon, *J. Geol., 89,* 269-298, 1981.

Hunt, C. B., Geologic history of the Colorado River, p. 59-130, Prof. Paper 669-C, U.S. Geol. Surv., 1969.

Kearsley, L. H., J. C. Schmidt, and K. D. Warren, Effects of Glen Canyon Dam on Colorado River sand deposits used as campsites in Grand Canyon National Park, USA, *Regulated Rivers, 9,* 137-149, 1994.

Kieffer, S. W., The 1983 hydraulic jump in Crystal Rapid: Implications for river-running and geomorphic evolution in the Grand Canyon, *J. Geol., 93,* 385-406, 1985.

Leopold, L. B., The rapids and the pools -- Grand Canyon, p. 131-145, *Prof. Paper 669-D,* U.S. Geol. Surv., 1969.

McKee, E. D., Original structures in Colorado River flood deposits of Grand Canyon, *J. Sed. Pet., 8,* 77-83, 1938.

Melis, T. S., R. H. Webb, P. G. Griffiths, and T. J. Wise, Magnitude and frequency data for historic debris flows in Grand Canyon National Park and vicinity, Arizona, *Water Res. Inves. Rept 94-4214,* U. S. Geol. Surv., 1994.

Miller, A. J., Debris-fan constrictions and flood hydraulics in river canyons: some implications from two-dimensional flow modelling, *Earth Surf. Proc. Ldfms., 19,* 681-697, 1995.

Nanson, G. C., Episodes of vertical accretion and catastrophic stripping: A model of disequilibrium flood-plain development, *Geol. Soc. Amer. Bull., 97,* 1467-1475, 1986.

Nanson, G. C. and J. C. Croke, A genetic classification of floodplains, *Geomorphology, 4,* 459-486, 1992.

Nelson, J. M., R. R. McDonald, and D. M. Rubin, Computational prediction of flow and sediment transport patterns in lateral separation eddies, abst., Eos, 75, 268, 1994.

O'Conner, J. E., L. L. Ely, E. E. Wohl, L. E. Stevens, T. S. Melis, V. S. Kale, and V. R. Baker, A 4500-year record of large floods on the Colorado River in the Grand Canyon, *J. Geol., 102,* 1-9, 1994.

Pemberton, E. L., Sediment data collection and analysis for five stations on the Colorado River from Lees Ferry to Diamond Creek, 159 p., U.S. Bur. Reclamation Glen Canyon Envir. Studies report, 1987. (NTIS No. PB88-183397/AS)

Powell, J. W., Exploration of the Colorado River of the West and its tributaries, 291 p., U.S. Govt. Printing Office, Wash., D. C., 1875.

Rubin, D. M., J. C. Schmidt, R. A. Anima, K. M. Brown, H. Ikeda, B. E. Jaffe, R. McDonald, J. M. Nelson, T. E. Reiss, R. Sanders, and R. G. Stanley, Internal structure of bars in Grand Canyon, Arizona, and evaluation of proposed flow alternatives for Glen Canyon Dam, 16 p., *Open-file Report OF 94-594,* U. S. Geol. Surv., 1994.

Rubin, D. M., J. C. Schmidt, and J. N. Moore, Origin, structure, and evolution of a reattachment bar, Colorado River, Grand Canyon, Arizona, *J. Sed. Pet., 60,* 982-991, 1990.

Schmidt, J. C., Compilation of historical hydrologic and geomorphic data for the upper Colorado River basin, Annual Report, Flaming Gorge Research Program Study No. 37, 5 p. w. append., 1994.

Schmidt, J. C., Recirculating flow and sedimentation in the Colorado River in Grand Canyon, Arizona, *J. Geol., 98,* 709-724, 1990.

Schmidt, J. C. and J. B. Graf, Aggradation and degradation of alluvial sand deposits, 1965 to 1986, Colorado River, Grand Canyon National Park, Arizona, 74 p., *Prof. Paper 1493*, U.S. Geol. Surv., 1990.

Schmidt, J. C., J. L. Mayers, and M. F. Leschin, Geomorphology of post-Glen Canyon Dam fine-grained alluvial deposits of the Colorado River near Point Hansbrough and Saddle Canyon in Grand Canyon National Park, 16 p., U.S. Bureau of Reclamation Glen Canyon Environmental Studies administrative report, Flagstaff, 1994a.

Schmidt, J. C., J. L. Mayers, M. F. Leschin, and D. M. Rubin, Geomorphic mapping of post-Glen Canyon Dam fine-grained alluvial deposits of the Colorado River in Grand Canyon, Arizona: Abstracts, Geol. Soc. Am. Annual Meeting, 1994b.

Schmidt, J. C., D. M. Rubin, and H. Ikeda, Flume simulation of recirculating flow and sedimentation, *Water Resour. Res., 29,* 2925-2939, 1993.

Stevens, L. E., J. C. Schmidt, T. J. Ayers, and B. T. Brown, Geomorphic influences on fluvial marsh development along the dam-regulated Colorado River in the Grand Canyon, Arizona, *Ecol. Applications, 5,* in press, 1995.

U.S. Bureau of Reclamation, Operation of Glen Canyon Dam, draft environmental impact statement, 324 p., Salt Lake City, 1993.

U.S. Water Resources Council, Guidelines for determining flood flow frequency, 183 p., Bulletin 17B, 1981.

Webb, R. H., *A century of environmental change in Grand Canyon,* in press, Tucson, Univ. Ariz. Press, 1995.

Wilson, R. P., Sonar patterns of Colorado River bed, Grand Canyon, in Proc. Fourth Fed. Interagency Sed. Conf., Las Vegas, Subcommittee on Sedimentation, Interagency Advisory Committee on Water Data, pp. 5-133 to 5-142, 1986.

Wolman, M. G. and R. Gerson, Relative scales of time and effectiveness of climate in watershed geomorphology, *Earth Surf. Proc. Lndf., 3,* 189-208, 1978.

Wolman, M. G. and L. B. Leopold, River flood plains -- some observations on their formation, p. 87-109, *Prof. Paper 282-C,* U.S. Geol. Surv., 1957.

Wolman, M. G. and J. C. Miller, Magnitude and frequency of forces in geomorphic processes, *J. Geol., 68,* 54-74, 1960.

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