Suspended-Load Deposition along Debris Flow-Affected Rivers of the Colorado Plateau

by

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Abstract

The fundamental channel unit of debris flow-affected rivers is the debris fan-eddy complex. In the downstream direction, this channel unit is comprised of (1) a hydraulic backwater upstream from the debris fan, (2) the debris fan and channel constriction, (3) an eddy or eddies and associated eddy bars, and (4) a gravel bar. These debris fan-eddy complexes exist at the mouth of every debris flow-generating tributary. Such tributaries exist along many, but not all, of the narrow canyons of the Green and Colorado Rivers. The channel of a debris flow-affected reach is steeper, has higher unit stream power, and has a coarser bed than other narrow valleys of the same river system. Eddy depositional processes account for about 75 percent of the total area of fine sediment along 2 study reaches in Grand Canyon and account for up to 30 percent of all deposits in similar canyons of the Green River. Prior to construction of Glen Canyon Dam, many eddy bars along the Colorado River in Grand Canyon were so much more extensive that separation and reattachment bar were amalgamated. Suspended load deposits can be grouped as (1) low elevation eddy bars shaped by discharges less than or equal to the effective discharge, (2) channel-margin deposits along hydraulic backwaters and downstream from large eddies that have elevations similar to the effective discharge, and (3) high elevation eddy bars formed by floods whose magnitude exceeds the effective discharge.

Introduction

Little attention has been paid to the characteristics of floodplains in extremely narrow valleys where debris flows deliver large amounts of coarse sediment to the valley floor. In the lee of debris fans, lateral separation eddies exist. These eddies are accumulation sites for suspended sediment and are the depositional setting for a significant proportion of the total volume of fine-grained sediments stored in debris flow-affected valleys.

Most research about fine-grained sediments in debris flow-affected valleys has concerned high-elevation slackwater deposits which contain the preserved evidence of rare high-magnitude discharges [Baker, 1984]. Little is known about lower elevation alluvial surfaces, their modes of deposition, whether they can be considered floodplains, and the nature of the relation between alluvial surfaces and calculated effective discharges. We do not expect these relations to be the same as for meandering streams in wide alluvial valleys because the width of the active alluvial valley (e.g. the meander belt in meandering rivers) affects the characteristics of channel bars [Ikeda, 1989] and floodplain process [Nanson, 1986]. Although models of floodplain formation for a wide range of valley widths have been summarized by Nanson and Croke [1992], little attention has been given to floodplain processes in debris flow-affected valleys. In this paper, we describe the spatial pattern and characteristics of fine-grained alluvial deposits in these valleys, drawing examples from the Colorado River through Grand Canyon in Arizona and the canyons of the Green River in Utah (Figure 1).

Methods

Reach scale attributes of the Green River were determined by photogeologic interpretation of large scale (approx. scale 1:5000) air photography taken at low discharge in 1963. Reconnaissance surficial geologic maps of the river corridor were made for 16 reaches, each about 17 km in length, which comprise approximately 40 percent of the entire river length between the Colorado River confluence and Split

Mountain Canyon. Mapping units distinguish active bars, vegetated terraces, gravel bars, and debris fans. The different components of debris fan-eddy complexes, as described below, are also mapped. In Grand Canyon, mapping at a scale of 1:2400 has been conducted in 3 reaches, each about 15 km long. All maps have been entered into a GIS data base.

Log Pearson type III flood recurrence analyses for 5 gaging stations on the Green and Colorado Rivers were completed for the period 1923 to 1962. This period is prior to widespread completion of dams. The Green River 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. The results of sedimentologic analyses of alluvial deposits in Grand Canyon are discussed below, and the methods employed are summarized by Rubin et al. [1990, 1994].

Effective discharge calculations for the Colorado River in Grand Canyon were determined from (1) flow duration data for hourly releases from Glen Canyon Dam [U. S. Bureau of Reclamation, 1988, written commun.], and (2) sand transport relations for the Colorado River near Grand Canyon, Arizona [Pemberton, 1987]. Attentuation of daily fluctuating dam releases is known (J. D. Smith and S. M. Wiele, U.S. Geological Survey, Boulder, written commun., 1994) but not incorporated into these analyses. Sand transport data were determined from sampling conducted in 1983 and between 1985 and 1986 [Garrett et al., 1993]. These limitations do not affect the general characteristics of the effective discharge described below, but they may affect the accuracy of the discharge increments used in the calculations.

Regional Setting

The earliest geomorphic investigations of the Colorado River system [Powell, 1875; Hunt, 1969] recognized the disparity between the present stream courses and the trend of the dominant geologic structures. This disparity causes the Green and Colorado Rivers to cross many geologic 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 valleys are affected by debris flows. Although the ratio of width of the alluvial valley to width of the bankfull channel is similar to fixed meander reaches, unit stream power in debris flow-affected reaches is much greater (Figure 2). Stream power values were calculated using (1) the 2-yr recurrence flood at the nearest gaging station, (2) average bankfull channel width determined from mapping, and (3) channel slope determined from 1:24000 scale topographic maps (Table 1).

The delivery of gravel and boulders causes large parts of the bed to be composed of gravel and coarser material (Table 1). On the Green River, the proportion of all alluvial deposits composed of gravel was calculated from surficial geologic maps. Between 35 and 64 percent of all alluvial bars include gravel in the debris flow-affected reaches of the Green River. In Grand Canyon, Wilson's [1986] side-scan sonar surveys indicate 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, large loads of sand are transported through these canyons as bed load in the form of ripples and dunes and as suspended load. Some of the suspended load, which also includes silt and clay, is deposited as bars and along the banks of debris flow-affected valleys, and the size distribution of eddy bar sediments and measured sediment loads are similar (compare Schmidt and Graf [1990, table 5] and [Garrett et al., 1993]). Andrews [1986, 1990] has shown that the magnitude of sediment transport has decreased by an order of magnitude since construction of Flaming Gorge and Glen Canyon Dams in 1962 and 1963, respectively.

The Debris Fan-Eddy Complex

Although the meandering pattern of debris flow-affected valleys may be similar to that of fixed meander reaches, the characteristics of alluvial sedimentation are very different. In narrow valleys unaffected by debris flows, alluvial deposits form long benches along alternating banks of the channel. Alluvium is comprised of large proportions of vertical accretion deposits, and levees line the channel [Nanson, 1986]. In contrast, debris flow-affected canyons have an array of depositional settings. Debris fans not only affect reach-scale channel attributes such as bed-material size and channel gradient, but fans also control the locations of gravel bar and suspended-load deposition (Figure 3). Upstream from the debris fan, a backwater of low-velocity flow may extend several kilometers [Kieffer, 1985].

Downstream from debris fans on the Green and Colorado Rivers, eddies exist in the lee of every constricting debris fan, and these eddies vary greatly in length. At high discharge, the downstream termination of these eddies is (1) caused by acceleration due to flow over or around a cobble/gravel bar, (2) 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 4). These channel irregularities cause eddies in debris-flow affected canyons to be shorter than those predicted from laboratory experiments with similarly scaled constriction geometries [Schmidt et al., 1993].

Suspended-load 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 (Figure 5). Reattachment bars form under the primary eddy cell (Figure 6). Deposits not formed in eddies are channel-margin deposits, and most of these deposits line the banks and resemble floodplains.

Gravel bars are common (1) upstream from constrictions within the backwater of the debris fan, and (2) downstream from the large eddies. These bars either exist as mid-channel bars, or they may be attached to one bank.

We refer to the geomorphic assemblage of backwater, constricting debris fan, eddy and eddy bars, and gravel bar as a debris fan-eddy complex. This assemblage is the fundamental geomorphic channel unit of debris flow-affected canyons, and this assemblage occurs at every tributary mouth where debris fans partially block the river. The size of each channel element is probably related to the size and characteristics of the associated debris fan, the time sequence of debris flows that replenish the fan, and the time sequence of main channel discharges.

Field Identification of Alluvial Deposits

Although Schmidt's [1990] classification of eddy bars has been applied to large alluvial deposits [Schmidt and Graf, 1990] and to campsites [Kearsely et al., 1994], the comprehensiveness of this classification can best be evaluated by detailed mapping of alluvial deposits in study reaches that include numerous debris fan-eddy complexes.

Figure 7 shows the correlation of mapped units in Grand Canyon and lists the field identification criteria. Separation and reattachment bars were identified using previously published criteria [Schmidt and Graf, 1990; Schmidt, 1990]. Where these deposits occur in the lee of obstructions but the attributes of separation and reattachment bars can not be distinguished, the deposits are mapped as undifferentiated eddy bars.

Where debris fans are small or of low relief, alluvial deposits resemble floodplains, and fine-grained deposits occur as continuous banks that extend 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. Divergent ridges occuring in series and which do not merge into higher downstream surfaces are interpreted as levees (Figure 8).

Channel-divergent ridges with sedimentary structures indicating rotary flow or where the crest of the ridges merges downstream with onshore alluvial surfaces are interpreted as narrow reattchment bars.

High-elevation terraces composed of silty very fine sand are common in some wide parts of 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. These high terraces are mapped as channel-margin deposits, although in some cases these deposits were also deposited within eddies.

Distribution of Suspended-Load Deposits

The distinctive characteristics of the debris fan-eddy complex permits identification of eddy bars on aerial photographs. Along the Green River, eddy deposits are only found in debris fan-affected reaches where they comprise between 1 and 29 percent of all fine sediment deposits (Table 1). In Grand Canyon, the proportion of fine-grained alluvium deposited within eddies is greater. In two study reaches, more than 75 percent of all fine-grained deposits occur as some type of eddy bar.

Sedimentology of Suspended-Load Deposits

Separation and reattachment bars have multiple topographic levels (Figure 9) which are related to specific ranges of discharges. Typically, separation bars are of higher elevation and record evidence of higher formative discharges.

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 (Figure 6), 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 (Figure

5). Wave structures are more common in separation bars because these sites are closer to the wave generation source in the rapids. The levees of channel-margin deposits are composed of dune foresets with transport directions perpendicular to the average main channel flow direction (Figure 8). The height of the ridge is approximately equal to the dune amplitude.

Although there are distinct topographic surfaces in the alluvial deposits throughout Grand Canyon, the thickness of the associated deposits varies greatly. There are extensive topographic surfaces related to (1) the largest post-dam disharge, which occurred in June 1983 and which was about 2820 $m^3 s^{-1}$, (2) high annual floods which occurred between 1984 and 1986 and which were about 1410 $m^3 s^{-1}$, and (3) fluctuating flows within the capacity of the Glen Canyon Dam powerplant and which are less than 890 $m^3 s^{-1}$ (Figure 9). The thickest deposits within eddy bars were formed by the 1983 flood, and there are significant thicknesses of fluctuating flow sands inset within the flanks of reattachment bars (Figure 10). Deposits of the 1984 to 1986 flows are thin, despite the extensive nature of the associated topographic surfaces.

<u>Depositional Patterns Prior to Reservoir Construction</u>

The distinctions between separation and reattachment bars are not distinct when there are large volumes of sediment stored in eddies. Aerial photographs of the Colorado River taken in 1935 show that the total amount of fine-grained sediments exposed at low discharge exceeds at any time since closure of Glen Canyon Dam. Eddies were typically completely filled with sediment in 1935, and separation and reattachment bars can not be distinguished.

Effective Discharge

One of the goals of an evaluation of geomorphic effectiveness is to understand the magnitude and frequency of discharges that form or shape alluvial deposits. The comparison between effective discharge and modern alluvial deposits in debris flow-affected rivers of the Colorado Plateau is complicated by the fact that these rivers are greatly affected by large reservoirs. Calculation of effective discharge is dependent on the number of years that are evaluated and the magnitude of floods that occur within an evaluated period. The frequency and magnitude of floods on a regulated river are determined by the hydrology of the drainage basin and the prevailing operating rule of the controlling reservoir. If the operating rule changes, then 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; the subsequent rule was to maintain a relatively full pool and thus, some floods were passed downstream [U. S. Bureau of Reclamation, 1993]. Between 1965 and 1980, the cumulative duration of discharges exceeding powerplant capacity was 0.2 percent. For this period, the effective discharge curve (Figure 11) resembles effective discharge curves for other rivers [e.g. Andrews, 1980]. The effective discharge is about 700 to 750 $m^3 s^{-1}$, but significant amounts of sand were transported by discharges as low as about 500 $m^3 s^{-1}$. Because they are so infrequent, discharges greater than 850 $m^3 s^{-1}$ have transported very little sand.

Effective discharge for the period 1980 to1990 is also about 725 $m^3 s^{-1}$, but the range of discharges responsible for the majority of sand transport is more narrowly confined to discharges between about 675 and 825 $m^3 s^{-1}$. The effective discharge curve for this period also shows that (1) the high peak discharges between 1983 and 1986 transported relatively large amounts of sand and (2) many increments of discharge transported little to no sand. Thus, the effective discharge curve has numerous subsidiary modes. The existence of subsidiary modes is related to the characteristics of dam operations at times when reservoir inflow is high and there is little available flood control capacity. In these circumstances, flows are maintained at maximum powerplant capacity. However, when overflow is necessary, discharge is increased to the maximum capacity of the available overflow facilities. In the case of Glen Canyon Dam, when flows exceed powerplant capacity, discharge is increased to the full capacity of two by-pass tubes. Maximum discharge of the powerplant and these tubes is about 1410 $m^3 s^{-1}$, depending on reservoir elevation. Thus, the Colorado River rarely has flows at discharges between 875 and 1150 $m^3 s^{-1}$. Similarly, there are many increments of discharge greater than 1410 $m^3 s^{-1}$ that have not occured given the engineering design of the emergency spillways.

Relation between Geomorphic Surfaces, Alluvial Deposits, and Effective Discharge

Alluvial deposits and topographic surfaces along the Colorado River in Grand Canyon can be related to the effective discharge peak of the 1980 to 1990 period and to subsidiary modes caused by the high discharges that occured between 1983 and 1986. Is one of these surfaces the active floodplain? Is one of these surfaces being constructed by the present river in the present hydrologic regime?

The flood sands of 1983 and the high flow sands of 1984 to 1986, regardless of depositional setting, formed beneath the water surface as eddy bars or levees. Bars typically build to within about 0.3 m of the water surface [Schmidt and Graf, 1990; Schmidt and Andrews, unpubl. data]. These bars have considerable relief, but there is consistency in the elevation of the part of the reattachment bar that forms near the flow-reattachment point. The correlation of these sites is an effective tool for estimating formative discharge water slopes (Figure 12). These surfaces, however, do not constitute floodplains in the sense that they are not incrementally constructed. Flood-level surfaces are constructed by one geomorphically effective event, and subsequent hillslope processes tend to modify the fluvial nature of the landforms.

There are lower elevation surfaces along the Colorado River in Grand Canyon that have formed by discharges within the range of powerplant capacity, and which are generally consistent with an effective discharge peak of about 725 $m^3 s^{-1}$. These surfaces constitute the deposits constructed by the river in the present regime. The mechanisms of deposition are (1) the same eddy processes that occur at higher discharge, or (2) vertical accretion of silt and clay on top of sand bars. The former process was documented by Rubin et al. [1990] and is shown on Figure 6f as a wedge of fine sand comprising the main platform of the reattachment bar. The latter process is illustrated in Figure 6a-d. This reattachment bar was an open reattachment bar in 1965. By 1973, this bar had been substantially colonized by marsh and woody riparian vegetation. The bar surface was completely vegetated by 1980 and was just inundated by flows of approximately 725 $m^3 s^{-1}$. Stevens et al. [1995] describe the succession of riparian plants on reattachment bars and show that these plants preferentially colonize silts and clays. Thus, there is a positive feedback between vegetation and fine sediment deposition.

Channel-margin deposits without levees, such as exist in reaches with low relief fans may also comprise floodplains (upstream part of Fifures 4a and 9a). These deposits have numerous levels, one that is inundated by effective discharge flows but others of which correlate with rarer floods.

Discussion

Alluvial deposits in debris-flow affected canyons preserve surfaces constructed by the effective discharge and by high magnitude floods. In the case of Grand Canyon, the deposits formed by rare post-dam floods and lower elevation deposits constructed by the effective discharge are both extensive. Along highly regulated rivers, such as the Colorado River in Grand Canyon, reattachment bars may become vegetated floodplains, but rare floods can reactivate these surfaces. This process is similar to the disequilibrium floodplain model of Nanson [1986].

Eddy bars persist in specific zones of recirculation because the channel obstructions that give rise to flow separation rarely change. 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 photgraphy (dating to the 1880's [Webb, in press] show that the locations of eddy sand bars have been stable for long periods. Observations about the relation between flow geometry and sand-bar location suggest that bars should be persistent over periods consistent with the frequency of events that substantially reshape flow-separation-inducing obstructions. In Grand Canyon, that time scale is on the order of 10 to 100 yrs [Melis et al., 1995].

Large floods may overtop debris fans and cause recirculation zones to diminish greatly in size or disappear [e.g. Kieffer and others, 1989, fig. 3.5]. Melis et al. [1995] have shown that most debris fans are overtopped by discharges at or greater than the pre-dam mean annual flood, and photographs of the river at discharges greater than 2830 $m^3 s^{-1}$ show that many eddies are thin or non-existent at this discharge. Because eddy deposits are composed of sedimentary structures indicative of recirculation, eddy bars must form in flows less than the magnitudes that drown the controlling constriction. Thus, fine-grain river deposits form at discharges less than those that overtop fans or during the descending limb of fan-overtopping floods after eddies have reestablished themselves.

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 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 channel geometry and discharge [Rubin et al., 1990]. 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 in the lee of high-elevation debris fans that are overtopped less frequently.

Conclusions

Eddies are the dominant environment of suspended load deposition in narrow debris flow-affected valleys. For the Green and Colorado Rivers, these reaches have unit stream power greater than 60 W m^{-2} at the 2-yr recurrence flood and are in alluvial valleys less than 5 times greater than the average bankfull channel width.

The fundamental geomorphic unit of debris flow-affected channels is the debris fan-eddy complex. It is composed of a low-velocity backwater upstream from the debris fan, a constricting debris fan, eddies and eddy bars, and a gravel bar. Mapping of alluvial deposits in Grand Canyon demonstrates that eddy bars, and the subclassifications of separation and reattachment bar characterize most of the depositional environments of the river corridor.

Suspended-load deposits in these rivers have topographic surfaces that can be correlated with the increment of discharge that has the greatest amount of sediment transport. However, there are other surfaces that correlate with subsidiary modes of sediment transport. Thus, the present river in the present regime forms longitudinally extensive levels associated with several different discharges.

The existence of multiple peaks in calculated effective discharge curves is related to the highly regulated nature of large Colorado Plateau rivers. Since construction of large dams, flood flows have been greatly decreased, but occassional high floods still occur, such as those in Grand Canyon between 1983 and 1986. Prior to dam construction, effective discharge curves probably were similar to those calculated by Andrews [1986, figures 9 and 10]. Thus, dam regulation appears to be creating a more diverse array of topographic levels along the debris-flow affected rivers of the Colorado Plateau.

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Figure Caption List

Fig. 1. Map showing the major rivers and physiographic features of the Colorado Plateau. Debris flow-affected canyons are shown as (G) Grand Canyon, (C) Cataract Canyon, (D/G) Desolation/Gray Canyons, (SM) Split Mountain Canyon, and (L) Canyon of Lodore. U.S. Geological Survey stream gaging stations used in flood frequency analyses are located with black circles: (GD) Green River near Greendale, UT, (J) Green River near Jensen, UT, (GR) Green River at Greenriver, UT, (LF) Colorado River at Lees Ferry, AZ, (GC) Colorado River near Grand Canyon, AZ. Numbers indicate approximate locations of two study reaches in Grand Canyon: (1) Point Hansbrough to Saddle Canyon. (2) near Little Colorado River confluence.

Fig. 2. Graph showing geomorphic characteristics of the Green and Colorado Rivers, and distinguishing restricted meander, fixed meander, and debris flow-affected valleys. Data listed in Table 1.

Fig. 3. Maps showing topography along two reaches of the Colorado River. Arrows point to large debris fans. Topographic base originally at 1:2400 scale and 0.5-m contour interval, June 1990. (a) 11-km reach near Point Hansbrough and Saddle Canyon that begins 70 km downstream from Lees Ferry. (b) 8-km reach near Little Colorado River confluence that begins 100 km downstream from Lees Ferry.

Fig. 4. Maps showing surface flow patterns at about 425 $m^3 s^{-1}$ and alluvial deposits in June 1990 in two reaches of the Colorado River in Grand Canyon. These maps show the large proportion of the surface flow field that are within lateral separation eddies. Vertical hatchures are separation bars, horizontal hatchures are reattachment bars, cross-hatchuring are undifferentiated eddy bars, and dotted patterns are channel-margin deposits. (a) Detail of part of reach shown in Figure 3a. (b) Detail of part of reach shown in Figure 3b.

Fig. 5. Flow patterns, topography, and bar evolution of a separation bar, Eighteen Mile Wash, Grand Canyon. (a) Flow patterns in the lee of two debris fans. (b) topography on August 2, 1985 at 850 m3 s-1. (c) Upstream migration of bar shown by two surveys along baseline and sedimentology of the resulting deposit. Water surface shown is approximately 1275 m^3 s^{-1}. Unit 0 is red sand gravel from tributary. Unit 1 is fine to very fine sand in highly truncated ripple crosslaminae. Unit 2 is fine to very fine sand in planar forsets. Unit 3 is fine sand composed of steep forsets. Unit 4 is very fine sand in complex ripple crosslaminae. Units 5 and 6 are reworked. The entire sequence of Units 1 to 4 were deposited during 33 dys after the May 22, 1984, survey. Data from Schmidt and Graf [1990]

Fig. 6. Reattachment bar evolution and sedimentology, Fifty-five Mile marsh, Grand Canyon. In parts a-d, light shading is bare sand, moderate shading is dense saltcedar, and darkest shading is marsh vegeation. Parts a-d show vegetation colonization of bar surface during interval of no floods and reestablishment of site as an active reattchment bar after high flows in 1983 and 1984. (a) Bar in spring 1965. (b) Bar in June 1973. (c) Bar in June 1980. (d) Bar in October 1984. (e) Topography and sediment transport directions interpreted from sedimentary structures in 1987. (f) Stratigraphic sequence in bar along cross section line shown in A-A'. Units R1 - R4 were deposited by high discharges between 1983 and 1986, and units P2 and P3 were deposited by powerplant flows. Data from Rubin et al. [1990]

Fig. 7. Correlation and description of map units for surficial geologic mapping in Grand Canyon.

Fig. 8. Flow patterns and stratigraphy of levee upstream from Little Nankoweap Creek, Grand Canyon. (a) Flow patterns at low discharge, 1992. (b) Descriptions of stratigraphy at four cross-sections of trench.

Fig. 9. Maps showing formative discharges of alluvial deposits in reaches of the Colorado River in Grand Canyon in June 1990. Comparison with Figure 4 shows that parts of individual bars have different formative discharges. Horizontal hatchures are deposits formed by discharges less that powerplant capacity, vertical hatchures are deposits formed by discharges that utilized the by-pass tubes between 1984 and 1986, cross-hatchuring are deposits formed by discharges that utilized the spillways in 1983, and dotted patterns are deposits formed by pre-dam discharges greater than 2750 $m^3 s^{-1}$.

Fig. 10. 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 sand deposits of 1983. this deposit truncates underlying pre-dam deposits and which are truncated offshore by the receding flows of 1983 and the high flows of 1984 to 1986. 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].

Fig. 11. Effective discharge curves for Colorado River near Grand Canyon, Arizona. Each symbol is calculated for a 25 $m^3 s^{-1}$ increment of discharge centered on the plotted point. X's are for 1965-1980 and crosses are for 1980-1990.

Fig. 12. Graph showing longitudinal correlation of flood sand and high flow sands in the 8-km reach near the Little Colorado River shown in Figure 3b.

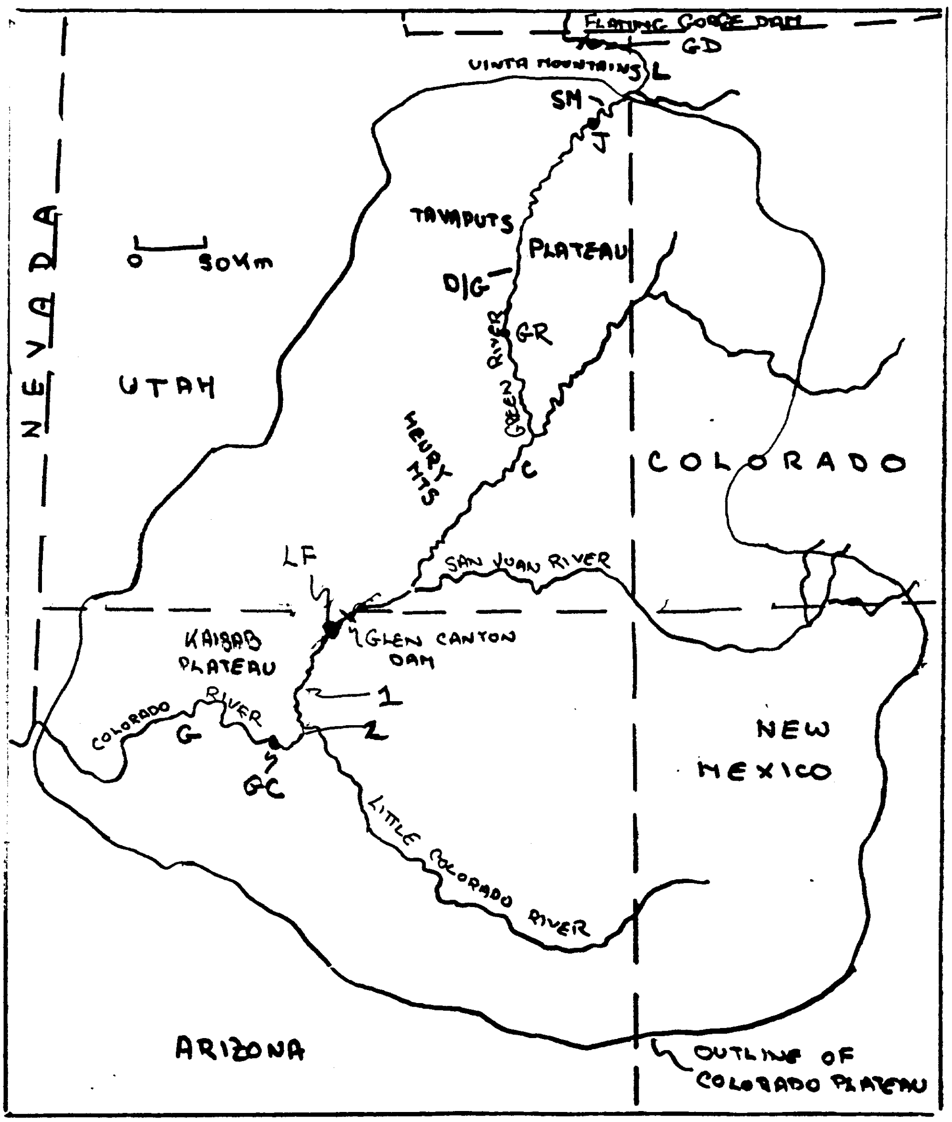
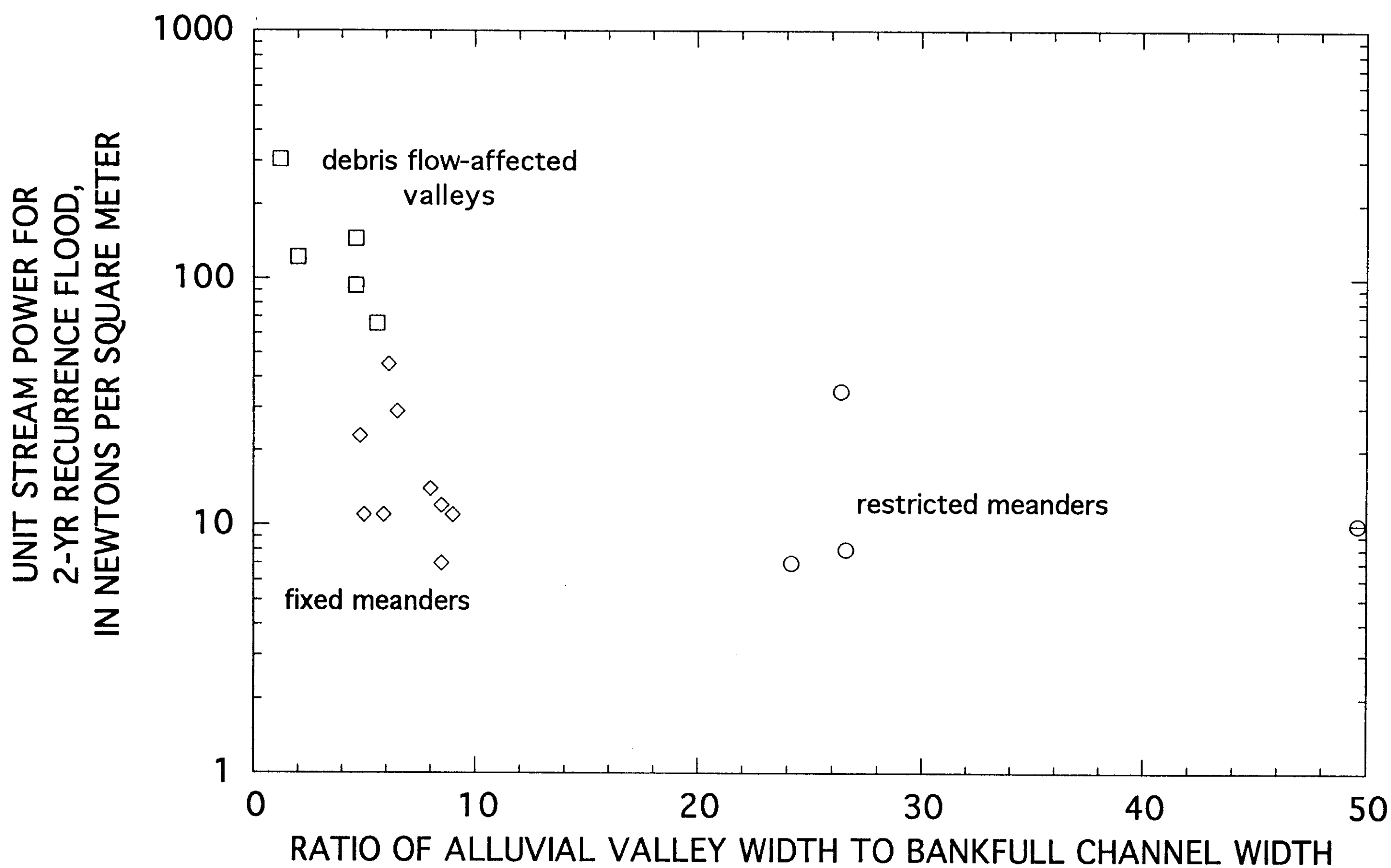
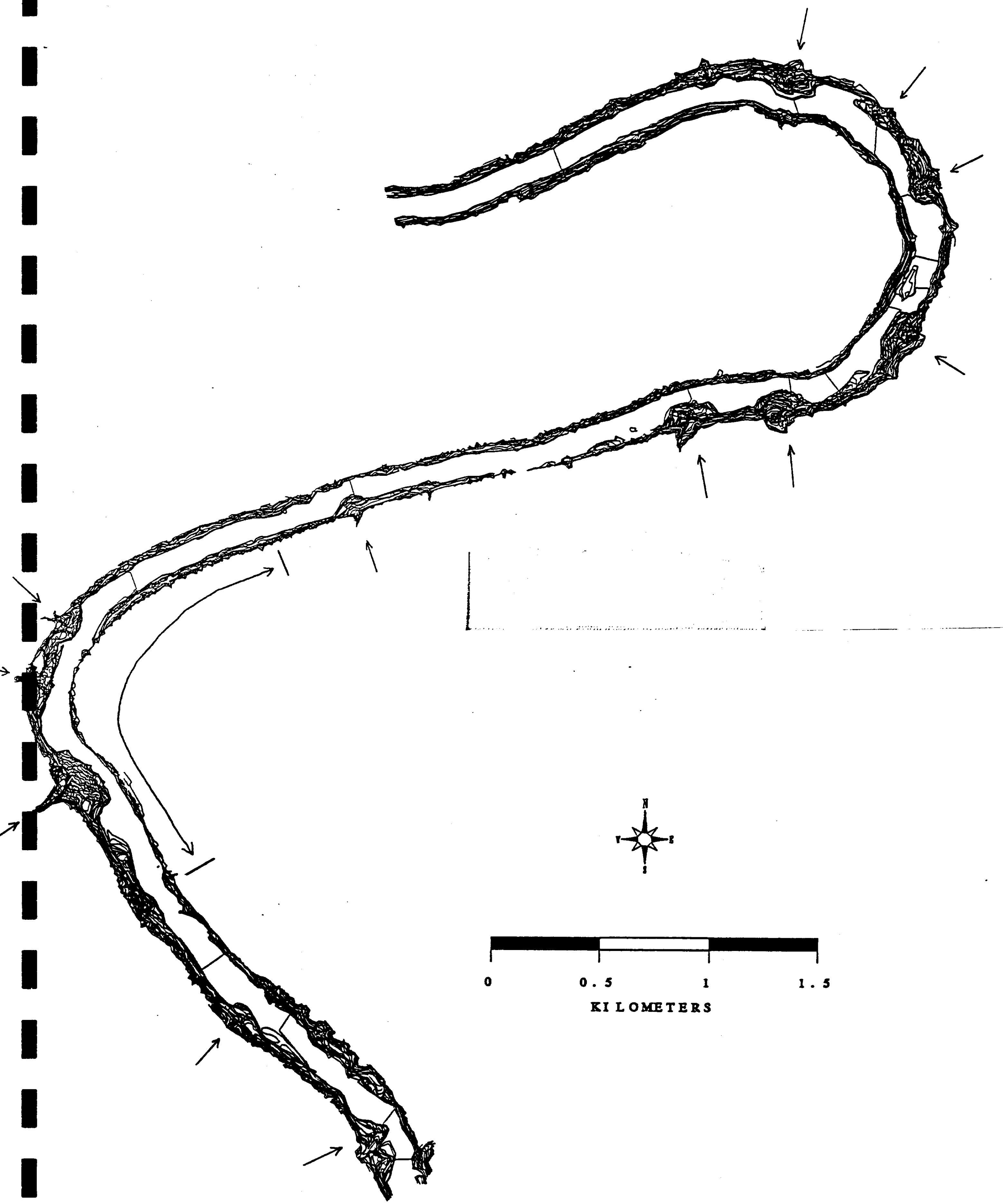
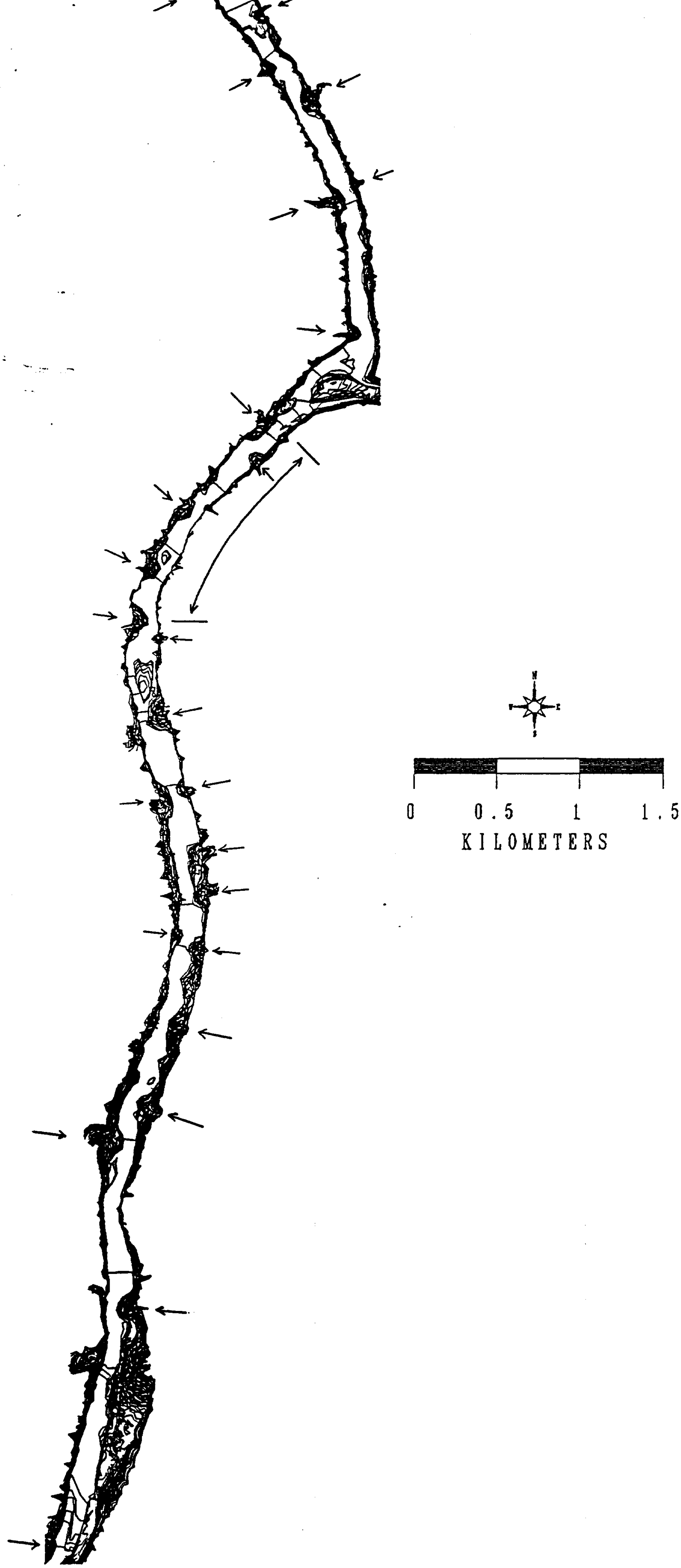
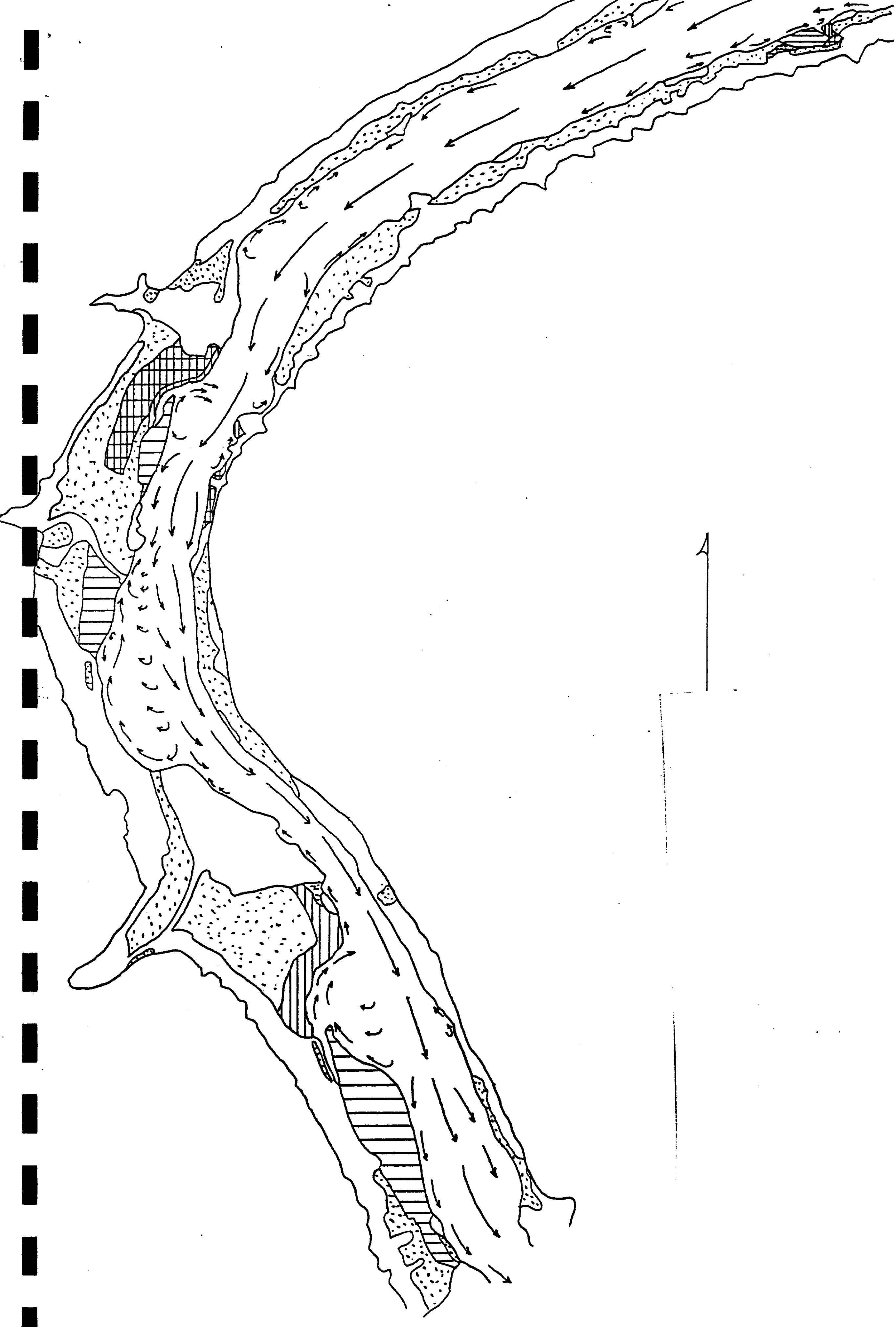

FLAMING GORGE DAM
GD
UINTA MOUNTAINS
L
SM
J
TAVAPUTS
PLATEAU
D/G
GR
GREEN RIVER
0
50Km
NEVADA
UTAH
HENRY MTS
C
COLORADO
LF
SAN JUAN RIVER
KAIBAB PLATEAU
GLEN CANYON DAM
1
2
COLORADO RIVER
G
GC
NEW MEXICO
LITTLE COLORADO RIVER
ARIZONA
OUTLINE OF COLORADO PLATEAU

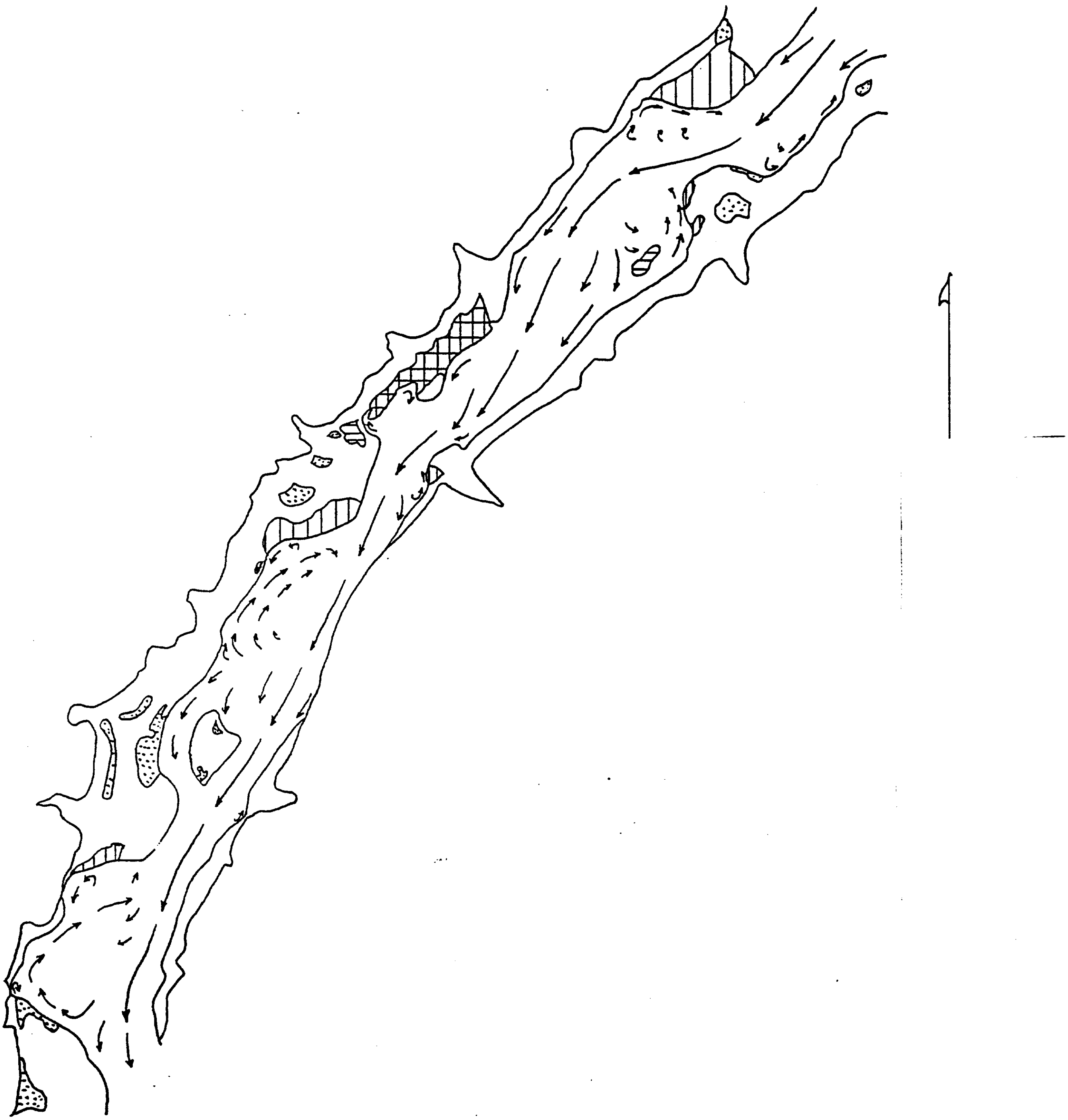
Fig 1

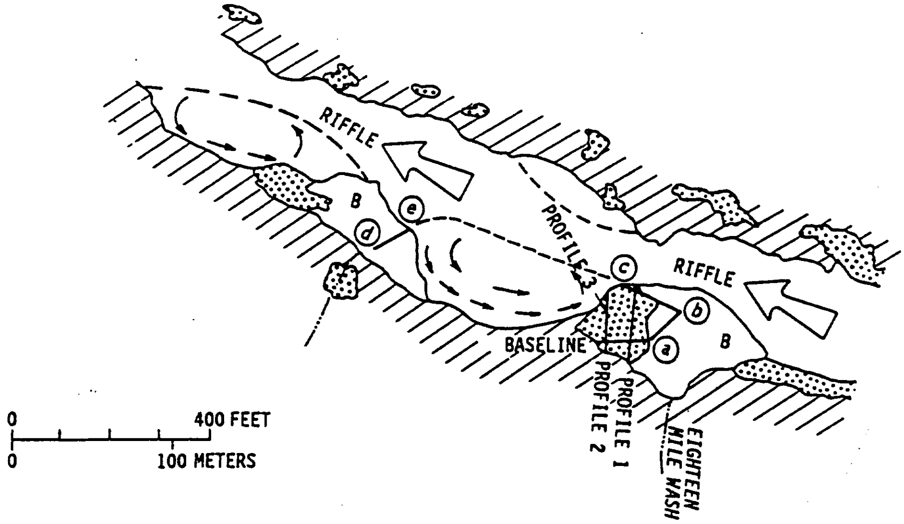

UNIT STREAM POWER FOR
2-YR RECURRENCE FLOOD,
IN NEWTONS PER SQUARE METER
1000
100
10
1
0
10
20
30
40
50
RATIO OF ALLUVIAL VALLEY WIDTH TO BANKFULL CHANNEL WIDTH
debris flow-affected
valleys
fixed meanders
restricted meanders

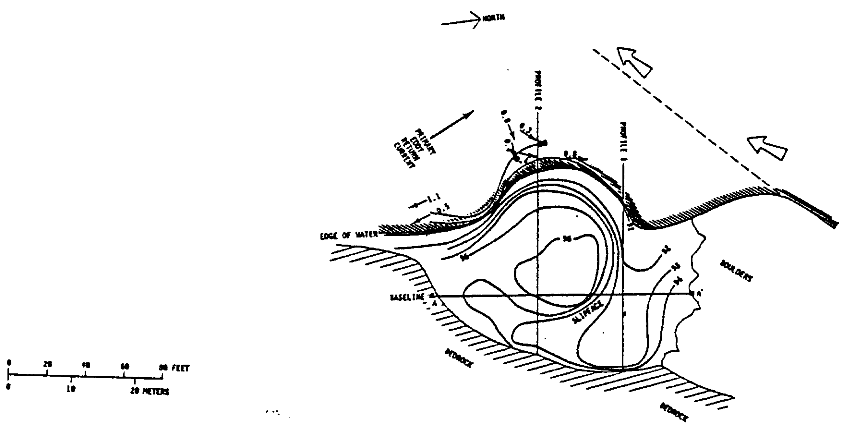

N
W
E
S
0
0.5
1
1.5
KILOMETERS

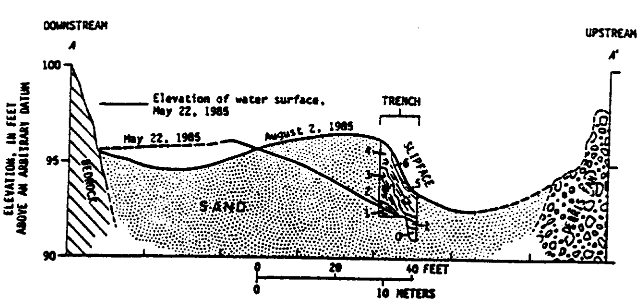

0 0.5 1 1.5
KILOMETERS

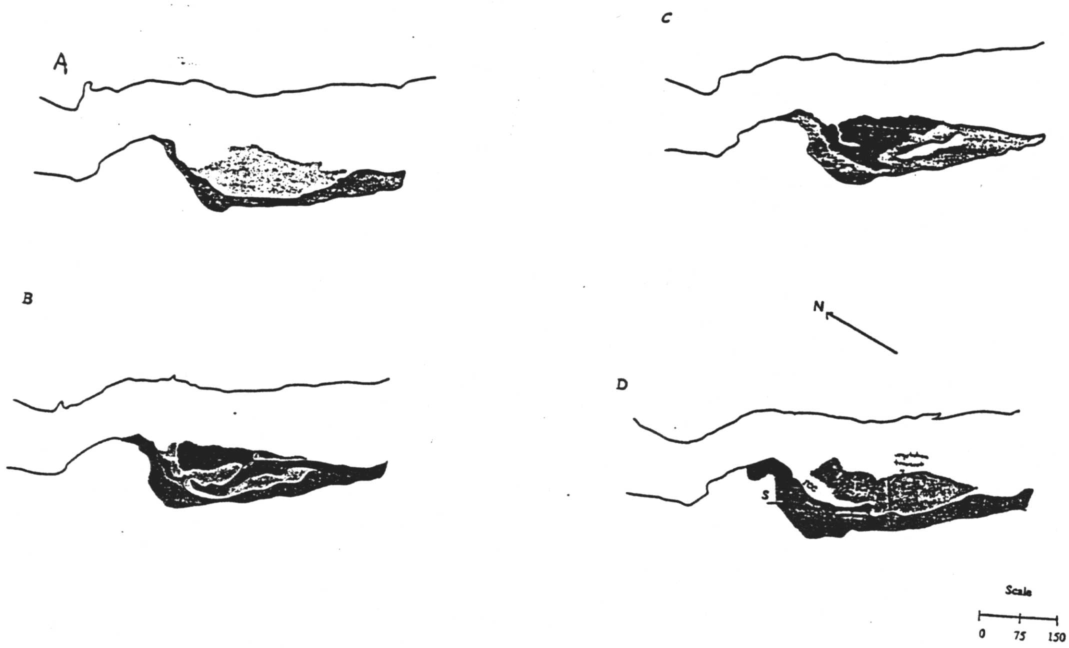


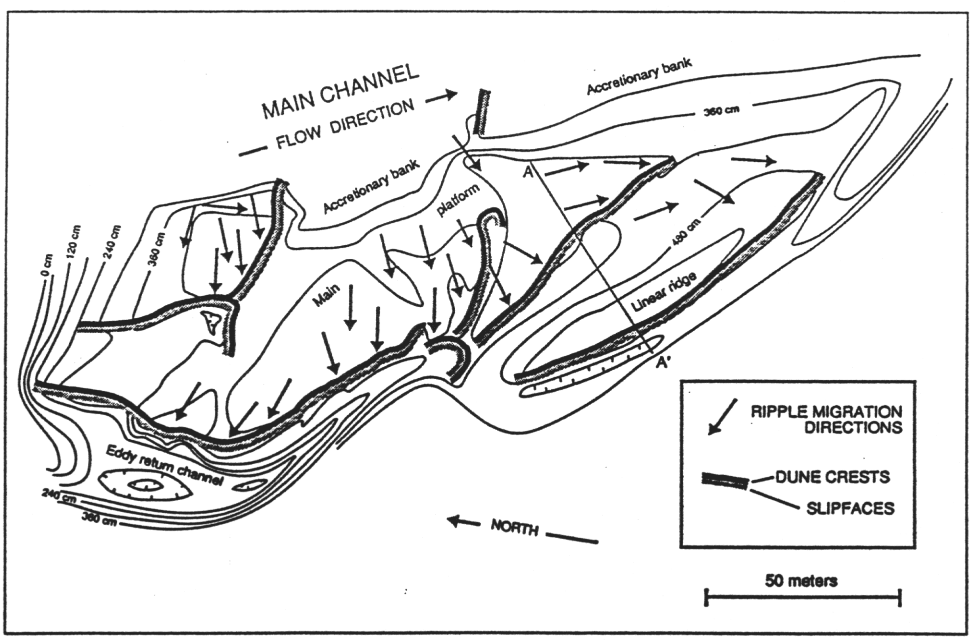


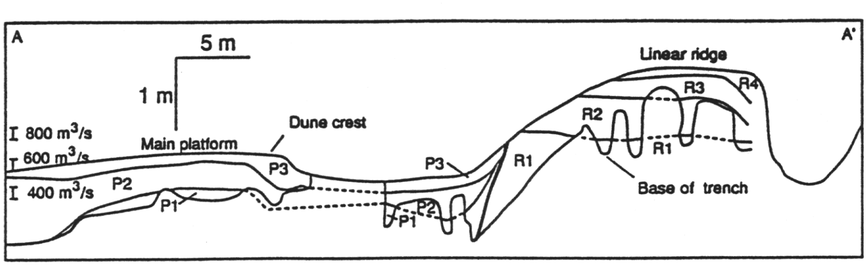

RIFFLE
RIFFLE
B
B
PROFILE 3
BASELINE
PROFILE 1
PROFILE 2
EIGHTEEN MILE WASH
0
400 FEET
0
100 METERS


NORTH
PROFILE 2
PROFILE 1
PRIMARY EDDY RETURN CURRENT
EDGE OF WATER
BASELINE
A
A'
SLIPFACE
BOULDERS
BEDROCK
BEDROCK

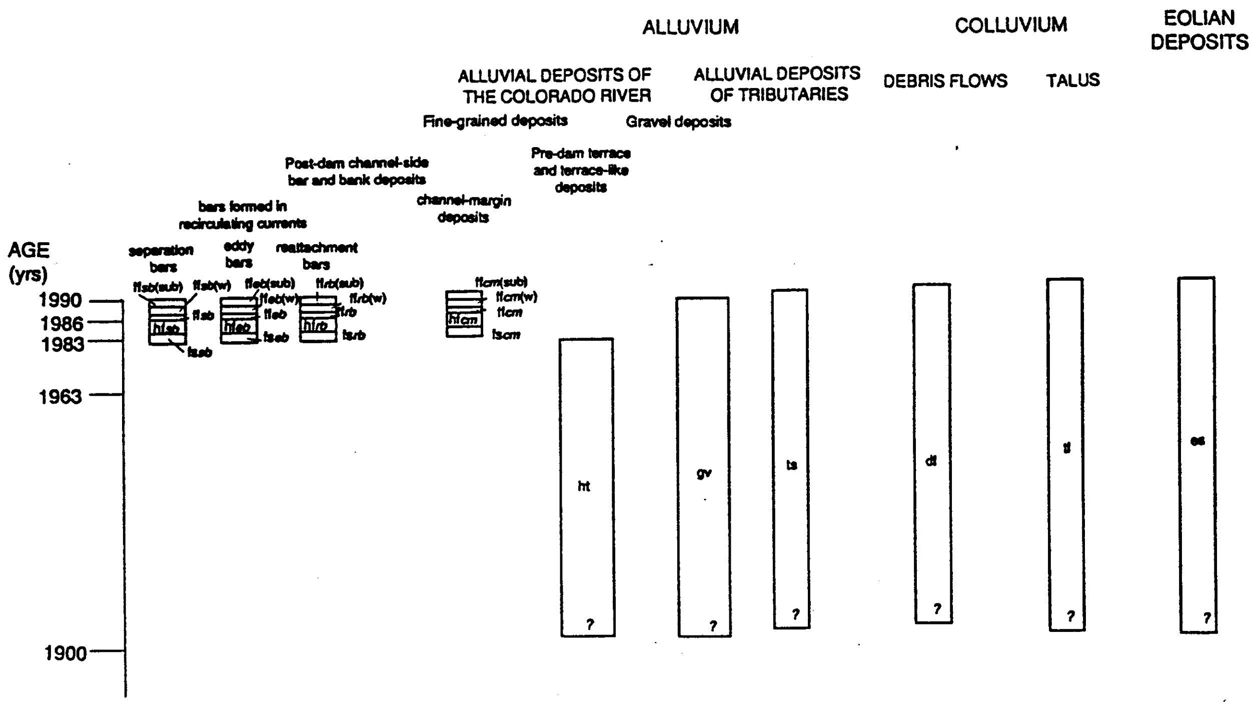

DOWNSTREAM
A
UPSTREAM
A'
ELEVATION, IN FEET ABOVE AN ARBITRARY DATUM
100
95
90
Elevation of water surface, May 22, 1985
May 22, 1985
August 2, 1985
TRENCH
SLIPFACE
BEDROCK
SAND
0
20
40 FEET
0
10 METERS
VERTICAL EXAGGERATION X 5


A
B
C
D
N
Scale
0
75
150


MAIN CHANNEL
FLOW DIRECTION
Accretionary bank
Accretionary bank
360 cm
platform
Main
0 cm
120 cm
240 cm
360 cm
A
A'
Linear ridge
Eddy return channel
240 cm
360 cm
NORTH
RIPPLE MIGRATION DIRECTIONS
DUNE CRESTS
SLIPFACES
50 meters


A
A'
5 m
1 m
800 m³/s
600 m³/s
400 m³/s
Main platform
Dune crest
Linear ridge
P1
P2
P3
P1
P2
P3
R1
R2
R3
R4
R1
Base of trench

CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

ALLUVIUM

ALLUVIAL DEPOSITS OF THE COLORADO RIVER

Post-dam channel-side bar and bank deposits

ff Fluctuating-flow sand (1990-1986) -- silty very-fine to fine grained sand, widely ranging colors of light gray, brown, and reddish brown, exposed thicknesses may exceed 1 m. Deposited by discharges less than 890 m^3/s.

hf High-flow sand (1986-1984) -- medium to very-fine grained sand, with some silty layers. Deposited by flows between 890 and 1400 m^3/s that occurred in successive late spring dam releases.

fs Flood sand of summer 1983 (June-July) -- medium to very-fine grained sand, very well-sorted to well-sorted, distinctive very light gray, salt-and-pepper color. Deposited by flows between 1400 and 2700 m^3/s.

Terrace and terrace-like deposits of pre-dam age

ht Pre-dam alluvium -- silty very-fine sand that forms three distinct topographic levels. The lower level has mature saltcedar with partially buried trunks. Upper levels have mature mesquite or acacia. Climbing ripple structures are abundant in all deposits. Deposition by floods in excess of 2700 m^3/s.

Gravel deposits

gv Gravel deposits (post-dam to prehistoric?) -- gravel, unconsolidated, gravel to cobble size, subrounded to rounded clasts of local Paleozoic formations.

COLLUVIUM

DEBRIS FLOWS

df **Undifferentiated debris-flow deposits** -- poorly sorted sand, gravel, cobbles, and boulders with scattered boulder larger than 1.5 m. Clasts angular to subangular, clast supported texture. Includes hyperconcentrated flow deposits of well-sorted gravel and tributary channel alluvium.

DEPOSITIONAL FACIES OF COLORADO RIVER ALLUVIAL DEPOSITS

Eddy bar complexes

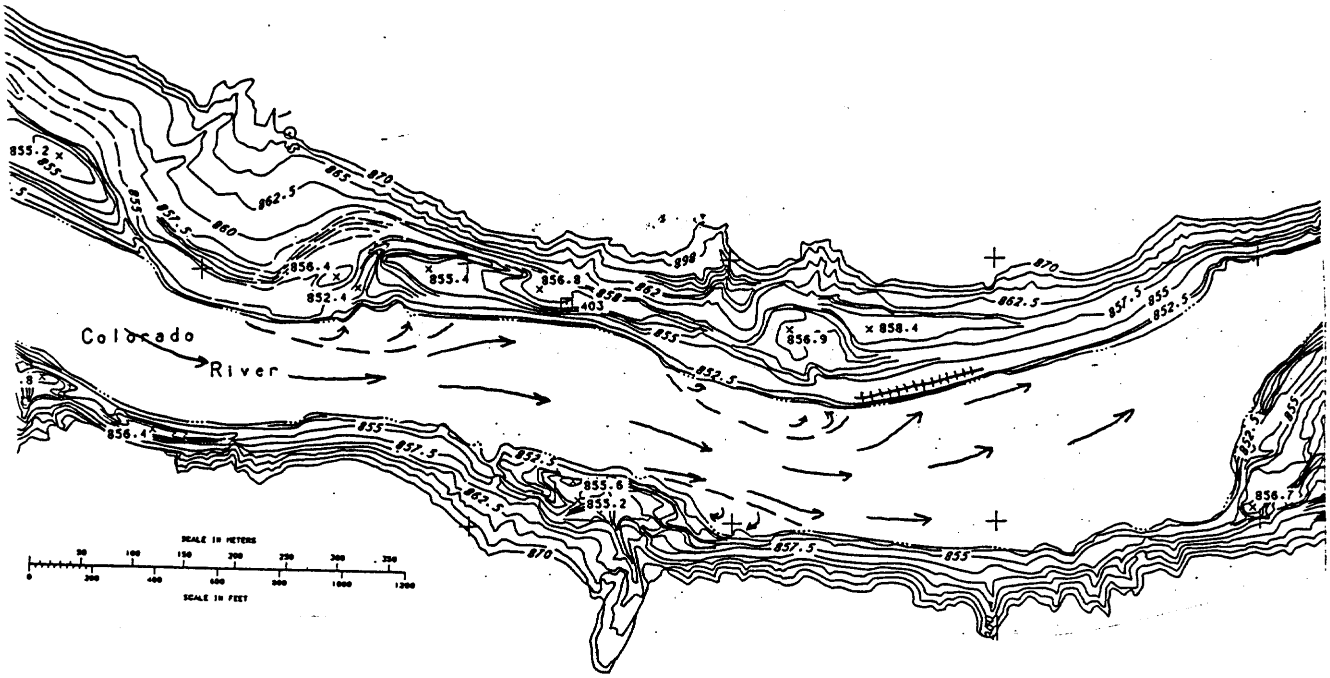
sb **Separation bars** -- Sand deposit on downstream side of debris fan or talus cone. Includes isolated boulders covering less than 25 percent of suface. Surface flat-lying to sloping. Surface may slope continuouly to water edge, be truncated by a cutbank, or be separated from water by debris flow deposits. Occurs as fluctuating-flow, high-flow sand, or flood sand.

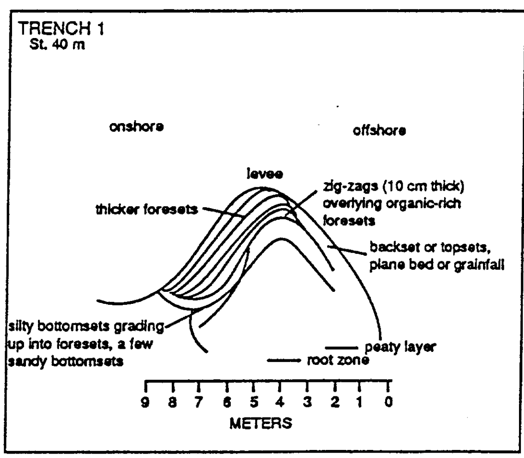
rb **Reattachment bars** -- Sand deposit composed of ridge which is highest at its downstream end and which slopes in the upstream direction. Deposit includes channel on shoreward side of ridge. Typically, more than 95 percent of surface is sand and contact with other map units is distinct.

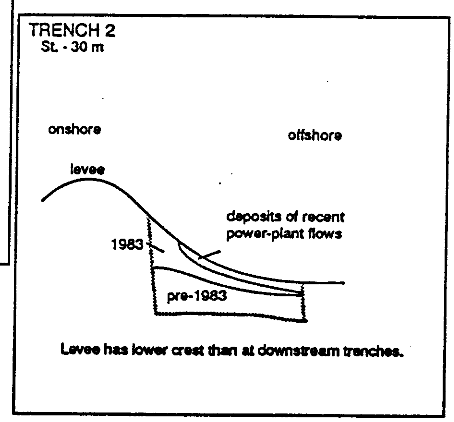
eb **Eddy bar** -- Undiferentiated separation and reattachment bars. Located downstream from debris fans or talus cones and (1) adjacent to reattachment or separation bar, or (2) in same site as former reattachment or separation interpreted from historical airphotos.

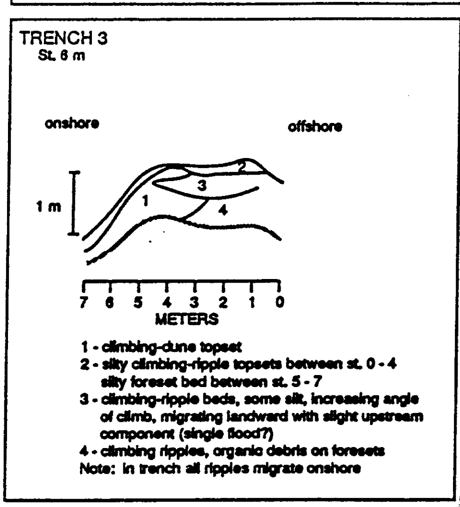
Terrace-like deposits

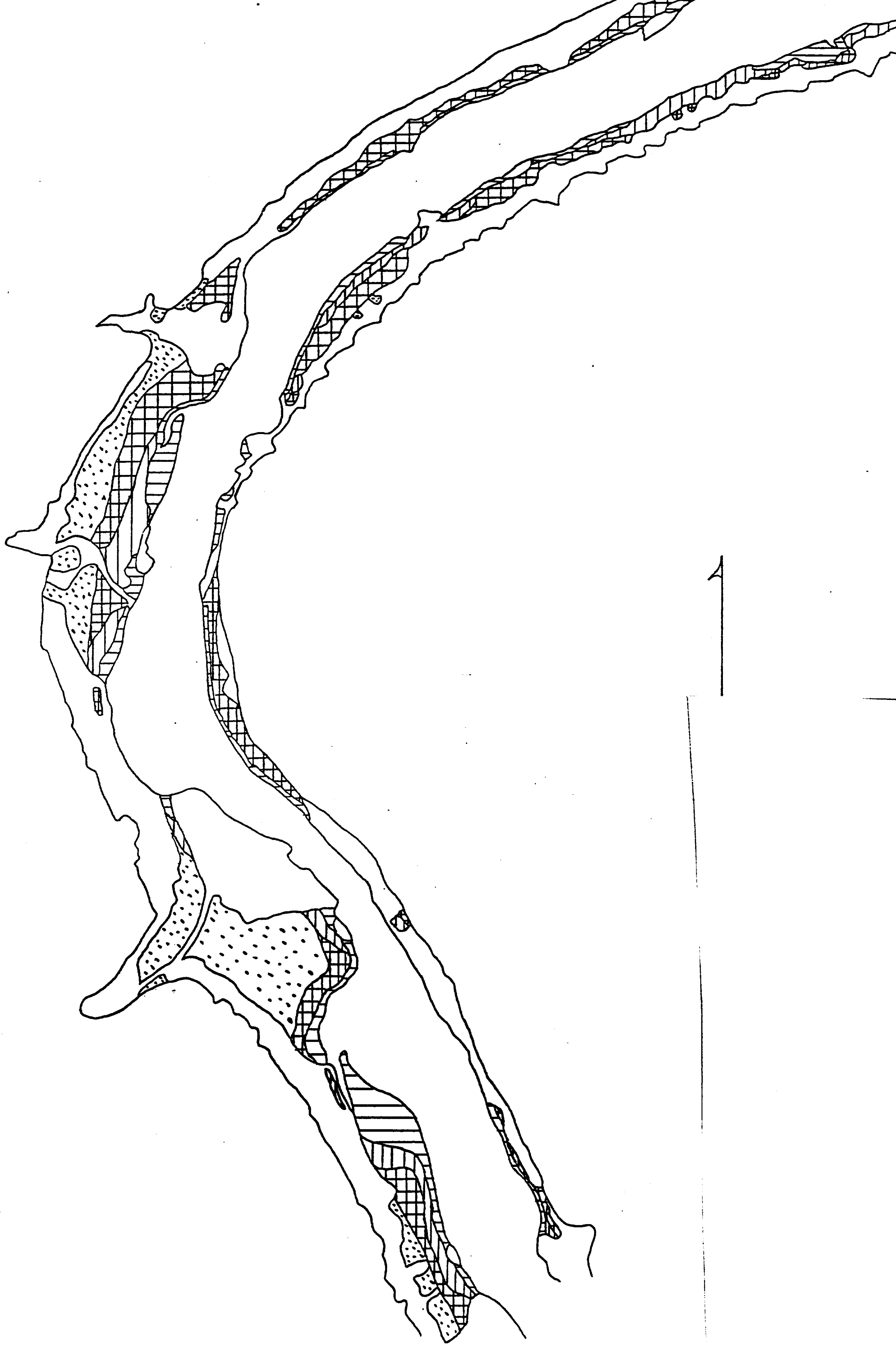
cm **Channel-margin deposit** -- Linear sand deposit resembling floodplain or terrace, may include up to 25 percent of surface covered by talus. Contacts with other map units are often gradational. This unit often includes a levee paralleling main channel. This map unit includes all fine-grained alluvial deposits not associated with eddies.

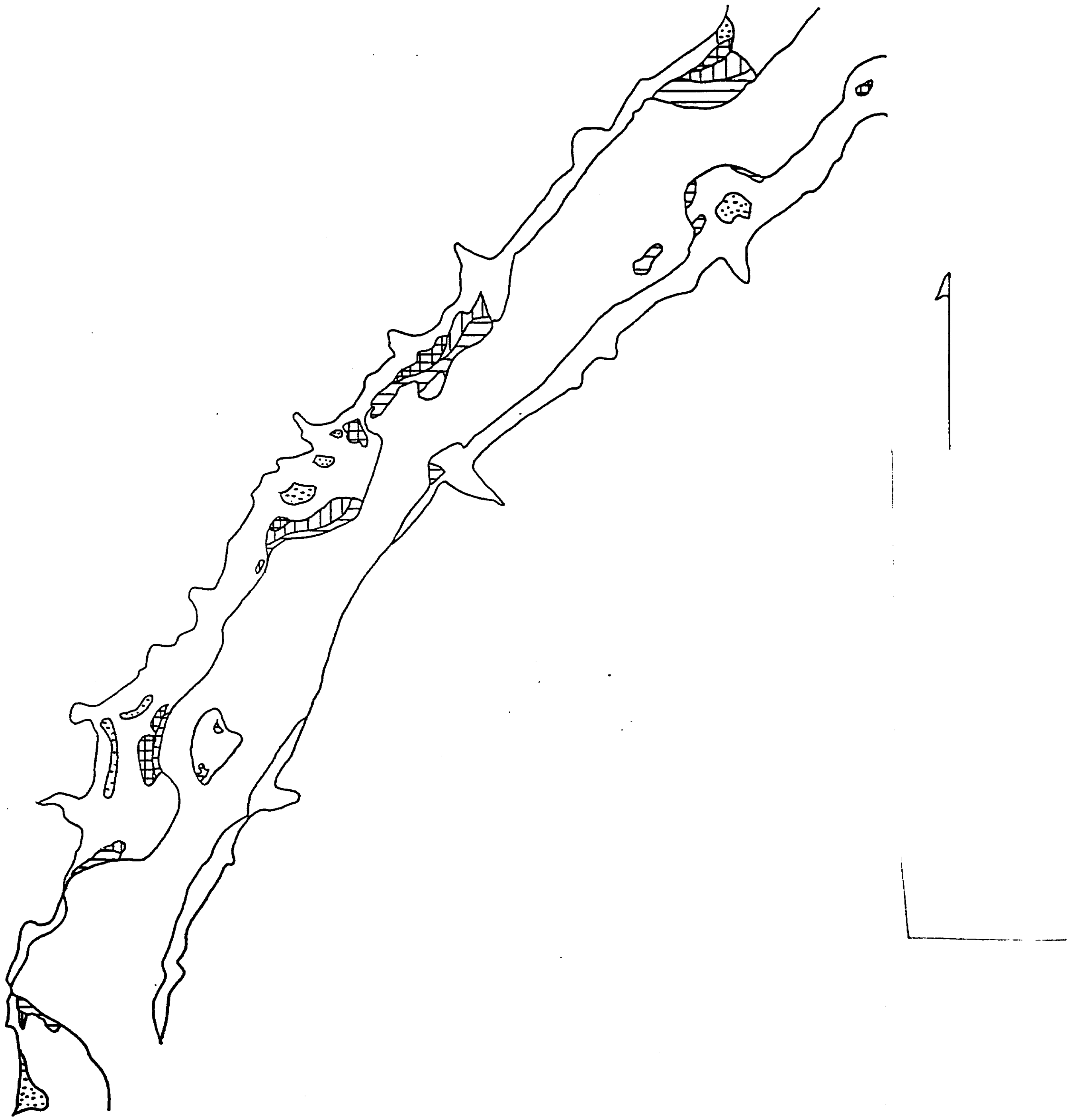

Colorado
River

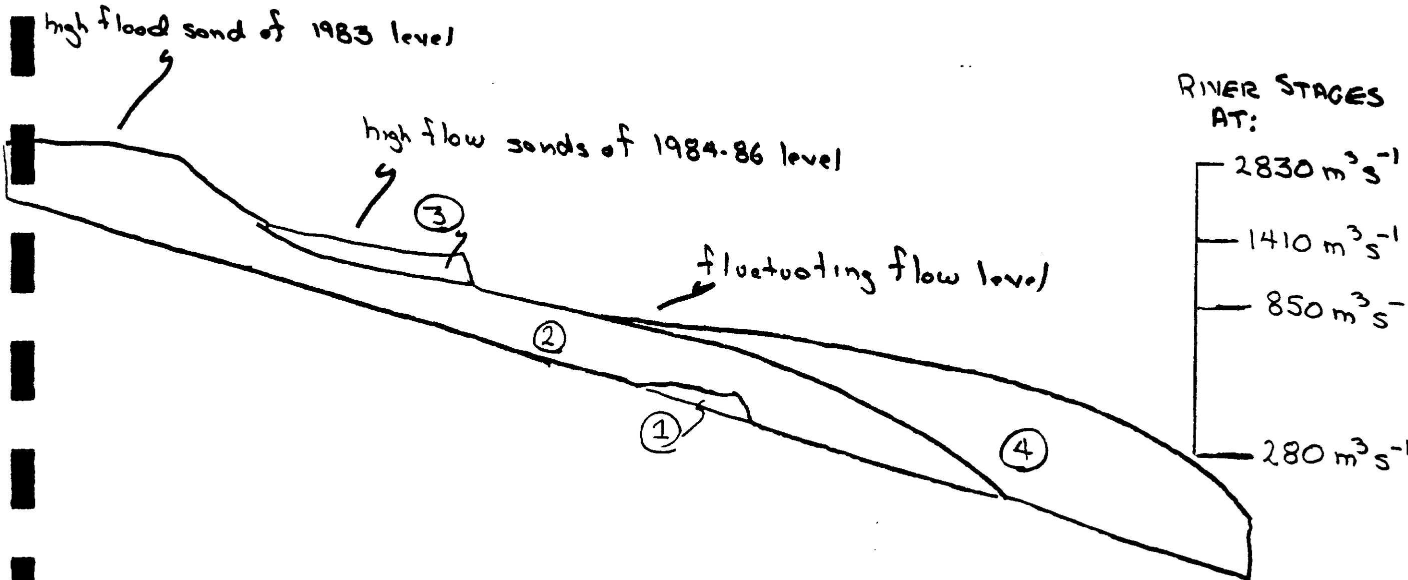

TRENCH 1
St. 40 m
onshore
offshore
levee
thicker foresets
zig-zags (10 cm thick) overlying organic-rich foresets
backset or topsets, plane bed or grainfall
silty bottomsets grading up into foresets, a few sandy bottomsets
peaty layer
root zone
9 8 7 6 5 4 3 2 1 0
METERS


TRENCH 2
St. - 30 m
onshore
offshore
levee
deposits of recent power-plant flows
1983
pre-1983
Levee has lower crest than at downstream trenches.

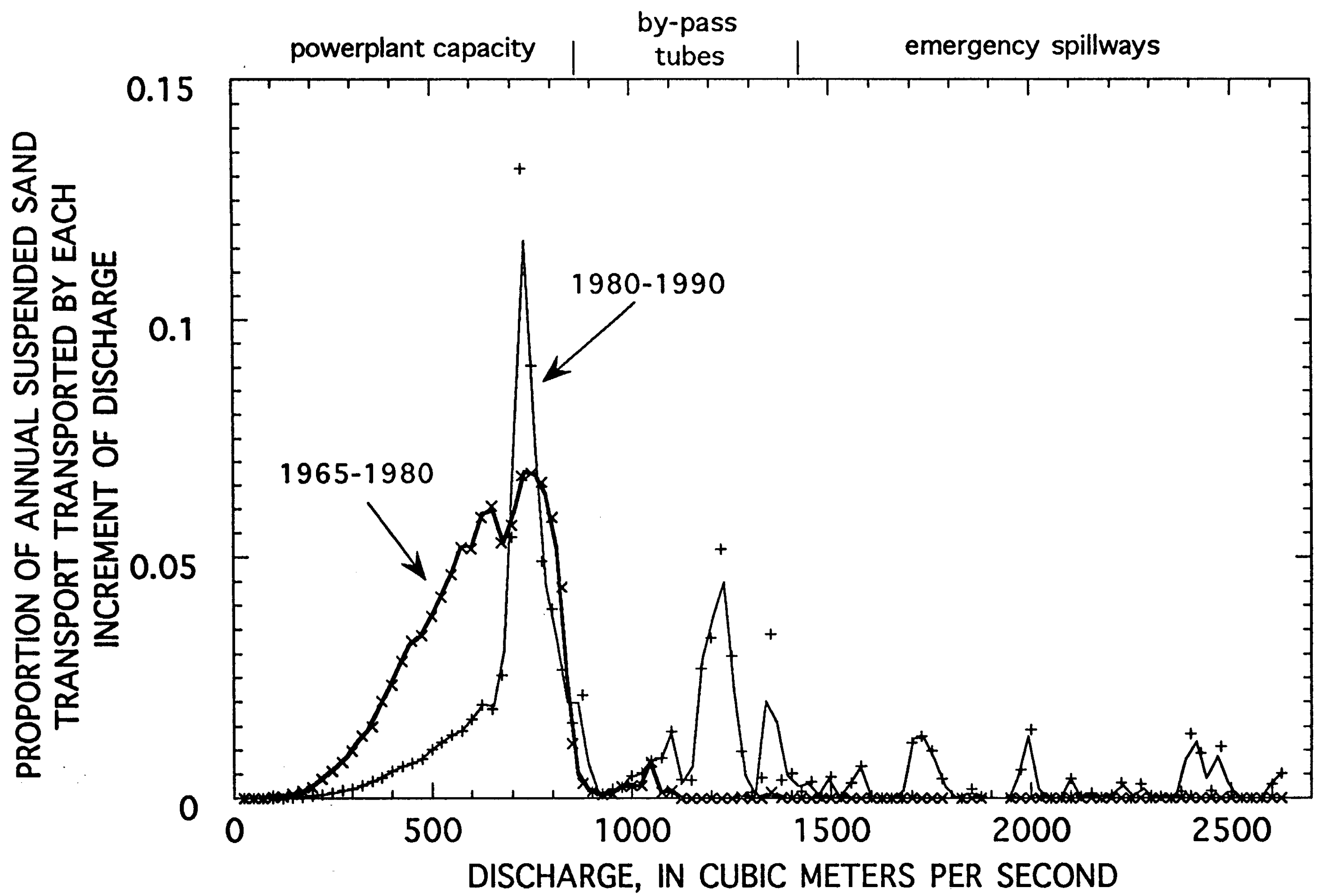

TRENCH 3
St. 6 m
onshore
offshore
1 m
1
2
3
4
7 6 5 4 3 2 1 0
METERS
1 - climbing-dune topset
2 - silty climbing-ripple topsets between st. 0 - 4
silty foreset bed between st. 5 - 7
3 - climbing-ripple beds, some silt, increasing angle of climb, migrating landward with slight upstream component (single flood?)
4 - climbing ripples, organic debris on foresets
Note: in trench all ripples migrate onshore







high flood sand of 1983 level
high flow sands of 1984-86 level
3
fluctuating flow level
2
1
4
RIVER STAGES AT:
2830 m³s⁻¹
1410 m³s⁻¹
850 m³s⁻¹
280 m³s⁻¹


powerplant capacity
by-pass
tubes
emergency spillways
0.15
0.1
0.05
0
PROPORTION OF ANNUAL SUSPENDED SAND
TRANSPORT TRANSPORTED BY EACH
INCREMENT OF DISCHARGE
1980-1990
1965-1980
0
500
1000
1500
2000
2500
DISCHARGE, IN CUBIC METERS PER SECOND

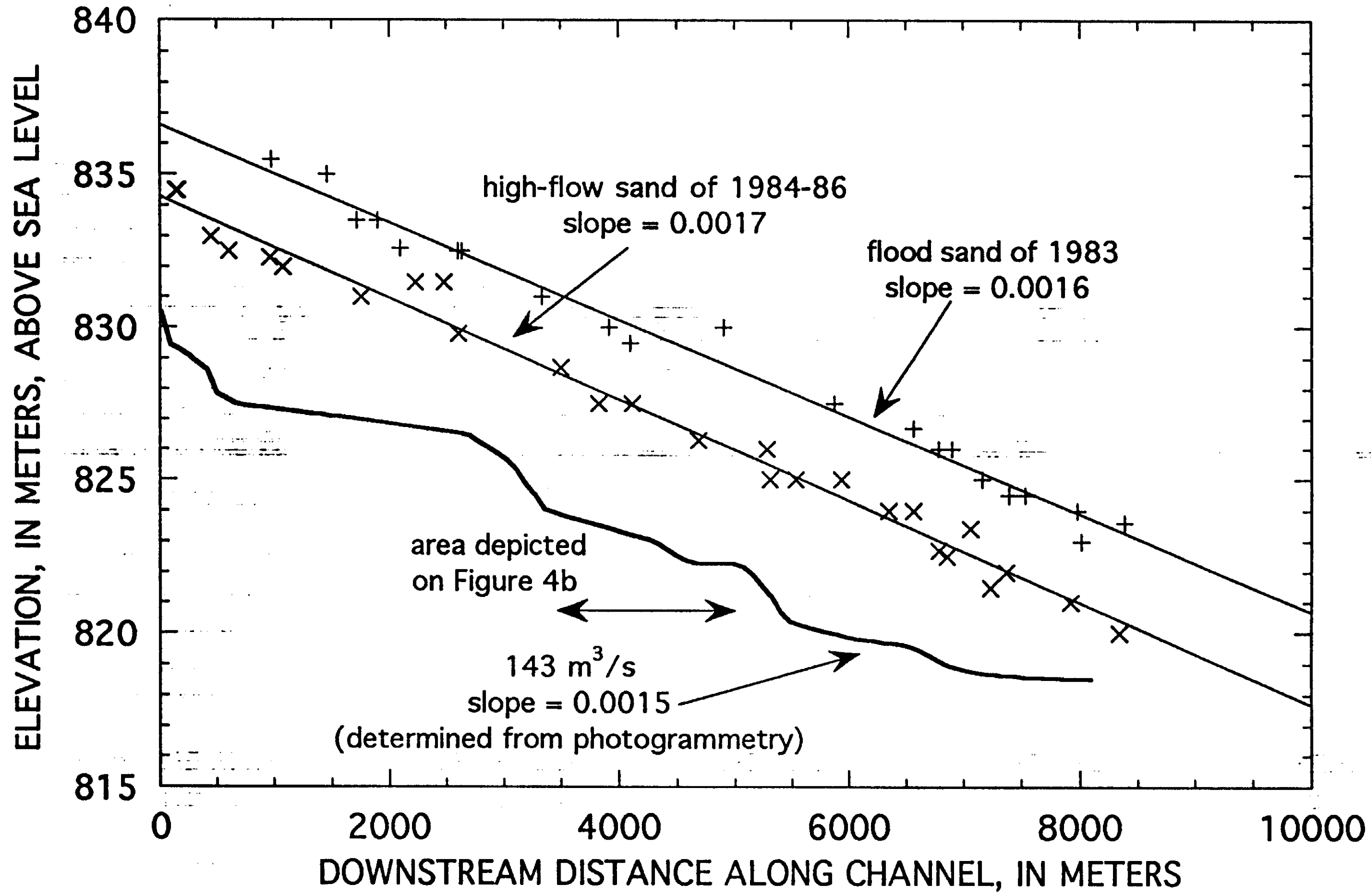

840
835
830
825
820
815
0
2000
4000
6000
8000
10000
ELEVATION, IN METERS, ABOVE SEA LEVEL
DOWNSTREAM DISTANCE ALONG CHANNEL, IN METERS
high-flow sand of 1984-86
slope = 0.0017
flood sand of 1983
slope = 0.0016
area depicted
on Figure 4b
143 m³/s
slope = 0.0015
(determined from photogrammetry)

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

Location	Length of Length of mapping, meters	2-yr 2-yr flood, cubic meters per second	Channel slope, in meters per meter	Channel width, in meters	Total stream power, in watts	Unit stream power, in watts per square meter	Average valley width, in meters	Ratio of valley to channel width, in meters per meter	Proportion of fine sediment deposited within eddies	Proportion of alluvial deposits that are gravel
Grand Canyon										
Little Colorado confluence	4020	2127	0.00155	106	32329	305	125	1.2	0.75	NA
middle Marble Canyon	10500	2148	0.00067	115	14112	123	225	2.0	NA	NA
Green River										
Lower Stillwater Canyon	15541	789	0.000373	125	2886	23	600	4.8	0	0
Upper Stillwater Canyon	17487	789	0.000279	150	2159	14	1200	8.0	0	0
Lower Labyrinth Canyon	16989	789	0.000182	133	1408	11	1200	9.0	0	0
Middle Labyrinth Canyon	12725	789	0.00019	139	1470	11	700	5.0	0	0
Upper Labyrinth Canyon	16088	789	0.0002	135	1547	11	800	5.9	0	0
below Gunnison Valley	16490	789	0.000572	153	4426	29	1000	6.5	0	0.14
Green River Valley	14093	789	0.0008	178	6190	35	4700	26.4	0	0.15
Grey Canyon	14929	789	0.00132	109	10213	94	500	4.6	0.29	0.36
Lower Desolation Canyon	16088	789	0.00204	108	15783	146	500	4.6	0.19	0.64
Middle Desolation Canyon	16120	789	0.00107	125	8279	66	700	5.6	0.12	0.35
Upper Desolation Canyon	16860	789	0.000245	164	1896	12	1400	8.5	0.01	0.03
southern Uinta Basin	16023	789	0.000189	213	1462	7	1800	8.5	0	0
central Uinta Basin (south)	16490	789	0.000194	207	1501	7	5000	24.2	0	0
central Uinta Basin (north)	15332	621	0.000235	141	1431	10	7000	49.6	0	0
northern Uinta Basin	13675	621	0.000235	188	1431	8	5000	26.6	0	0.02
downstream from Split Mountain	16088	621	0.000985	132	5998	45	800	6.1	0	0.87