Geomorphology of Post-Glen Canyon Dam Fine-Grained Alluvial Deposits of the Colorado River in the Point Hansbrough and Little Colorado River Confluence Study Reaches in Grand Canyon National Park, Arizona

FINAL

by

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Glen Canyon Environmental Studies

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October 13, 1995

David L. Wegner, program manager
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U.S. Bureau of Reclamation
P. O. Box 22459
Flagstaff, Arizona 86002-2459

FINAL

Dear Dave,

Enclosed please find copies of two reports in partial fulfillment of the obligations of Cooperative Agreement No. 2-FC-40-12880. One report summarizes the map unit descriptions of all surficial maps developed in this project. The second report is an interpretative report discussing some of the implications of our results. Computer files of all maps for sites 3 and 5 have already been submitted to ~~you.~~ PATRICK WRIGHT, COR/DENVER.

At this time, we enclose 6 copies of the interpretative report and one copy of the map unit description report. The other five copies of this report will be submitted next week, as soon as our map printer is running again.

Thank you for the opportunity to work with GCES on this project.

Sincerely,

Jack

John C. Schmidt

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COLLEGE OF NATURAL RESOURCES

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ABSTRACT

Geologic mapping of fine-grained alluvial deposits along the Colorado River in the Point Hansbrough and LCR (Little Colorado River) confluence study reaches shows that large proportions of fine-grained deposits form within eddies. Linear channel-margin deposits are common in reaches where debris fans are very large, very small, or non-existent, such as the Big Bend area of the LCR confluence study reach. Post-Glen Canyon Dam deposits comprise geomorphically distinct surfaces associated with (1) the flood level of summer 1983, (2) the high flow level of 1984 to1986, and (3) power-plant releases that occurred after 1986. The combination of different formative discharges and different depositional facies creates a mosaic of post-dam alluvial deposits in this reach. The areal extent of these deposits is less than their extent interpreted from 1935 aerial photography. Inactive primary-eddy return-current channels, that constitute nursery habitat for humpback chub in the post-dam river, exist in all years of photography that were analyzed. Analysis of photographs from different years shows that fine-grained deposits gradually erode; since 1986, the area of high-elevation deposits has decreased with time and the area of low-elevation deposits has increased with time. Aggradation in eddies in the Tapeats gorge downstream from the Little Colorado River was widespread in winter 1993, but aggradation was much more restricted in the Big Bend area.

INTRODUCTION AND PURPOSE

Although the Grand Canyon is well-known as one of Earth's most spectacular bedrock gorges, much of the Colorado River is discontinuously lined by fine-grained alluvial sediments of Holocene age. These sediments have been deposited by a wide range of discharge. Relatively little geomorphic research has focused on these deposits, except for those studies concerned with reconstruction of paleoflood hydrology (O'Conner and others, 1994). However, issues of environmental management, especially since creation of the GCES (Glen Canyon Environmental Studies program of the U.S. Bureau of Reclamation) in 1983, have redirected research interests, however. One management objective of Glen Canyon Dam, which regulates flow of the Colorado Riverthrough Grand Canyon, is the maintenance of the fine-grained alluvial deposits. Fine-grained alluvial deposits form beaches used as campsites by recreational boaters and are also the substrate of the riparian plant community. Expansive, unvegetated sand bars were a distinctive attribute of the pre-dam river corridor landscape, and are one goal of environmental restoration efforts.

The purposes of this study are to:

(1) map the surficial geology of selected parts of the Colorado River corridor of Grand Canyon National Park, with concentration on fine-grained alluvial sediments deposited after closure of Glen Canyon Dam;

(2) interpret the status of fine-grained alluvial deposits depicted on historical aerial photographs; and,

(3) analyze temporal and spatial patterns of sediment storage change by comparing the distribution of fine-grained alluvial sediments in different years.

The maps and interpretations are intended for use (1) in long-term monitoring of river corridor deposits, and (2) in development of hypotheses regarding the effect of anticipated habitat-building floods.

This report summarizes findings and analyzes data from mapping of two study reaches. Examples are drawn from surficial geologic maps and map unit descriptions from the companion report of Leschin and Schmidt (1995). Geographic information system files of all geologic data, within an Arc-Info format, were sent to the GCES under separate cover. The upstream reach described here begins 92 km downstream from Glen Canyon Dam and 68 km downstream from Lees Ferry, Arizona (Fig. 1). This study area, known as the Point Hansbrough reach, is approximately 10.5 km in length. The second reach begins 124 km downstream from Glen Canyon Dam and 100 km downstream from Lees Ferry. This area, known as the LCR (Little Colorado River) confluence reach, is approximately 20.5 km in length. The base maps of each reach are detailed 1:2400 scale topographic maps, prepared from June 1990 aerial photography that depict the river corridor with a 0.5-m contour interval. The Point Hansbrough reach is designated as GIS Site 3, and the LCR confluence reach is designated as GIS Site 5 by the GCES; this project was funded by the GCES.

METHODS

Geologic field mapping, aerial photograph interpretation, and computer-assisted geographic analysis were conducted in this project. Initial classification and mapping on the 1990 photography occurred in the office. Field work, conducted between 1991 and 1994, consisted of inspection of river corridor topography, excavations and stratigraphic descriptions, counting the rings of some buried trees, and revision of mapped contacts. Stratigraphic descriptions have been summarized by Rubin and others (1994) and Schmidt and Rubin (1995). Virtually the entire length of each study reach was inspected in the field. Compilation onto 1:2400 orthophoto base maps occurred in the office following all field work; these maps depict the distribution of alluvial deposits in June 1990.

The distribution of alluvial deposits in other years was interpreted from aerial photographs. These photos vary widely in quality and scale (Table 1). Identification and mapping of the distribution of deposits was made on overlays of these photos. Information was transferred from the overlays to the 1:2400 base maps using a stereo zoom transfer scope. Transfers were accomplished by rectifying known points, such as large boulders, on the historical air photos and on orthophoto base maps.

As described below, many map units of fine-grained or gravelly alluvium were classified by the discharge level that inundated them. Discharge levels and formative discharges are typically the same for fine-grained deposits, because these bars and banks are composed of suspended-load deposits. The discharge level is not the same as the formative discharge for gravelly deposits because inundation is insufficient for transport and deposition of gravel. In many cases, the relationship between the discharge level and mapped geomorphic surfaces was not obvious, and longitudinal profiles were used to assist in correlation. Profiles of the low-discharge water surface and the highest points of separation and reattachment bars within each discharge-level map unit were constructed using June 1990 topographic data. Estimates of the longitudinal profile of the maximum elevation of (1) the flood of 1983, (2) high flows that occurred between

1984 and 1986, and (3) powerplant flows were made. These longitudinal profiles were constructed by (1) identifying reattachment bars of a particular discharge level, (2) determining the elevation of the highest points of these deposits, (3) projecting these elevations onto a channel centerline and measuring the longitudinal distance along this centerline, (4) plotting a longitudinal profile of these elevations, (5) comparing the deviation of each point from the best-fit line through all these points, (6) reevaluating map units of deposits that differed greatly from the best-fit relation, and (7) recalculating the best fit line. In addition, direct observation and measurement of high discharge water stage was made in May 1985 and May 1986 at some sites.

Longitudinal correlation of the elevation of fine-grained deposits formed near reattachment points 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. Deposits formed near the reattachment point may be recognized by reversing flow directions [Rubin and others, 1990]; otherwise, the highest elevation part of reattachment bars is taken as the approximation of the water surface. The elevation of separation bars was not included in longitudinal correlations because the water surface of the upstream part of eddies, near the separation point, is lower than that of the reattachment point and 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 than the elevation of the adjacent downstream-flowing water surface.

Hand-drawn maps of each year's river corridor geology were then entered into an Arc-Info data base by referencing tick marks on the ortho-photo base maps. The U.S. Bureau of Reclamation conducted an accuracy assessment of the methods used in this study by comparing the location of common features identified on an aerial photograph and on our transferred data set as registered to a 1:2400 scale orthophoto base map. This assessment was conducted for 1 base map using the 1990 data set. Patrick Wright (D. P. Associates Inc., contractor to U.S. Bureau of Reclamation, 1995, written commun.) determined that the maximum error associated with this mapping and data transfer was 4 m (Appendix A). The error is greater for those maps whose original historical air photo data is of a small scale, such as those of 1935 and 1965. Measured areas of map units are accurate to the nearest 250 m^2.

Arc-Info computer files of surficial geology maps for each year are compatible with the GCES/NPS geographic information system data base. Maps showing the difference in the distribution of alluvial deposits between different years were used to analyze sediment storage change (Fig. 2). Erosion was interpreted wherever an alluvial deposit changed from a higher discharge level in one year to a lower level in a subsequent year. For example, if a deposit was mapped as "fluctuating flow (wet)" in 1984 and "fluctuating flow (submerged)" in 1990, the area was considered to have eroded during the intervening period. The area of erosion and deposition was measured, and statistics calculated for each eddy complex in each study reach. An eddy complex was defined as the contiguous area composed of the largest extent of reattachment, separation, and eddy bars mapped in all years (Fig. 3). There were 53 eddy complexes defined in the Point Hansborough study reach and 102 eddy complexes in the LCR study reach. Appendix B includes maps showing all eddy complexes in the two reaches.

Two measurements were made of the extent of change in the distribution of fine sediment within eddy complexes from year to year. In the LCR confluence reach, the relative proportion of each eddy complex that eroded during each time interval was calculated by dividing the total area of erosion or deposition within each eddy complex by the eddy complex area. In both reaches, we analyzed the response of each eddy complex by measuring the area of each map unit within each eddy complex in 1984, 1990, 1992, and 1993 (Appendix C). The area of sand at three topographic levels within each complex was calculated. These three levels were: (1) all sand at all levels, (2) all sand above base flow, and (3) all sand deposited between 1983 and 1986. The relative change in size of each eddy complex was then determined by dividing values for each complex by the 1984 value. Values less than 1 indicate that a particular deposit was smaller than it had been in 1984. Values between 0.75 and 1.25 were not considered significant. We determined the number of bars that were significantly smaller or larger than they had been in 1984, and we determined how these numbers changed from year to year.

History of River Flows and Discharge at the Time of Photography

The size and distribution of sand bars along the river are a function of the history of streamflow preceding the photography and river discharge at the time of photography. Sand bars are deposited at higher elevations by higher river discharges, and photographs preceded by high annual floods typically have more widely distributed sand bars at higher elevations. Because river discharge at the time of each photo series differs, it is necessary to account for water stage differences when comparing patterns of erosion or deposition among photo series. If a more recent photo series was taken at higher river stage, less sand is exposed even if no net erosion has occurred. If a later photo series was taken at a lower river stage than previous photos, analysis of change is biased to show aggradation. In all years except 1973, discharge at the time of photography of each reach was nearly steady and was estimated by correlation with nearby gaging stations (Table 1). Discharge at the time of the 1973 photographs varies with position along the river because of non-steady dam releases. Estimation of river discharge in each reach was based on time-of-travel estimates (Lazenby, 1987) and the extent of exposure of large rocks at study sites with known stage-to-discharge relations (Schmidt, unpubl. data) .

The history of streamflow in Grand Canyon can be divided into pre-dam and post-dam periods. The last year of unregulated streamflow was 1962, and Glen Canyon Dam was officially completed in March 1963. The 2-yr recurrence annual peak discharge of the Colorado River at Lees Ferry, Arizona, was 2148 m^3s^{-1} for the period 1923 to 1962, and was 796 m^3s^{-1} for the period between 1963 and 1993. Average annual peak floods during the 1930's and 1940's were similar and greater than the average floods of the 1950's (Fig. 4). The annual peak discharge in 1935 was 2970 m^3s^{-1}, and was approximately a 5-yr recurrence flood as calculated for the 1923 to 1962 period. Aerial photograhs were taken on December 31, 1935, at very low discharge (Fig. 5a).

Streamflow in 1963 and 1964 was very low, but high dam releases occurred between late April and late June 1965. Photos taken in 1965 occurred in the midst of these high releases (Fig. 5b). Bare, damp sand bars depicted in the 1965 photos had been submerged by flows as large as 1267 m^3s^{-1} that had occurred 6 dys prior to the photographs. The 1965 photographs were taken when discharge in the study reach was approximately 735 m^3s^{-1}, and flows subsequently rose to 1702 m^3s^{-1} approximately 1 mth after the photos were taken.

Dam releases were always less than the capacity of the Glen Canyon Dam powerplant during the period between the 1965 floods and the photography of 1973. In 1973, maximum hourly releases were approximately 850 m^3s^{-1} during most of April, but daily maximum releases were highly variable in May (Fig. 5c). Daily maximum releases were approximately 850 m^3s^{-1} for the 7 dys preceding the photographs. Releases were less than powerplant capacity for the rest of the 1970's, but high releases occurred in spring 1980 when Lake Powell reservoir filled for the first time. Annual peak discharge in that year was 1267 m^3s^{-1} (Fig. 4).

In 1983, the highest post-dam river discharges occurred; annual peak discharge at Lees Ferry was 2752 m^3s^{-1}. Mean daily discharge exceeded 2500 m^3s^{-1} for 1 dy, exceeded 2250 m^3s^{-1} for 8 dys, and exceeded 1750 m^3s^{-1} for 16 dys. High releases occurred again in 1984, 1985, and 1986 (Fig. 4). Dam releases utilized the by-pass tubes but not the spillways in these years and were very steady. For example, in 1984 mean daily discharge varied between 1230 and 1281 m^3s^{-1} for 37 dys (Fig. 5c). In 1985, mean daily discharge exceeded 1219 m^3s^{-1} for two periods of 19 and 11 dys, but the annual instantaneous peak discharge for the year of 1355 m^3s^{-1} was only 11 percent greater. In 1986, mean daily discharges were within 90 percent of the annual instantaneous peak for 21 consecutive dys.

In 1984, daily discharge was approximately 735 m^3s^{-1} for 45 dys prior to precipitous decrease of dam releases to 141 m^3s^{-1} for the particular days when the photographs were taken (Fig. 5d). Sand bars photographed in this series reflect the influence of very high flows that had occurred 15 mths earlier, high flows that had occurred 3 mths earlier, and steady discharges that had occurred until the 2 dys immediately preceding the photographs. Previously active bedforms are evident on many bars that had been subaerially exposed for only 2 dys and on some bars that had been exposed for 3 mths; bedform migration directions at high power-plant discharge can be determined from these bedforms.

Discharge at the time of the 1990, 1992, and 1993 photographs was steady. Photographs taken in 1990 reflect the effect of 3 yrs of hydroelectric peak power production that occurred after 1986 (Fig. 5e). Photographs taken in 1992 reflect the effect of 2 yrs when dam releases were either constrained for the purpose of (1) testing the effects of alternative discharge regimes, or (2) minimizing downstream erosion under the interim flow rules (Fig. 5f). Photographs taken in 1993 record the effect of unusually high winter discharges of the Little Colorado River (Fig. 5g). Unvegetated sand bars are common in much of the LCR confluence study reach.

DESCRIPTION OF STUDY REACHES

Point Hansbrough Reach

The Point Hansbrough reach is within Marble Canyon, a narrow, deep canyon upstream from the Grand Canyon. Physiographically, Grand Canyon begins near the confluence of the Colorado River and Nankoweap Creek. In this study reach, the distance across the canyon, as measured from rim to rim, is between 3100 and 4300 m, and the canyon is approximately 950 m deep. Along the river corridor, the cross-sectional distance between bedrock outcrops is between 150 and 300 m, and the average channel width is about 100 m. The only named tributaries to the Colorado River in this study reach are Tatahoysa Wash and Saddle Canyon.

Bedrock at river level along the river corridor is the Cambrian Muav Limestone. Channel width-to-depth ratio in the study reach, as measured at 5 cross-sections in fall

1983 at a discharge of 679 m^3s^{-1}, was between 16.3 and 26.8, and channel depths were between 4.1 and 6.3 m (U.S. Geological Survey - WRD, Tucson, written commun.). The study reach is entirely within what Schmidt and Graf (1990) call Lower Marble Canyon (river miles 40 to 61.5[1]) and what Smith and Wiele (J. D. Smith and S. M. Wiele, Flow and Sediment Transport in the Colorado River between Lake Powell and Lake Mead, unpubl. U. S. Geological Survey - WRD report) term the Mid and Lower Paleozoic Limestone reach (river miles 23 to 50). Lower Marble Canyon's average gradient of 0.0010, as determined from the 1927 survey of the river, is the second lowest of any reach of Grand Canyon (Schmidt and Graf, 1990, table 2). As measured on the large-scale topographic maps used in this study, the average gradient over the 10.5-km study reach is 0.00072. The steepest part of the study reach is at the apex of the river bend around Point Hansbrough where the canyon intersects the Eminence Break fault (Fig. 6). In contrast, the section near Triple Alcoves and Saddle Canyon is very flat despite the fact that the Saddle Canyon debris fan is the largest in the study reach.

In this study area, large debris fans exist at the mouths of each tributary whose drainage basin is greater than about 1 km^2. Large fans occur (1) on river left (as viewed facing downstream) where the Colorado River flows around Point Hansbrough, and (2) on river right at Triple Alcoves and Saddle Canyon (Fig. 7). Smaller fans occur downstream from Saddle Canyon. Fine-grained Colorado River alluvial deposits exist along both banks between river miles 42 and 43, river miles 45 and 46, and downstream from Saddle Canyon. These deposits also exist in association with each large debris fan. There are two prominent gravel bars in the channel: one downstream from President Harding Rapid and one near river mile 48. Eolian dunes, composed of reworked river alluvium, occur on the highest parts of some debris fans, but are uncommon.

LCR Confluence Reach

This study area is in the upstream end of Grand Canyon. In contrast to Marble Canyon, the canyon rims adjacent to the study reach are relatively far apart; the distance between north and south rims is between 9700 and 14,500 m. The canyon is also much deeper here than in Marble Canyon; elevations of the north and south rims near the study reach are 2410 and 2290 m above sea level, respectively, while the elevation of the river at the downstream end of the study reach is 800 m above sea leval.

[1] Locations along the Colorado River are described by River Mile, as established by the U. S. Geological Survey (1922) and shown on the 1:2400 scale base maps of the U. S. Bureau of Reclamation. These locations refer to the distance downstream from Lees Ferry, Arizona; thus, River Mile 42 is located 70 km downstream from Lees Ferry.

Two distinct lithologies are exposed at river level and give rise to two very different canyon profiles within this study reach. Upstream from Palisades Creek at river mile 65.4, bedrock at river level is the resistant Cambrian Tapeats Sandstone or the lower member of the Precambrian Dox Sandstone (Billingsley and Elston, 1989), and we informally refer to this section of the study reach as the Tapeats gorge. Vertical cliffs and ledges dominate the near-river environment; the cross-sectional distance between bedrock outcrops along the river is between 120 and 180 m. Downstream from river mile 65.4, the erodible upper part of the Dox and the overlying Cardenas Basalt are exposed at river level. This part of the study reach is termed the Big Bend area (Billingsley and Elston, 1989). The canyon is much wider in this reach; riverside hillslopes are gently sloping, and the cross-sectional distance between bedrock outcrops is between 240 and 470 m. Named tributaries to the Tapeats gorge are Sixtymile Creek, Little Colorado River, and Carbon Creek, and named tributaries in the Big Bend area are Lava Creek, Palisades Creek, Espejo Creek, Comanche Creek, Tanner Canyon, Basalt Creek, and Cardenas Creek.

Channel width-to-depth ratio in the study reach, as measured at 13 cross-sections at a discharge of 679 m^3s^{-1}, was between 15.2 and 67.1, and channel depths were between 2.7 and 10.5 m (U. S. Geological Survey - WRD, Tucson, written commun.). In the Tapeats gorge, channel width-to-depth ratios were between 15.2 and 21.7, and these ratios were between 17.3 and 67.1 in the Big Bend area. As measured on the large-scale topographic maps used in this study, the average gradient of this reach is 0.00163. The steepest parts of the reach are in the Big Bend area, presumably because the channel bed is composed of gravel (Fig. 8).

Debris fans are common in the Tapeats gorge (Fig. 9); 13 occur in a 4.5-km reach downstream from the Little Colorado River (Fig. 8). In the Big Bend area, the frequency of debris fans decreases. Fans in the Big Bend area are very large, and in some cases an individual fan borders the Colorado River for a distance of more than 600 m (Fig. 9b).

OVERVIEW OF THE GEOMORPHOLOGY AND SEDIMENTOLOGY OF ALLUVIAL DEPOSITS IN GRAND CANYON

The principal geomorphic elements of the Colorado River corridor in Grand Canyon are (1) debris-flow deposits that form fans at the mouths of tributaries, (2) fine-grained alluvial deposits, and (3) gravel bars. These elements are arranged in a distinctive assemblage termed the fan-eddy complex (Schmidt and Rubin, 1995). The number, size, and characteristics of these complexes are related to the frequency of tributary junctions, the size and characteristics of fans, the frequency and magnitude of the debris flows that replenish fans, and the frequency and magnitude of main channel floods that rework fans.

Upstream from each debris fan, a backwater of low velocity may extend several kilometers (Leopold, 1969; Kieffer, 1985; Miller, 1995), and fine-grained alluvium may line these banks. Immediately downstream from each debris fan, channel cross-section area increases, and eddies may occur along one or both channel banks, depending on the relation between the orientation of main channel flow and the orientation of the banks. These eddies vary greatly in length and width depending on discharge; eddies are longer at higher discharges. The downstream end of eddies typically occurs where (1) flow accelerates over or around a cobble/gravel bar, (2) the channel narrows, or (3) main channel flow impinges on a curving channel bank (Schmidt and others, 1993). At low flow, many eddies terminate at exposed reattachment bars which had formed previously at higher discharges.

Wilson's (1986) side-scan sonar surveys of the Colorado River show that the percentage of the bed 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 as suspended load and as bed load in the form of ripples and dunes. Some of the suspended load, which also includes silt and clay, is deposited as bars and along the channel banks. The suspended load diffuses or is advected into eddies where it is deposited (Andrews, 1991; Nelson and others, 1994); thus, the size distribution of eddy bar sediments and measured suspended sediment loads are similar (Howard and Dolan, 1981; Schmidt, 1990; Schmidt and others, 1993).

Eddy bars have distinctive topography and locations relative to the geometry of recirculating flow (Schmidt, 1990). Separation bars form near the flow-separation point and mantle the downstream side 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. Although Kearsley and others (1994) and Schmidt and others (1995) used this classification of eddy bars for purposes of assessing long-term change in sediment storage, no studies have mapped the detailed distribution of fine-grained bars and banks in an effort to assess the adequacy of this classification scheme.

Schmidt and Rubin (1995) described the general sedimentology of fine-grained alluvial deposits in canyons with abundant debris fans. Separation and reattachment bars often have multiple topographic levels. Typically, separation bars are of higher elevation and have 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 and others, 1994). In all cases, reattachment bars are composed of sedimentary structures indicative of rotary flow. Similar to the pattern described by Rubin and others (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 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; saltcedar are dense at these sites. Excavations of these levees reveal foresets indicating transport onshore and 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.

Gravel bars are common upstream from constrictions within backwaters of debris fans, and downstream from large eddies. These bars either exist in mid-channel, 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. These bars are only entrained at high discharges.

PREVIOUS GEOMORPHIC RESEARCH IN THE STUDY REACHES

Parts of the Big Bend area have been intensively studied by Hereford (1993) and Hereford and others (1993, 1995). The primary focus has been on the relation between surficial geology and archeologic sites in four areas: (1) upstream from Unkar Rapid, (2) downstream from Basalt Creek, (3) near Tanner Canyon, and (4) near Palisades Creek. Surficial geologic mapping at scales between 1:1000 and 1:2000 was conducted, and numerous relative and absolute dating techniques were used to establish an alluvial chronology for these study sites. Five distinct pre-dam fine-grained alluvial deposits were identified and form terrace and terrace-like landforms. The earliest of these alluvial deposits are the "striped alluvium" and the "pueblo alluvium" which each contain archeologic remains. Deposition of the striped alluvium probably began about 400 B.C. and continued for about 700 yrs. Deposition of the pueblo alluvium began about 700 A.D., and the deposit contains some Pueblo I archaeologic material and contains locally abundant Pueblo II ceramic material.

Two other pre-dam terraces, the "upper and lower mesquite terraces," are topographically lower than the striped and pueblo terraces. Vegetation on these terraces is the old high water zone of various riparian ecological studies. Hereford and others (1993) state that the upper mesquite terrace was inactive by 1890 but that the lower mesquite terrace was overtopped by the July 1884 flood that has been estimated to have had a peak discharge of 8,500 m^3s^{-1}. Hereford and others (1993) also identified a "pre-dam alluvium" surface that is topographically lower than the lower mesquite terrace but is higher than deposits formed by high discharges of 1983. The pre-dam alluvium has large, mature, and partially buried saltcedar (*Tamarix chinensis* Lour.). Hereford and others (1993) state that dates obtained from two trees indicate germination in 1937 and 1951 on this surface, and they state that this surface aggraded during the larger floods of the 1930's and 1957. Hereford (1993) identified 3 post-dam deposits: "flood sand of summer 1983," "high flow sand" deposited between 1984 and 1986, and "fluctuating flow sand." Hereford (1993) mapped the locations of these post-dam deposits as they were distributed in 1989 and 1990; the depositional facies of eddy bars and channel-margin deposits were not mapped. These map units conform to map units identified in this project.

Large-scale geomorphic descriptions of the study reaches and of specific fan-eddy complexes and measurements of topographic changes in sand bars are reported by Howard and Dolan (1981), Beus and others (1985), Schmidt and Graf (1990), and Kaplinski and others (1995). Graf and others (1995a, b) have depicted the bathymetry of parts of the Colorado River channel between the Little Colorado River confluence and Tanner Rapid. Rubin and others (1994) describe the stratigraphy and sedimentology of some bars within the study reaches.

HOLOCENE GEOLOGY OF THE STUDY REACHES AND DISTRIBUTION OF DEPOSITS IN JUNE 1990

Debris fans

Debris flows originate beyond the river corridor by stream flow or rainfall onto the clay-rich shales that form flat-lying slopes within Grand Canyon. Debris flows in Grand Canyon have been described by Webb and others (1989), and the magnitude and frequency of these events have been analyzed by Melis and others (1994). Hereford

(1993) and Hereford and others (1995) distinguish debris-flow deposits of different ages. In our study, no such distinctions were made for the older parts of debris flows, however, new debris flows that occurred since 1990 were specifically mapped. Table 2 lists the tributaries where these new debris flows were identified, as well as the year of their occurrence and the size of the resulting deposit.

Gravel deposits

Bars composed of gravel- and cobble-size clasts with a sandy matrix (Kondolf and others, 1989) are prominent in some parts of the study reaches (Fig. 6 and 9). There are two large bars in the Point Hansbrough reach -- one between President Harding Rapid and Eminence Break camp and the other at river mile 48. In the LCR confluence reach, cobble/gravel bars are common at the Little Colorado River confluence, elsewhere in the Tapeats gorge, and throughout the Big Bend area.

Eolian dunes

In the Point Hansbrough reach, eolian dunes exist near the apex of three debris fans near President Harding Rapid and at Saddle Canyon. In one case, inversely-graded high-angle tabular cross-stratification is evident and unambiguously confirms the eolian interpretation of the deposit. At the other sites, determinations were made based on landform characteristics.

There are few eolian dunes in the Tapeats gorge. In the Big Bend area, dunes are common on the upper surface of many large debris fans and gravel bars such as those at Palisades Creek, Comanche Creek, Tanner Canyon, Basalt Creek, and Cardenas Creek. Hereford (1993) termed these features copice dunes and active slipfaces are typical.

Pre-dam Terrace Deposits

Terraces, predominantly composed of very-fine sand and silt, pre-date closure of Glen Canyon Dam and are common in both study reaches in the vicinity of large debris fans. Extensive terrace deposits occur (1) upstream and downstream from individual debris fans near Point Hansbrough, (2) near Triple Alcoves and Saddle Canyon (Fig. 10a), (3) near river mile 48.5, and (4) in the Big Bend area. These terraces are discrete features located upstream from large debris fans, at flooded tributary mouths, or downstream from large debris fans. These terraces are not long linear features characteristic of terraces on alluvial rivers.

Exposures, such as in the unnamed stream draining Eminence Break debris fan, show that terrace deposits are comprised, in part, of climbing ripple cross-stratification. Some of this cross-stratification includes structures that are supercritically climbing, similar to deposits described by McKee (1938). Exposures in many ephemeral drainages show that alluvial deposits are interbedded with tributary alluvium and colluvium.

Reconnaissance stratigraphic observations were made in this investigation, and dates were not determined for the terrace deposits. However, stratigraphic and topographic relations suggest that multiple terraces exist. This observation is consistent with that of Hereford (1993) and Hereford and others (1993, 1995). Upstream from President Harding Rapid and downstream from Triple Alcoves riffle within the Point Hansbrough study reach, there are extensive areas of relatively low-elevation surfaces on which are found large, presumably old, saltcedar that are partially buried by fine-grained silt and very fine sand. These surfaces are termed the "high tamarisk terrace" in this study. Driftwood lines less than 1 m above this surface include railroad ties and sawn timber. The similarity of vegetation characteristics and topographic position between this terrace and the "pre-dam alluvium" mapped by Hereford and others (1993) in eastern Grand Canyon suggests that the two units are correlative .

Distinctions were not made concerning higher, and presumably older, terraces that might correlate with the "striped alluvium" and "pueblo alluvium" of Hereford and others (1993), although two such distinct levels were identified upstream from the debris fan at President Harding Rapid, at Saddle Canyon, and at some other sites. The highest terraces grade into eolian dunes, such as on the upper part of the debris fan at Eminence Break camp and the debris fan at river mile 48.5R.

Post-dam fine-grained Colorado River deposits

Post-dam Colorado River alluvial sediments were mapped as those deposited in 1983, those deposited between 1984 and 1986, and those deposited since 1986 (Fig. 10). The 1983 deposits are termed "flood level of 1983" in our classification, which is a map unit similar to that established by Hereford and others (1993). These deposits exist at several topographic levels because flood discharges in 1983 were not steady.

Because the annual peak discharges in each year between 1984 and 1986 were very similar, it is not possible to distinguish deposits of any of these years in the field based on topography. Rubin and others (1990) distinguished different years of deposition at one site by excavating trenches and recognizing the presence of eolian sedimentary structures between fluvial deposits. These deposits are collectively mapped as "high flow level of 1984-86." Photography taken in October 1984 was especially helpful in distinguishing these deposits from those formed in 1983. The 1984 photos were taken 3 mths after recession from spring peak flows of that year and 15 mths after recession from the 1983 high flows. The associated deposits had not yet been substantially reworked or colonized by vegetation, and distinct geomorphic surfaces and extensive areas of bare sand are evident in these photographs.

Fluctuating flow deposits are those that were formed after 1986. They were distinguished as the "submerged" level, "wet" level, and "fluctuating flow" level in each year of photography. Water clarity was high in all reaches in 1990, 1992, and 1993, and submerged deposits are abundant in these years. Upstream from the Little Colorado River, clarity was also high in 1973 and 1984. Clarity was low in other reaches and at other times. The contact between wet and dry sand is sharp in most cases, and wet sand areas occur at lower elevations than do areas of dry sand. Wet sand areas also include low elevation areas covered by a veneer of dark color silt or clay. It was assumed that this contact represents a pseudo-topographic level because the sediment sizes of fine-grain eddy bars are similar (Schmidt, 1990) and the magnitude of capillary rise is assumed to be similar.

Depositional facies of post-dam fine-grained Colorado River deposits

Fine-grained alluvial deposits in both study reaches are classified as either eddy bars or channel-margin deposits (Fig. 11). Eddy bars were subdivided into reattachment and separation bars where possible, especially where the primary eddy return current channel was obvious. In these cases, as well as in cases where a fine-grained deposit occurred in the lee of an obstruction, the term "undifferentiated eddy bar" was applied.

Reattachment bars exist downstream from most debris fans or talus cones in the study area. Reattachment bars vary in size from those that fill the entire channel expansion to those which fill only the downstream part. When these bars fill the entire eddy, primary-eddy return-current channels may not be well developed. Reattachment bars are numerous and are large landscape elements near Point Hansbrough and downstream from Triple Alcoves in the Point Hansbrough reach. Reattachment bars occur in the lee of many debris fans in the Tapeats gorge but less frequently in the Big Bend area.

Channel-margin deposits line much of the river corridor where debris fans are small or absent. This map unit was applied to all fine-grained alluvial deposits that do not have topography characteristic of eddy bars. Within the Point Hansbrough study reach, these areas are between river miles 42 and 43, river miles 45.3 and 46.8, and near river mile 48. The longest continuously mapped channel-margin deposits occur between river miles 42 and 43 and near river mile 45.5 where individual units may be as much as 275 m in length. There are also extensive channel-margin deposits in parts of the Big Bend area. These channel-margin deposits typically slope gently away from the river channel and some may have sharp-crested levees parallel to the channel. In most cases, channel-margin deposits have steep banks that drop to a lower, and younger, surface or to the water's edge.

Occasionally, channel-margin deposits occur in isolated areas near the apex of debris fans and are composed of clean sand that slopes continuously to the water's edge. These areas do not fit the criteria for separation bars because they are not located on the downstream part of the debris fan. These deposits are probably formed in association with eddies, but the relationship is not clear.

A number of excavations and stratigraphic descriptions were made within the study areas. In all cases, 1983 deposits are thick and extensive. Deposits created between 1984 and 1986 are thin, despite the presence of continuous topographic levels formed by these discharges. These characteristics are consistent with descriptions made by Rubin and others (1994) and Schmidt and Rubin (1995).

DISTRIBUTION OF FINE-GRAINED ALLUVIAL DEPOSITS

The area of fine-grained alluvial deposits and the relative proportion of those deposits that form within eddies varies widely along the river. Fine-grained alluvial deposits are largest in the Big Bend area; the area of fine-sediment along the river in this reach is between 64,000 and 154,000 m^2 km^{-1} (Table 3). In the Point Hansbrough reach and in the Tapeats gorge, the area is less than 57,000 m^2 km^{-1} and is as low as 18,000 m^2 km^{-1} in the Tapeats gorge. These values are very small in comparison to typical alluvial valleys with meandering channels; the equivalent width of fine-grained alluvial deposits that continuously lines the channel never exceeds 12 m in the two study reaches. Eddy deposits comprise a large proportion of all fine-grained alluvium in the Tapeats gorge and in parts of the Point Hansbrough reach (Fig. 12).

The flow regimes of 1983, 1984-86, and post-1986 have each left their imprint on the Colorado River corridor, and the proportion of all deposits formed by each of these three flow regimes varies longitudinally. Fluctuating flow deposits formed since 1986 comprise the largest proportion of deposits in the Tapeats gorge and in parts of the Point Hansbrough reach (Fig. 13); elsewhere, deposits formed in 1983 comprise the largest portion of all deposits.

Figure 14 shows that there is a 0.5 m scatter around the estimated water-surface for each of the discharge levels. In many cases, the scatter is due to the fact that the water surface at higher discharges has a stair-stepped profile characteristic of the low-discharge water surface. Two other sources of error are the use of 0.5-m topographic base maps for the determination of bar surface elevations, and the assumption that all reattchment bars build to the water surface. Scatter of the data for the flood level of 1983 is greater than for other levels because these deposits probably formed at several discharges. There is good agreement in the Point Hansbrough study reach between the estimated water-surface elevation based on this geologic evidence and a surveyed water surface slope measured in May 1985 at Eminence Break camp (Fig. 14a).

CHARACTERISTICS AND SPATIAL CHANGES OF FINE-GRAINED COLORADO RIVER DEPOSITS IN DIFFERENT YEARS

Map Units Used in 1935, 1965, and 1973

The designations "flood level of 1983" and "high flow level of 1984-86" have no application in the interpretation of photographs taken in 1935, 1965, or 1973. Map unit designations of discharge levels applied to sand deposits in these years are "submerged," "wet," "clean," and "upper." Submerged and wet levels were identified by the same criteria as used in the mapping of 1990 deposits, as described above. The "clean" level was applied to those dry sand deposits that were composed of nearly uniform white sand and on which there are no plants. The "upper" category was applied to areas topographically higher than clean levels and lower than high terrace levels.

Map Units Used in 1984, 1992, and 1993

Map units used in these years were the same as those used for the 1990 photography. The 1984 photography provide excellent data concerning flow levels because fluctuating flow deposits had been submerged until 2 dys prior to the photos and previously submerged bedforms are distinct. Deposits of the high flow level of 1984 had been subaerially exposed for only 3 mths and deposits of the flood level of 1983 had only been exposed for about 15 mths. Clean sand deposits at the highest elevations of the fluctuating flow level exist in the 1993 photographs downstream from the Little Colorado River. These deposits were formed in January and February 1993 when the Little Colorado River had three large peak flows (Fig. 5g).

The River Corridor in 1935

Sand bars are extensively exposed in these photographs; discharge at the time of these photographs was about 108 $m^3 s^{-1}$, which is less than at the time of any other photographs analyzed in this project. Interpretation of these photos was hampered by their very small scale and by deep shadows. Areas of old high water zone vegetation exist at some sites, especially in the Big Bend area, but for the most part, the river corridor is comprised of water, bare deposits of fine-grained alluvium, terraces, talus, debris fans, and bedrock (Fig. 15). Clean sand deposits extend to high elevation and were presumably deposited by that spring's flood. Most of the large gravel bars in the Big Bend area that exist in mid-channel or as alternate bars in subsequent years are overlain by sand in these photos. Areas of stagnant water in abandoned eddy return-current channels exist in some locations, although there are generally fewer such areas than in subsequent years. Some eddy complexes which did not have sand bars in the period 1965 to 1992, such as EC25 and EC29 (Fig. 3 and 15b), were filled with sand in 1935.

The River Corridor in 1965

Only high-elevation parts of sand bars are exposed in this photo series because the discharge at the time these photos were taken was between 700 and 760 m^3s^{-1} (Table 1). There are extensive clean and unvegetated separation and reattachment bars in these photos, which indicates that bars at elevations comparable to the "high flows of 1984-86" and "flood of 1983" levels were widespread in 1965 (Fig. 16). The distribution of these newly deposited bars in 1965 provides an indication of the size of eddies at a discharge of 1267 m^3s^{-1}, which was the peak discharge that had occurred 6 dys prior to the photos. Large, newly-deposited sand bars exist near every large debris fan at the apex of Point Hansbrough except President Harding Rapid; large accumulations of sand also exist at Triple Alcoves, Saddle Canyon, and a few unnamed sites further downstream. In the Tapeats gorge of the LCR confluence reach, newly deposited reattachment bars are rare and small; bars at the Hopi Salt Mines and Carbon Creek are the only ones of large size. Stagnant flow in inactive eddy return channels exists at very few sites in these photos. However, there are some eddies where the spatial distribution of wet and dry sand demonstrates that these areas would exist at slightly higher, and also lower, discharges.

The River Corridor in 1973

Discharge at the time of these photos differs greatly in the two study reaches because of wide-ranging hourly fluctuations of discharge (Table 1). In the Point Hansbrough reach, discharge was between 142 and 283 m^3s^{-1}, which is the second highest discharge of any photo series used in this project. Reattachment bars appear to be of low elevation, because most of the bar platforms are "wet" (Fig. 17). There are large areas of stagnant flow in inactive eddy return channels in these photos, but these areas were likely eliminated at slightly higher discharges than those of the photos because the low-elevation bar platforms would be overtopped by recirculating flow. In the LCR confluence reach, discharge at the time of the photography was between 297 and 411 m^3s^{-1}, and the area of exposed sand bars is correspondingly small. These photos demonstrate that (1) primary eddy return current channels did form during years of wide ranging daily fluctuating discharge, and (2) areas of stagnant backwater habitat in these return channels probably only existed during the low-discharge period of each day.

Change that Occurred between 1973 and 1984

Discharge during the 1973 photography was more than twice the discharge at the time of the 1984 photography. Comparison of the distribution of exposed fluvial deposits is biased to indicate aggradation, because water-surface elevation in the later photo series is lower. Areas of degradation can be safely interpreted from the photos.

In the Tapeats gorge, small parts of many reattachment bars degraded during this time interval, but there was no consistent pattern to the location of these degraded areas (Fig. 18b). In some cases, the eroded areas had been broad eddy bars in 1973 and became eddy return current channels in 1984. This style of change is consistent with erosional styles described at specific sites (Schmidt and Graf, 1990). In the Big Bend area, erosion occurred in only three eddy complexes; elsewhere, there was essentially no erosion. Although aggradation is suggested in most eddy complexes, there is no way to evaluate the effect of water stage in causing the differences in the distribution of deposits.

The average proportion of each eddy complex in which erosion occurred was 0.073 for the LCR confluence reach; the proportion of each eddy where deposition occurred was more than twice as great, but the larger value may be entirely due to water stage differences (Table 4). In the Tapeats gorge, the value for areas of erosion was 0.062, and in the Big Bend area the value was 0.087. Eddy complexes upstream from the Little Colorado River confluence had a value of 0.062; downstream from the confluence, this value was 0.075. A few sites had large areas of erosion. Two of these sites are very large eddy complexes: EC65 and EC95 (Cardenas Creek, a critical marsh site). Large eddy complexes with significant areas of erosion were EC17, EC50, and EC101.

The River Corridor in 1984

These photographs show the effects of high discharges that occurred in 1983 and 1984. They also show the many barforms and bedforms that were inundated by the high power-plant discharges of about 735 m^3s^{-1} that had occurred during the previous 45 dys. Large reattachment bars fill most eddies (Fig. 2a and 19). The area of exposed sand is significantly greater than that exposed in 1973 but still less than that exposed in 1935. There are large areas of stagnant flow in inactive eddy return current channels.

Change that Occurred between 1984 and 1990

The general pattern of sand bar change during this period was that high elevation parts of sand bars were eroded, and the area of low-elevation sand within eddies increased (Fig. 2c and 20). The areas of new, low-elevation deposition were slightly larger than were the areas of erosion. Discharge at the time of the 1984 and 1990 photographs was the same; therefore, it is possible to evaluate erosional and depositional patterns. In the LCR confluence reach, the typical pattern of change occurred at some separation bars and at many reattachment bars. This style of change is consistent with trends measured by Schmidt and others (1989) during this period; sand deposited by high discharges of the period 1983 to 1986 was subsequently eroded by normal powerplant operations that occurred after summer 1986.

Comparison of the proportions of each eddy complex that aggraded or degraded also reflect the erosional and depositional adjustment. The mean proportion of each eddy complex in the LCR confluence reach that eroded during this period was 0.115, and the proportion that aggraded was 0.132 (Table 5). The erosion proportion value was about 0.6 times greater than the erosional proportion value for the period between 1973 to 1984. The aggradational proportion was less than the proportion for the 1973 to 1984 period, but the aggradation proportion for the period between 1973 and 1984 was biased because of water stage differences. Aggradational proportions for the period between 1984 and 1990 were the same in the Tapeats gorge and Big Bend area, but the erosional proportion was higher in the Tapeats gorge. Upstream from the Little Colorado River confluence, the proportion of each eddy complex that aggraded was higher and the area of erosion was lower than were the proportions downstream from the LCR; this suggests that sediment influx from the Little Colorado River dis not have a long-term effect on sand bar topography. Large eddy complexes with large areas of aggradation were EC8, EC44, EC65, and EC80; in each case, all of the aggradation occurred at low elevation. Large eddy complexes with large areas of erosion were EC42 and EC62, all of which occurred at high elevation.

The River Corridor in 1990 and 1992

Separation and reattachment bars are much smaller in 1990 than in 1984 in both study reaches (Fig. 2b and 21). There are large areas of very low-elevation sand, mapped as "submerged" or "wet," in the 1992 photography (Fig. 22). The newly created, low-elevation deposits were typically at sites where (1) such deposits had existed in 1973, and (2) where those deposits did not exist in 1984. The margins of most high-elevation sand deposits eroded between 1990 and 1992 while the lowest elevation parts of eddies aggraded (Fig. 23).

The mean proportion of each eddy complex in the LCR confluence reach that eroded during this period was 0.152, a higher value than in the 1973-84 or 1984-90 periods. The proportion of each eddy complex that aggraded was 0.106, a lower value than in the prior two periods (Table 6). Areas of erosion exceeded areas of deposition in Tapeats gorge, the Big Bend area, and downstream from the Little Colorado River. Only upstream from the LCR were the areas of erosion and deposition similar. No large or very large eddy complexes had large areas of aggradation, but EC42 and EC46 had large areas of erosion.

Change that Occurred between 1992 and 1993

Large parts of eddy complexes downstream from the Little Colorado River aggraded significantly in winter 1993, but complexes upstream from the Little Colorado River degraded. Aggradation was caused by the winter floods of 1993 of the Little Colorado River (Fig. 5g). These changes are evident by comparison of Figures 22b and 24 and by inspection of Figure 25. Several eddies that had no sand in 1992 became filled with sand in 1993. The mean proportion of each eddy complex in the LCR confluence reach that eroded during this period was 0.117, and the proportion that aggraded was 0.211 (Table 7). The deposition proportion was the largest measured in any time period of this study. There was a dramatic difference in the style of sand bar change above and below the Little Colorado River. Areas of erosion (0.121) exceeded areas of deposition (0.070) upstream from the Little Colorado River, but areas of deposition (0.238) were twice as large as areas of erosion (0.116) further downstream. Deposition areas were larger in the Tapeats gorge (0.254) than in the Big Bend area (0.154). Eddy complexes EC28, EC29, EC34, and EC50 had large areas of deposition. Upstream from the LCR, EC1 had a large area of erosion during the same period. Many medium and small-sized eddy complexes had large areas of erosion despite the fact that deposition of new sediment was widespread downstream from the LCR.

GENERAL TRENDS IN THE SIZE OF EDDY COMPLEXES: 1984 TO 1993

Although reach-average trends provide insight into the characteristic behavior of different river segments, the behavior of individual eddy complexes may be of more interest to river managers. The response of individual eddy complexes was analyzed by comparing the areas of sand deposits at different levels between 1984 and 1993. Results were tabulated by size of eddy complex, but the behavior of eddy complexes did not differ in most cases. Variability in the response of very small eddy complexes (less than 2500 m^2) was high, and no trends could be discerned. In all cases, high-elevation sand deposits that formed between 1983 and 1986 steadily eroded in subsequent years. In 1992, 45 percent of the high-elevation deposits in the eddy complexes of the Point Hansbrough reach were 0.75 times less than their size in 1984 (Table 8). In 1993, more than 40 percent of the high-elevation deposits in the eddy complexes of the LCR confluence reach were less than 0.75 times their size in 1984 (Fig. 26). Net erosion of sand deposits above a base flow discharge of approximately 141 m^3s^{-1} was also widespread between 1984 and 1992, and continued through 1993 upstream from the Little Colorado River confluence. Downstream from the Little Colorado River, aggradation in eddy complexes was widespread between 1992 and 1993. Sand within eddies was more widespread in 1993 than it was in 1984. Collectively, these trends further confirm the widespread erosion of older high-elevation sand downslope into eddies. Inspection of maps of sand-deposit change show that eddy return channels fill with sediment the area of low-elevation sand increases. Aggradation within eddy complexes downstream from the Little Colorado River between 1992 and 1993 appears to have compensated for the previous post-dam erosion of deposits at elevations between baseflow and the high ebb of powerplant discharges.

DISCUSSION

Implications for the Development of a Grand Canyon Sediment Monitoring Program

Schmidt and others (1993) realized that temporal changes in sediment storage in bars and banks could be measured in rivers with abundant debris fans because the large eddies in which bars occur do not change location. Eddy bars persist in specific zones of recirculation because the coarse-grained debris fans which obstruct the river channel give rise to flow separation, and these fans are rarely modified by the river. Although bars change shape with discharge, they remain within specific lateral separation eddies and do not migrate from eddy to eddy. Eddy bars do not migrate down the channel in a manner characteristic of alluvial rivers. 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 bars have been stable for long periods. Observations about 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 and others, 1994). Measurement of topographic changes of the bars provides an indication of system-wide reponse in sediment storage. The changing characteristics of eddy bars are the focus of topographic and photographic monitoring programs.

Numerous factors control the size and shape of eddies, as well as their hydraulic characteristics. Schmidt and Graf (1990) noticed that eddies differ greatly in size, but that they all elongate with increasing discharge. Schmidt (1990) suggested that long eddies develop where the width-to-depth ratio of the constricted channel is low, and Schmidt and others (1993) showed that downstream bars and channel geometry partly control eddy length. Numerical modeling confirms these field and laboratory observations (Nelson and others, 1995; Wiele and others, 1995). The diversity of natural conditions in Grand Canyon are such that individual eddies vary greatly in many characteristics. Thus, the development of a canyon-wide sediment monitoring program must account for the diversity of natural characteristics displayed by eddies.

One approach to development of such a monitoring program is to repeatedly survey a very large set of eddies such that the inherent variability of the system is included in the sample size. However, logistical considerations prevent field measurement of this many sites. Presently, 32 sand bars are measured annually by Kaplinski and others (1995); many other sites are photographed on a daily basis by Dexter and others (1994). The diversity of Grand Canyon is so large that it is unlikely that this number of monitored sites is sufficiently large to account for the inherent variability of sand bar response in Grand Canyon. Widespread trends can nevertheless be detected. The widespread trends, detected by repeated topographic measurement, include (1) the system-wide aggradation of many sites caused by the high flows of 1983 to 1986 (Beus and others, 1985), (2) the system-wide erosion of most bars following 1986 (Schmidt and others, 1988), and (3) the widespread aggradation in eddies that occurred in 1993 downstream from the Little Colorado River (Kaplinski and others, 1995). However, other trends have been detected only by photographic means because photographs are the only available data about Grand Canyon sand bars prior to 1974, and topographic measurements have been made at only a few eddy complexes. Analysis of photographs has shown that (1) there was significant erosion of sand bars between 1965 and 1973, (2) aggradation between 1983 and 1986 was not ubiquitous, and many sites eroded substantially, and (3) that catastrophic changes in bar topography can occur over short time periods (Dexter and others, 1994). The general conclusions of this study are consistent with those of Kaplinski and others (1995), and the significantly less invasive methods of this study suggest that air photo analysis of bar change may be a suitable substitute for annual sand bar measurement field trips.

The data that have been developed in this project provide the first opportunity to systematically analyze the behavior of all fine-grained deposits in Grand Canyon. The limitations associated with photo interpretation and analysis are sufficiently great that only large-scale trends can be detected at each complex; the advantage of photo interpretation and analysis is that the behavior of *every* complex can be analyzed in a consistent manner. Thus, analysis of the behavior of different complexes, and the classification of styles of response to changing river regime, provides an opportunity to develop a more comprehensive approach to identifying monitoring sites that are representative of the diversity of eddy bar and channel-margin deposit behavior in Grand Canyon.

The data included in this report are also of fundamental importance to the understanding of the dynamics of eddy bar behavior. The patterns of erosion and deposition within each eddy complex can be classified, and the channel geometry and associated hydraulics of each class of eddy bars can be characterized. Detailed analysis of the hydraulic determinants of sand bar response are beyond the scope of this project. Analysis of the geometric characteristics of the channel at stable and unstable sand bars will be conducted in a subsequent project. Results presented above, however, show that there are always bars that behave in a manner inconsistent with the general trend of sand bar behavior. Some bars aggrade while most degrade, and vice versa. The maps of this project can be the basis of an analysis of system-wide behavior against which the behavior of individual sites can be compared. Thus, further analysis of the data developed in this project provides an opportunity to (1) characterize the different styles of sand bar response to different river regimes, (2) characterize the channel geometry of each distinctive suite of eddy bars, (3) integrate these results with on-going modeling research in an effort to predict the behavior of each type of eddy complex in relation to different dam release regimes, and (4) integrate these data with biological data on the distribution of vegetation communities.

System-Wide Trends in Sediment Storage Change

The photographs of 1935 demonstrate that the characteristic landscape of the pre-dam Grand Canyon was rock, talus, sand, and water. Vegetation was a minor element of this river environment, and open clean sand bars were abundant. Comparison of the distribution of sand within eddy complexes shows that some complexes that rarely have had sand bars in the post-dam era, were filled with sand in 1935.

It is not fruitful to compare the distribution of sand between 1935 and 1965 because the water stage in the two photo series differs greatly. There is also a significant difference in water stages between 1935 and 1973 photography. Comparison of the distribution of sand bars between 1935 and 1984 shows that the total area of sand has decreased greatly in the post-dam era. This conclusion is consistent with Kearsely and others' (1993) documentation of irreversible decreases in campsites that occurred between 1965 and 1973. The most distinctive change in sand bar distribution between 1935 and 1984 is that separation and reattachment bars are much more recognizable in 1984 photography. In earlier photographs, sand is dispersed throughout the entire eddy complex, but well-defined sand bars near the flow stagnation points exist in the 1984 photography. Interpretation of 1935 photos recognizes few separation or reattachment bars.

Between 1973 and 1984, about 7 percent of each eddy complex in the LCR confluence reach eroded. Depositional trends could not be evaluated because of differences in water stage, but deposition at many high-elevation sites is well-known from sedimentologic studies. A few eddy complexes had unusually high proportions of their deposits that eroded during this period. One very large eddy complex that extensively eroded was the Cardenas Marsh site. Thus, despite well-documented aggradation throughout Grand Canyon during the later part of this time interval, some sites extensively eroded.

Between 1984 and 1990, there was substantial adjustment of the topographic distribution of sand within eddy complexes. In the LCR confluence reach, the area of each eddy complex that aggraded (13 percent) and eroded (12 percent) were similar. Tabulation of the specific history of change of each eddy complex in the two reaches shows that the area of sand deposited between 1983 and 1986 eroded at many sites to less than 75 percent of the 1984 area. However, there was little change at these sites in the total area of all sand at all elevations. Inspection of maps, such as Figure 2c and 20, shows that the highest parts of these eddy bars eroded while low-elevation parts of the same sites aggraded. Thus, eddy bar topographic relief tended to decrease. Nevertheless, there were some large eddy complexes that significantly aggraded or degraded during this period.

Similar trends were measured between 1990 and 1992. In the LCR confluence reach, slight differences in the areas of each eddy complex that aggraded (11 percent) and eroded (15 percent) suggest more extensive erosion than was measured between 1984 and 1990. Data from individual sites is consistent with this conclusion, and demonstrates continued downslope movement of sand and widespread deposition at lowest elevations. A few complexes had unusually large areas of erosion and none had unusually large areas of aggradation.

Aggradation of new sand downstream from the Little Colorado River was widespread in the Tapeats gorge. Twenty-four percent of each eddy complex aggraded between 1992 and 1993, and only 12 percent of each complex eroded. Upstream from the Little Colorado River, the spatial patterns differed greatly; only 7 percent of each complex aggraded and 12 percent eroded. At least 50 percent of all complexes in the Tapeats gorge increased in area to sizes that exceeded their 1984 condition.

The Distribution of River Corridor Deposits

Although there were approximately 40 different map units used in this project, fine-grained alluvium can be broadly classified as either channel-margin deposits or eddy bars. The large number of map units is caused by the different inundation discharges within each type of deposits, as well as by the recognition of separation bar, reattachment bar, and channel-margin facies. The determination of inundation discharge level was critical to the recognition of patterns of erosion and deposition; mere mapping of the total extent of sand bars is inadequate in the assessment of change.

Eddy deposition processes are the dominant alluvial process in some parts of Grand Canyon, but eddy are less important in other reaches, such as the Big Bend area. The strong emphasis on eddy process modeling in the GCES research program is an appropriate orientation towards understanding sedimentation in the narrow, debris fan dominated parts of Grand Canyon. Other research strategies would be better suited towards the understanding fluvial processes in the Big Bend area, and perhaps elsewhere in Grand Canyon.

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 with abundant debris fans may also help define which dam-controlled discharges are of most importance in managing the downstream environment.

The effective discharge may be defined as the modal value of the product of streamflow frequency and sediment transport rate. This determination is therefore dependent on (1) the number of years that are evaluated, (2) the magnitude of floods that have occurred within the evaluated period, and (3) changes in sediment storage and supply which may affect the sediment transport rate from year to year. 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, the time period must be consistent with the duration over which a particular reservoir operating rule is in effect, because the frequency and magnitude of floods on a regulated river are determined by the hydrology of the drainage basin and by the prevailing operating rule of the controlling reservoir. If the operating rule changes, then the statistical distribution of downstream releases will change and the effective discharge will change.

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, 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 appropriate suspended sand-transport rate. 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.

Between 1965 and 1980, the operating rule for Glen Canyon Dam was to completely control floods so as to fill Lake Powell 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 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 (Fig. 4). The cumulative duration of hourly releases from Glen Canyon Dam that exceeded powerplant capacity was 0.2 percent between 1966 and 1980. During the filling of the reservoir (1965 to 1980), the effective discharge curve of the Colorado River in Grand Canyon has a single mode (Figure 27). 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 $m^3 s^{-1}$, but significant amounts of sand were transported by discharges as low as about 500 $m^3 s^{-1}$. Because they are so infrequent and of limited duration, discharges greater than 850 $m^3 s^{-1}$ transported very little sand.

Effective discharge for the period 1980 to1990 was also about 725 $m^3 s^{-1}$, but the dominant mode was more narrowly confined to discharges between about 650 and 825 $m^3 s^{-1}$. The effective discharge curve for that 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 $m^3 s^{-1}$, depending on reservoir elevation. Thus, the Colorado River rarely has had flows at discharges between 875 and 1150 $m^3 s^{-1}$. 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 3 dominant rates, and there are many increments of discharge greater than 1410 $m^3 s^{-1}$ that did not occur.

Longitudinal Correlation of Geomorphic Surfaces and Relation to Effective Discharge

The water-surface elevation of the modal discharge increment of the product of streamflow frequency and sediment transport is typically compared with the elevation of the active floodplain in order to determine the formative flow of alluvial rivers [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 (Kieffer, 1985). Nevertheless, we can determine if any of the discontinuous fine-grained alluvial deposits are longitudinally correlative, have similar depositional characteristics, and correlate with modes of the product of streamflow frequency and sediment transport. If such correlations exist, then the modal discharge increment may be considered "effective" for a particular suite of deposits even if other parts of the channel are shaped by extreme discharges.

In this study, discontinuous fine-grained deposits known to have formed by the same discharge were identified from mapping and sedimentologic analysis [Rubin et al., 1990; Schmidt and Graf, 1990]. The elevation of reattachment bars known to have formed in 1983 and between 1984 and 1986 correlate well over long distances of about 70 channel widths, and the average longitudinal slope of these deposits parallels that of the average low flow slope (Fig. 14). The correlation of these deposits thus can be an useful tool for estimating formative discharges.

In the case of the Colorado River in Grand Canyon, topographic surfaces of the three longitudinally correlative surfaces are associated with different modes of the product of streamflow frequency and sediment transport 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. Deposits associated with the modal discharge increment are less extensively exposed than are higher flood deposits. Deposits formed 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 subsidiary mode. Each of these suites of high flow deposits are 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 are usually about 1 m thick 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 decreased due to depletion of sediment available for entrainment, 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 $m^3 s^{-1}$. These deposits are incrementally constructed by the river by discharges that occur nearly every year (Fig. 4). 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 and others (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. Stevens et al. (1995) described the succession of riparian plants on reattachment bars and show that such plants preferentially colonize silts and clays.

Alluvial deposits in canyons with abundant debris fans have numerous surfaces constructed by several discharges. In the case of Grand Canyon, the 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].

CONCLUSIONS

The fundamental geomorphic unit of the Colorado River in Grand Canyon is a complex of features influenced by debris fans. These fan-eddy complexes are 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, typify most of the depositional environments of the river corridor. Eddies are the dominant depositional environment of fine-grained deposits in the Point Hansbrough reach and the Tapeats gorge. However, the Big Bend area is distinct in its steep gradient, extensive gravel deposits, and relatively few eddies.

Fine-grained deposits 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 hydrologic regime forms deposits having longitudinally extensive levels associated with several different discharges. The multiple peaks derived from calculations of the product of streamflow frequency and sediment transport are caused by extensive river regulation, and Hirsch and others (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. Prior to dam construction, effective discharge curves probably were similar to those calculated by Andrews (1986) for the Green River. Since construction of large dams, flood flows have been greatly controlled, but occassional high floods still occur, such as those in Grand Canyon between 1983 and 1986. Resulting effective discharge curves have numerous modes. Because topographic surfaces form in association with many of these modes, dam regulation may be creating a more diverse array of topographic levels of fine-grained alluvium than existed prior to dam construction.

Mapping of fine-grained deposits at different discharge levels provides a basis for analysis of spatial patterns of erosion and deposition. Comparison of the distribution of alluvial deposits in the many years of photography analyzed in this project show that general trends can be discerned that are consistent with other data developed from topographic resurveys and inventories. Our analysis also shows that specific eddy complexes respond in patterns inconsistent with overall river behavior. Development of river management strategies must acknowledge that desired objectives of overall system response will not always be consistent with the behavior of any one site.

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FIGURE CAPTIONS

Figure 1 Map showing location of the study reaches.

Figure 2 Maps showing the distribution of surficial geologic deposits in 1984 and 1990 and the areas of aggradation and deposition in the same reach that occurred between 1984 and 1990. Map units are described by Leschin and Schmidt (1995). The reach shown is part of the Tapeats gorge downstream from the Little Colorado River and is located on Figure 9a. Discharge at the time of each photo was 141 m^3s^{-1}. A. Map (scale 1:7060) showing deposits in 1984. B. Map (scale 1:7060) showing deposits in 1990. C. Map (scale 1:6000) showing areas of aggradation and degradation. Red areas show degradation and green areas indicate aggradation. Debris fans are shown in yellow.

Figure 3 Map showing eddy complexes and surficial geology in 1990 in part of the Tapeats gorge downstream from the Little Colorado River. Eddy complex numbers are labeled. The area within each complex is the maximum area of all eddy deposits mapped in all years. Thus, complexes are larger than the area of eddy deposits in any one year, such as 1990.

Figure 4 Graph showing annual maximum discharge of the Colorado River at Lees Ferry, Arizona (stream gaging station 09380000), and near Grand Canyon, Arizona (09402500). Lees Ferry data are depicted with x's and Grand Canyon data with +'s. Horizontal dashed line is maximum powerplant capacity of Glen Canyon Dam. Solid line is a best fit smooth curve of the Lees Ferry data using the locally-weighted least squared error method, based on a smoothing factor computed from the nearest 15 percent of the total population surrounding each point.

Figure 5 Graphs showing hydrographs of mean daily discharge of the Colorado River at Lees Ferry, Arizona, for the 365 dys preceding each aerial photograph series, and for the Colorado River near Grand Canyon, Arizona, for the 365 dys preceding the 1993 photography. A. Period preceding December 31, 1935. B. Period preceding May 14, 1965. C. Period preceding June 16, 1973. D. Period preceding October 21, 1984. E. Period preceding June 30, 1990. F. Period preceding October 11,

1992. G. Period preceding May 30, 1993, at Lees Ferry (solid line) and near Grand Canyon (dashed line).

Figure 6 Graph showing longitudinal profile of the low discharge (143 m^3s^{-1}) water surface in June 1990 of the Point Hansbrough study reach and showing the locations of debris fans, indicated by arrows, along the river corridor.

Figure 7 Map showing topography of the Point Hansbrough study reach in June 1990. Debris fans are shown in black. Gravel bars are shown in shading. The river flows from north to south. The extent of detailed maps of the reach near Saddle Canyon, such as Figure 10a, is indicated by the enclosed area. River miles are numbered.

Figure 8 Graph showing longitudinal profile of the low discharge (143 m^3s^{-1}) water surface in June 1990 of the LCR confluence study reach and showing the locations of debris fans, indicated by arrows, along the river corridor.

Figure 9 Map showing topography of the LCR confluence study reach in June 1990. Debris fans are shown in black. Gravel bars are shown in black. The extent of detailed maps of part of the Tapeats gorge downstream from the Little Colorado River, such as Figure 2, is indicated by the enclosed area. A. Upstream part of reach, primarily within the Tapeats gorge. B. Downstream part of reach, primarily within the Big Bend area.

Figure 10 Maps showing discharge levels of fine-grained deposits in two reaches of the Colorado River in Grand Canyon. Stippled areas are the fluctuating flow level, arrowheads are the high flow level of 1984 to 1986, horizontal hatchures are the flood level of 1983, and areas of dashed lines are pre-dam deposits higher than those of 1983. River miles are numbered. A. Near Saddle Canyon in the Point Hansbrough study reach. B. Downstream from the Little Colorado River in the Tapeats gorge part of the LCR confluence study reach.

Figure 11 Maps showing surface flow patterns at about 425 m^3s^{-1} and major classes of river corridor deposits in June 1990. Dark-shaded areas are debris fans, horizontal hatchures are separation bars, vertical hatchures are reattachment bars, cross-hatchures are undifferentiated eddy bars, areas of broad lines are channel-margin deposits, and areas with large dots are gravel bars. A. Near Saddle Canyon in the Point Hansbrough study reach. B. Downstream from the Little Colorado River in the Tapeats gorge part of the LCR confluence study reach.

Figure 12 Graph showing longitudinal distribution of the area, between designated river miles, of all fine-grained deposits (x's) and of all eddy deposits (+'s) in the two study reaches in June 1990.

Figure 13 Graph showing longitudinal distribution of the area, between designated river miles, of fine-grained alluvial deposits formed at the flood level of 1983 (triangles), at the high flow level of 1984-86 (+'s), and at the fluctuating flow level(x's) deposits, in June 1990.

Figure 14 Graphs showing longitudinal correlation of flood level of 1983, high flow level of 1984-86, and fluctuating-flow level in the two study reaches. A. Point Hansbrough reach. Dark circles and dark triangles are surveyed water surface elevations in 1985 at indicated discharges. B. LCR confluence reach.

Figure 15 Maps (scale 1:7060) showing the distribution of surficial geologic deposits in parts of the two study reaches on December 31, 1935. Map units are described by (1995). A. Part of the Point Hansbrough reach near Saddle Canyon. B. Part of the Tapeats gorge downstream from the Little Colorado River.

Figure 16 Maps (scale 1:7060) showing the distribution of surficial geologic deposits in parts of the two study reaches on May 14, 1965. Map units are described by Leschin and Schmidt (1995). A. Part of the Point Hansbrough reach near Saddle Canyon. B. Part of the Tapeats gorge downstream from the Little Colorado River.

Figure 17 Maps (scale 1:7060) showing the distribution of surficial geologic deposits in parts of the two study reaches on June 16, 1973. Map units are described by Leschin and Schmidt (1995). A. Part of the Point Hansbrough reach near Saddle Canyon. B. Part of the Tapeats gorge downstream from the Little Colorado River.

Colorado River. Red areas show degradation and green areas indicate aggradation. Debris fans are shown in yellow.

Figure 26 Graphs showing the proportion of eddy complexes that are significantly smaller or larger than they were in 1984. High-elevation deposits are those formed between 1983 and 1986, "all sand above base flow" deposits are those higher in elevation than a stage associated with a discharge of about 141 m^3s^{-1}, and "all sand deposits" includes submerged deposits.

Figure 27 Graph showing effective discharge curves for the 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.

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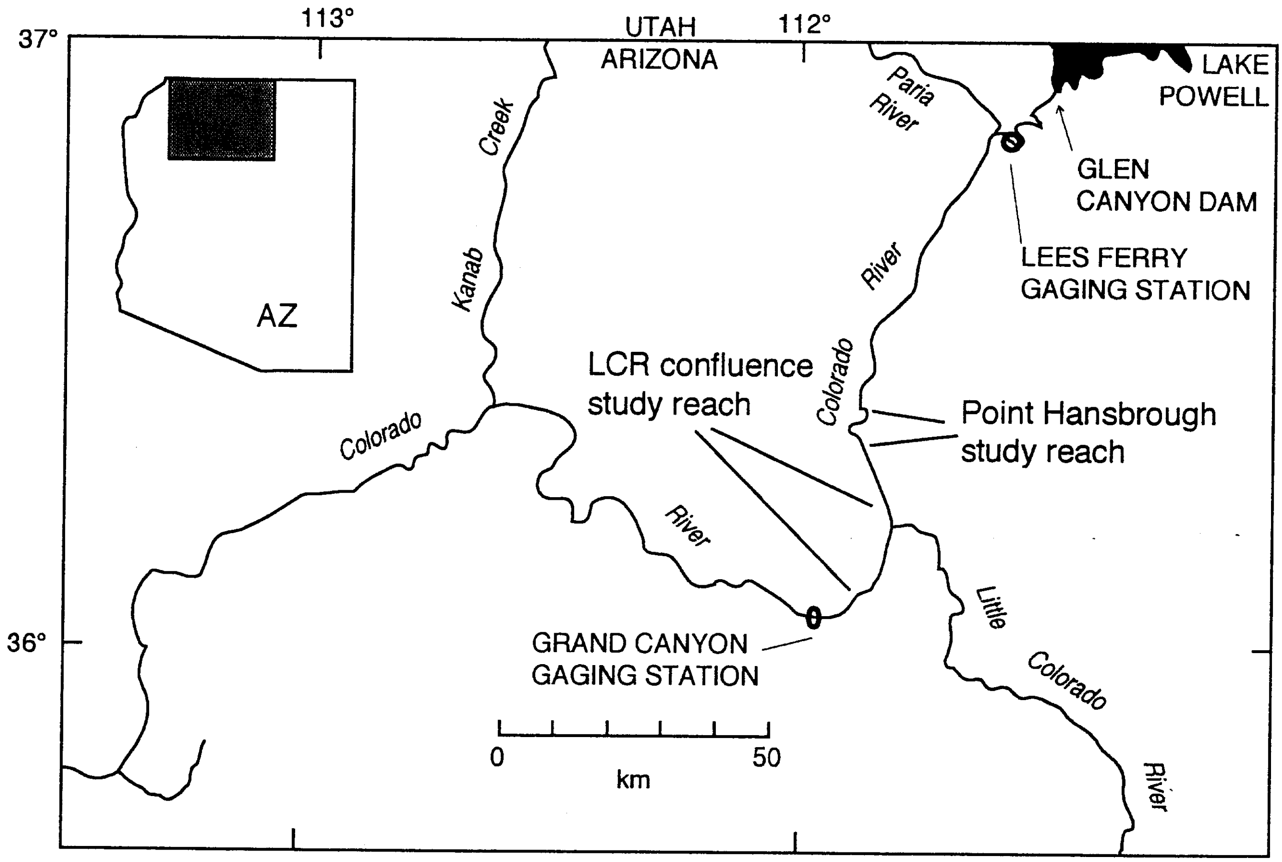

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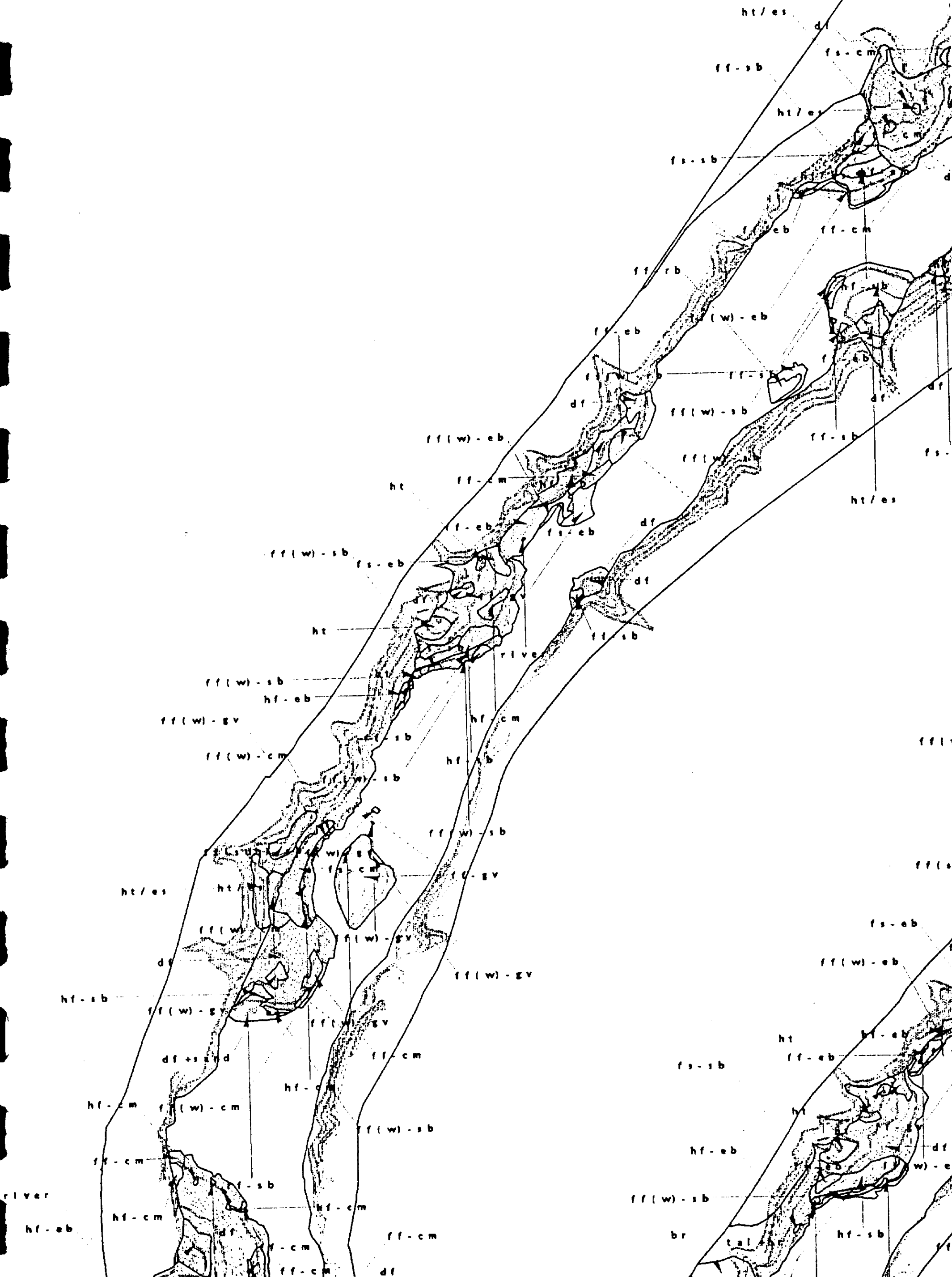
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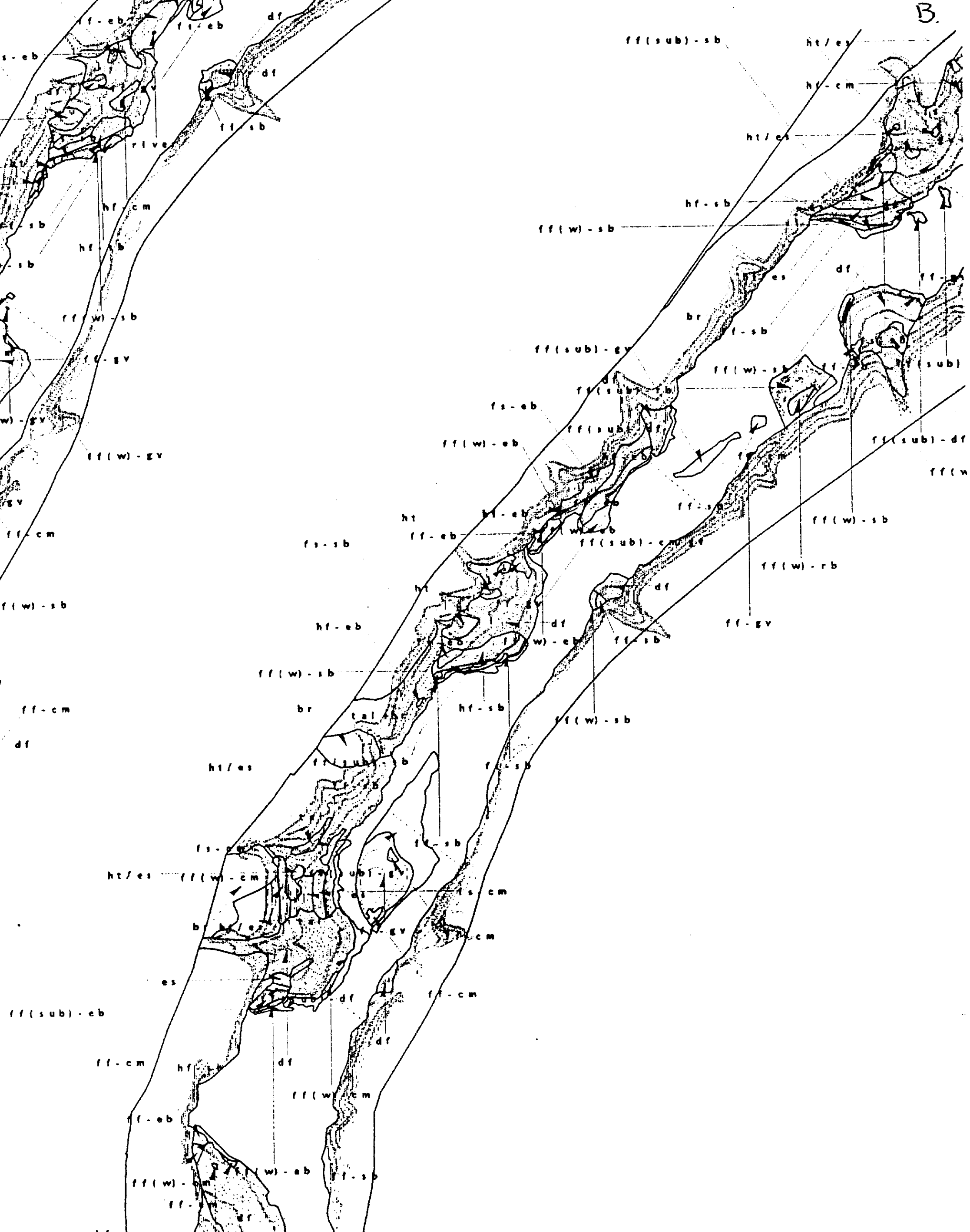
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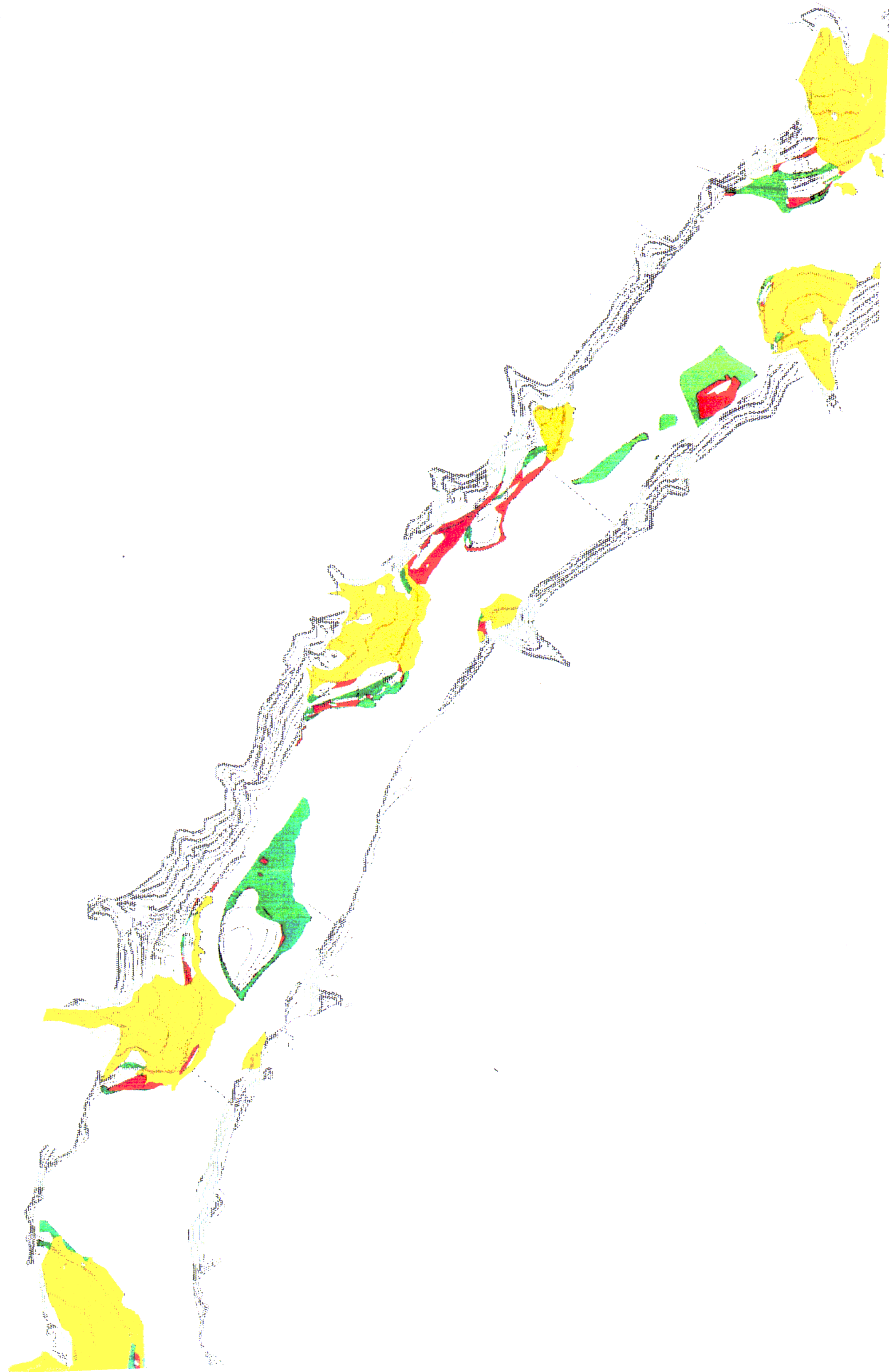

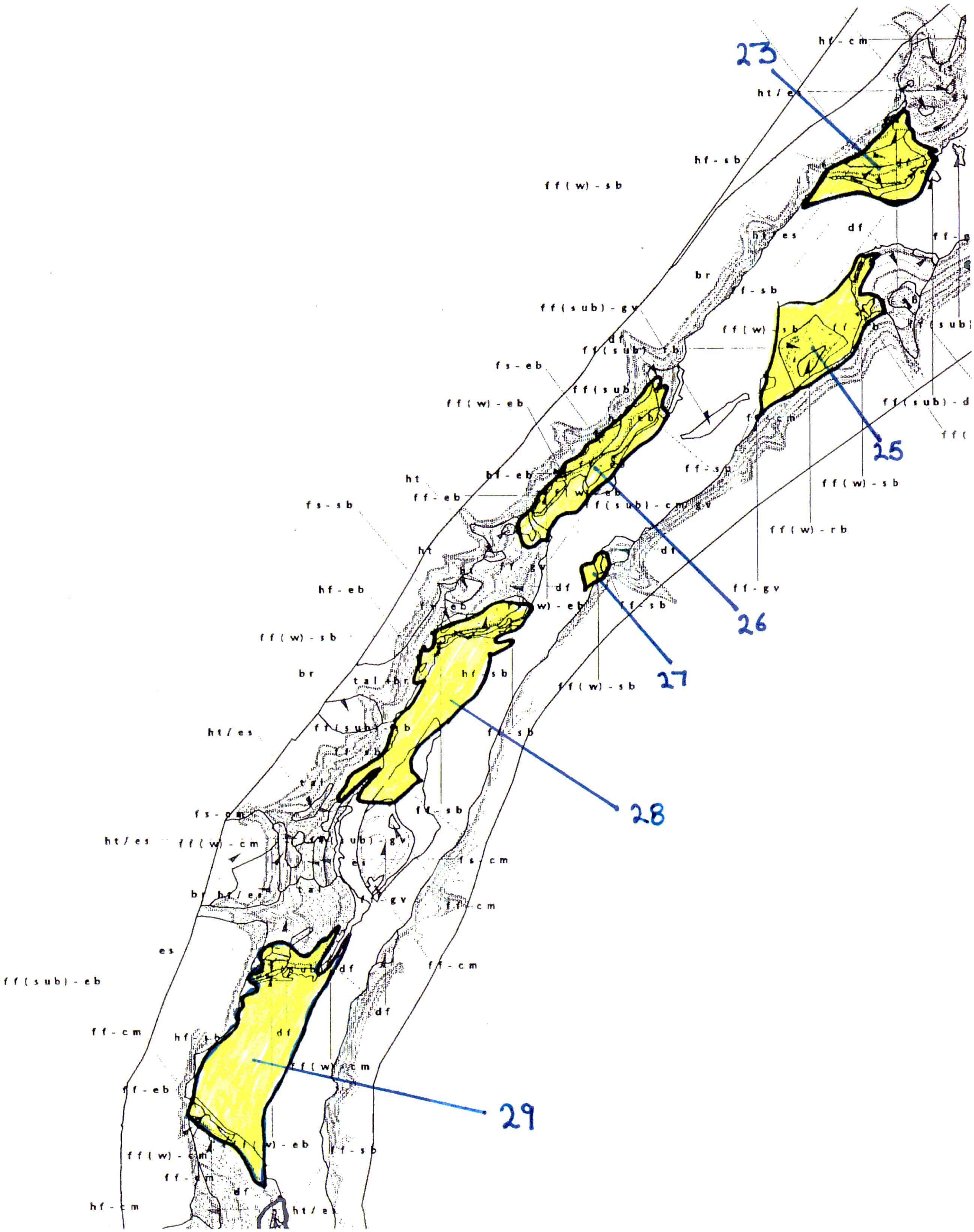

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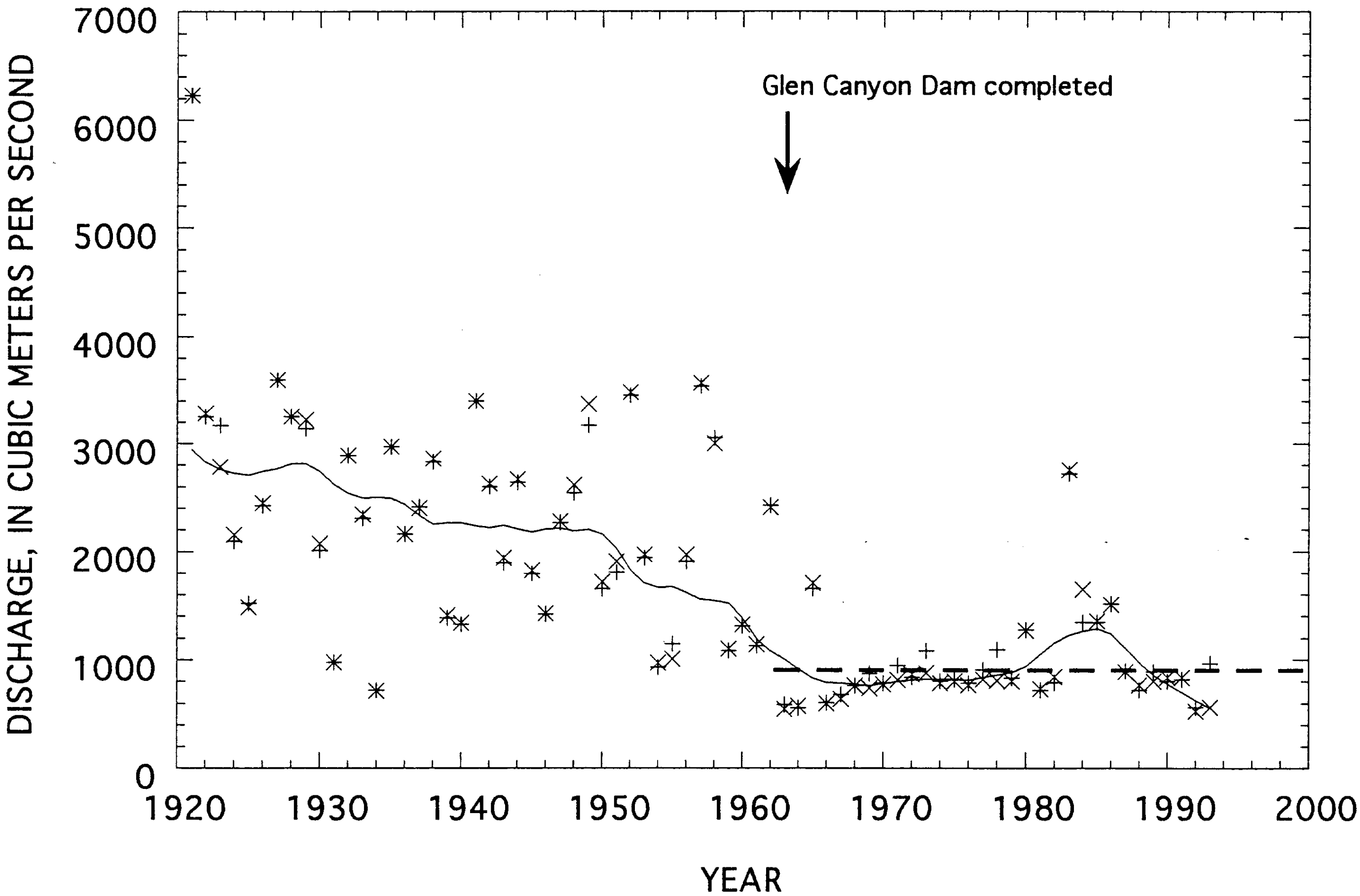
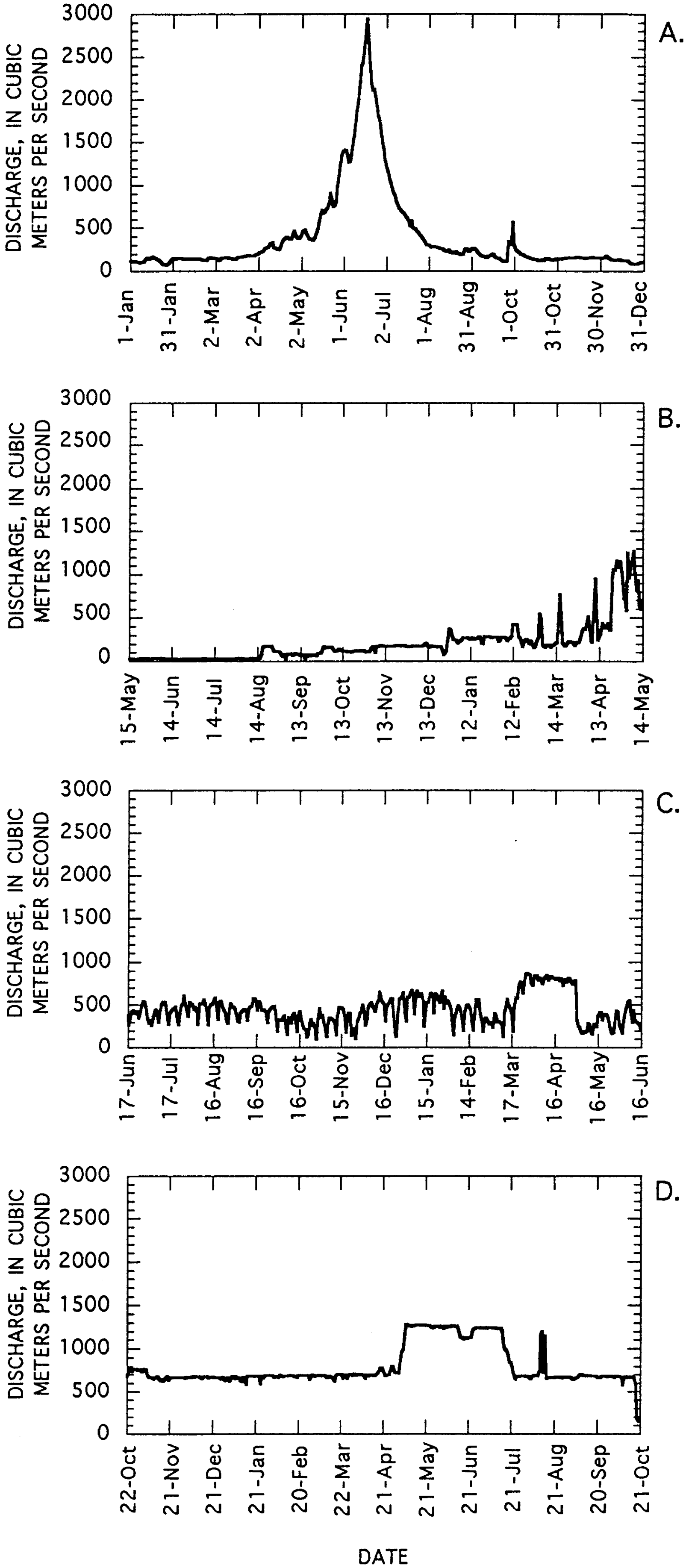
fs - sb
ff (w) - rb
ff - gv
hf - eb
ff (w) - sb
br
ht / es
fs - cm
ht / es
ff (w) - cm
es
ff (sub) - eb
ff - cm
ff - eb
ff (w) - cm
hf - cm
ff - sb
ff (sub) - d

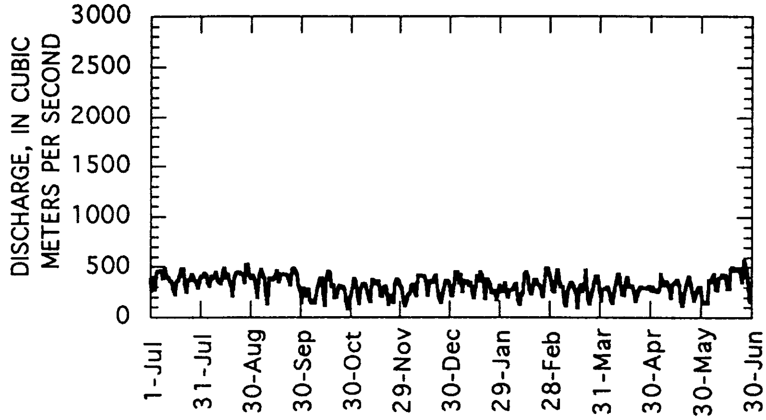
#4

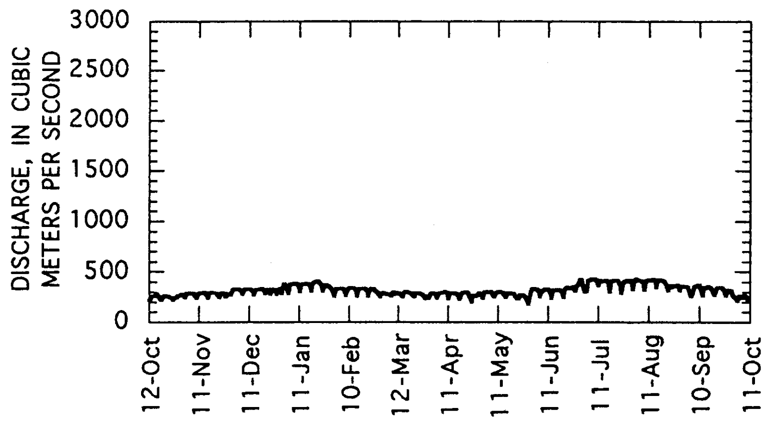

Glen Canyon Dam completed
DISCHARGE, IN CUBIC METERS PER SECOND
YEAR
0
1000
2000
3000
4000
5000
6000
7000
1920
1930
1940
1950
1960
1970
1980
1990
2000

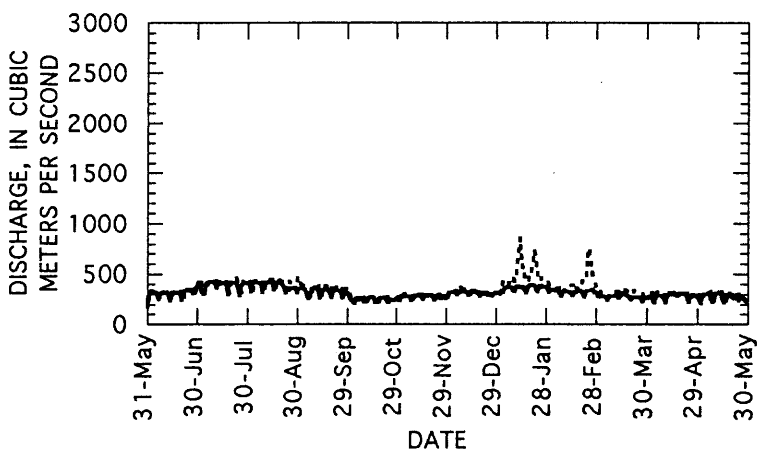
#5


DISCHARGE, IN CUBIC METERS PER SECOND
3000
2500
2000
1500
1000
500
0
A.
1-Jan
31-Jan
2-Mar
2-Apr
2-May
1-Jun
2-Jul
1-Aug
31-Aug
1-Oct
31-Oct
30-Nov
31-Dec
B.
15-May
14-Jun
14-Jul
14-Aug
13-Sep
13-Oct
13-Nov
13-Dec
12-Jan
12-Feb
14-Mar
13-Apr
14-May
C.
17-Jun
17-Jul
16-Aug
16-Sep
16-Oct
15-Nov
16-Dec
15-Jan
14-Feb
17-Mar
16-Apr
16-May
16-Jun
D.
22-Oct
21-Nov
21-Dec
21-Jan
20-Feb
22-Mar
21-Apr
21-May
21-Jun
21-Jul
21-Aug
20-Sep
21-Oct
DATE

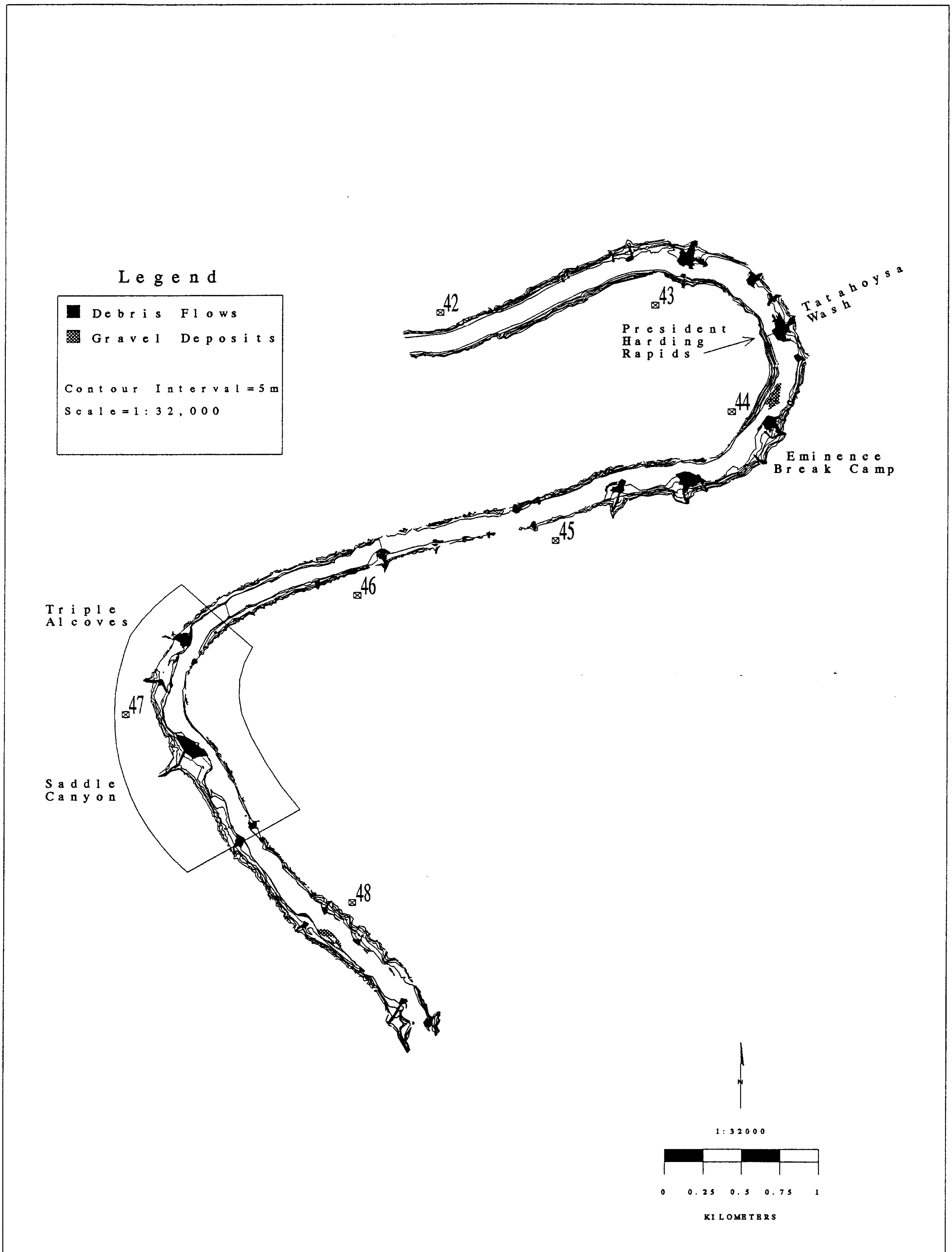
#5


DISCHARGE, IN CUBIC METERS PER SECOND
3000
2500
2000
1500
1000
500
0
1-Jul
31-Jul
30-Aug
30-Sep
30-Oct
29-Nov
30-Dec
29-Jan
28-Feb
31-Mar
30-Apr
30-May
30-Jun
E.

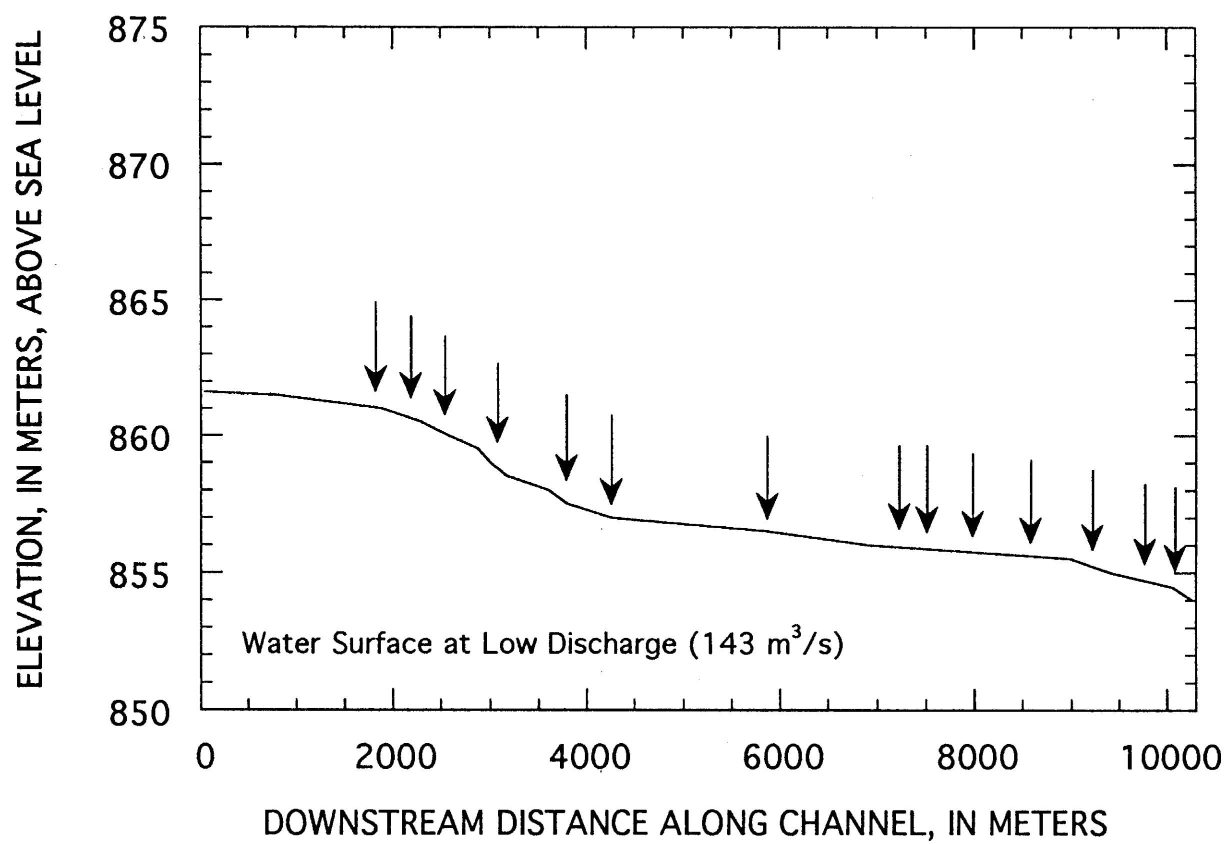

DISCHARGE, IN CUBIC METERS PER SECOND
3000
2500
2000
1500
1000
500
0
12-Oct
11-Nov
11-Dec
11-Jan
10-Feb
12-Mar
11-Apr
11-May
11-Jun
11-Jul
11-Aug
10-Sep
11-Oct
F.


DISCHARGE, IN CUBIC METERS PER SECOND
3000
2500
2000
1500
1000
500
0
31-May
30-Jun
30-Jul
30-Aug
29-Sep
29-Oct
29-Nov
29-Dec
28-Jan
28-Feb
30-Mar
29-Apr
30-May
DATE
G.

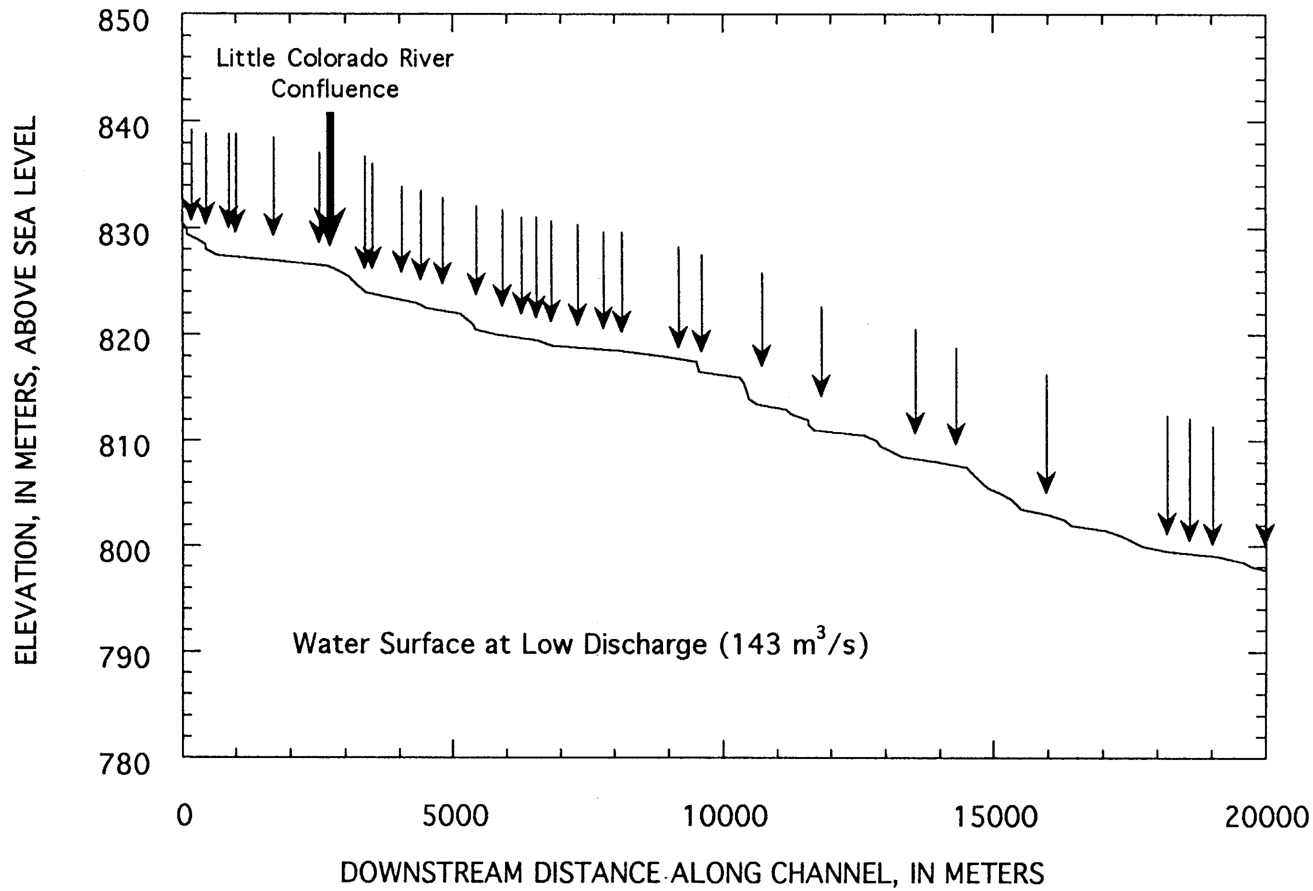
#6



Legend
Debris Flows
Gravel Deposits
Contour Interval=5m
Scale=1:32,000
42
43
44
45
46
47
48
Tatahoysa Wash
President Harding Rapids
Eminence Break Camp
Triple Alcoves
Saddle Canyon
N
1:32000
0
0.25
0.5
0.75
1
KILOMETERS

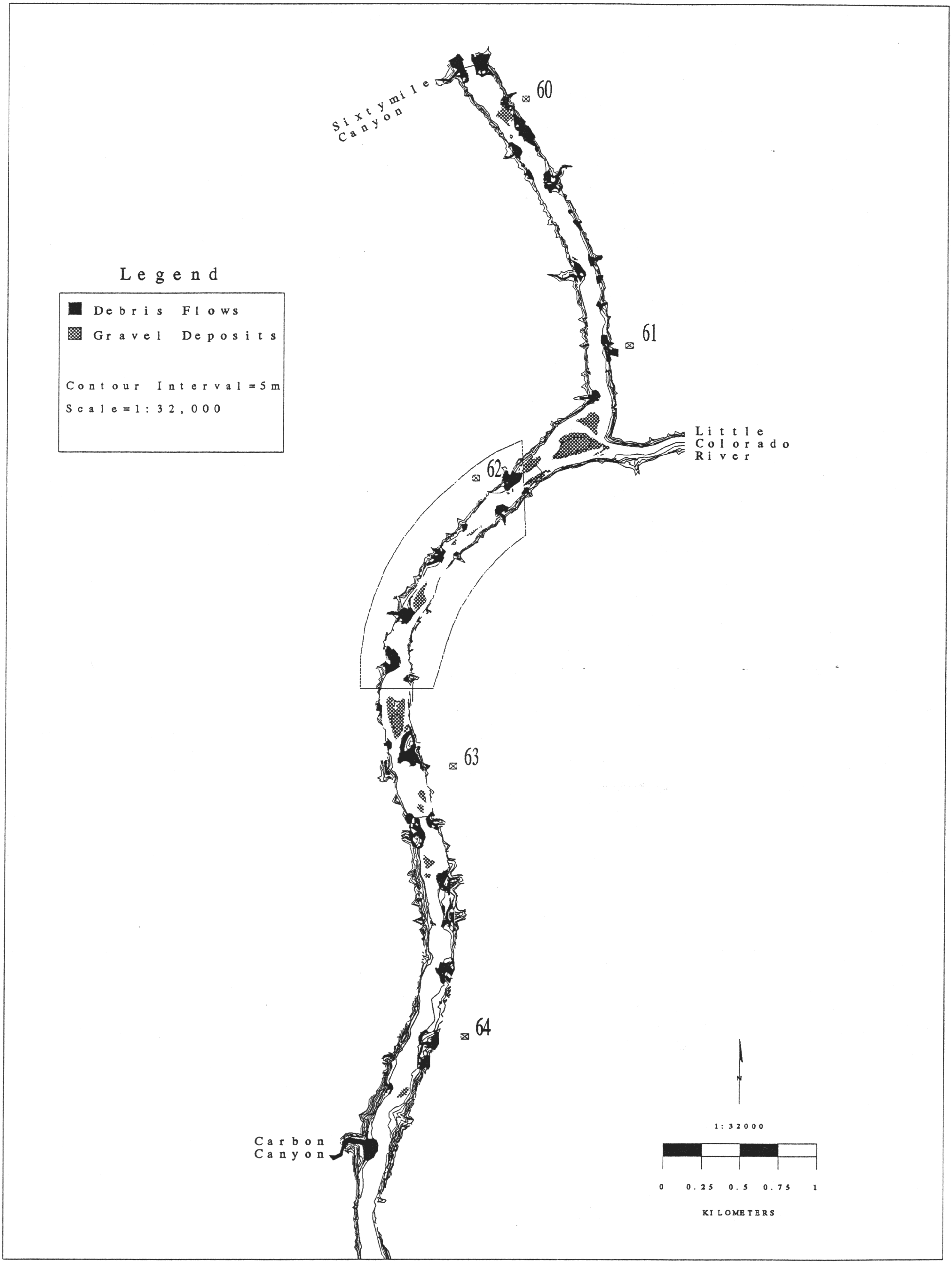

875
870
865
860
855
850
0
2000
4000
6000
8000
10000
ELEVATION, IN METERS, ABOVE SEA LEVEL
DOWNSTREAM DISTANCE ALONG CHANNEL, IN METERS
Water Surface at Low Discharge (143 m3/s)

#7


Little Colorado River
Confluence
Water Surface at Low Discharge (143 m3/s)
ELEVATION, IN METERS, ABOVE SEA LEVEL
850
840
830
820
810
800
790
780
0
5000
10000
15000
20000
DOWNSTREAM DISTANCE ALONG CHANNEL, IN METERS

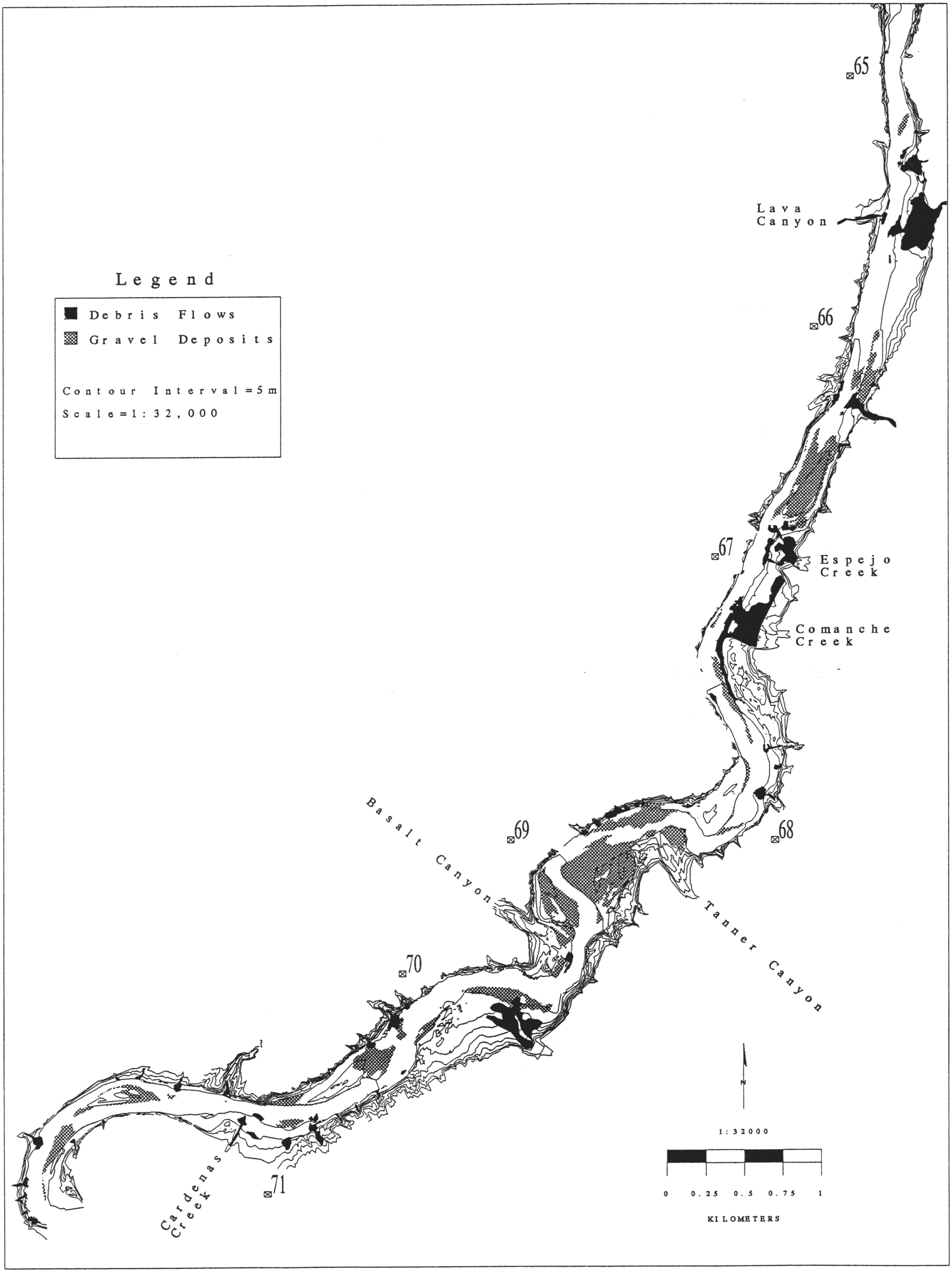
#8

#9a



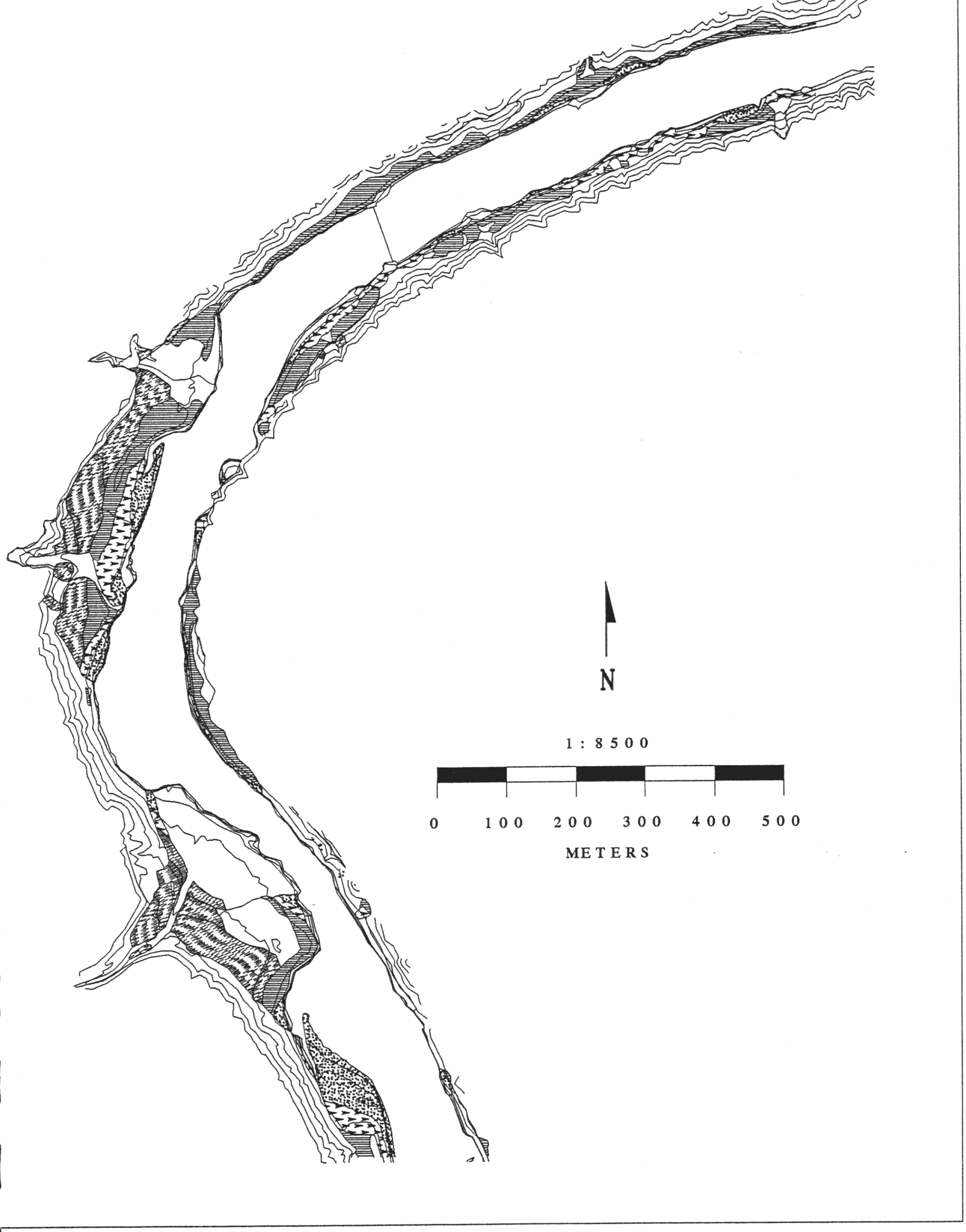
Sixtymile Canyon
60
61
Little Colorado River
62
63
64
Carbon Canyon
Legend
Debris Flows
Gravel Deposits
Contour Interval=5m
Scale=1:32,000
N
1:32000
0 0.25 0.5 0.75 1
KILOMETERS

#96

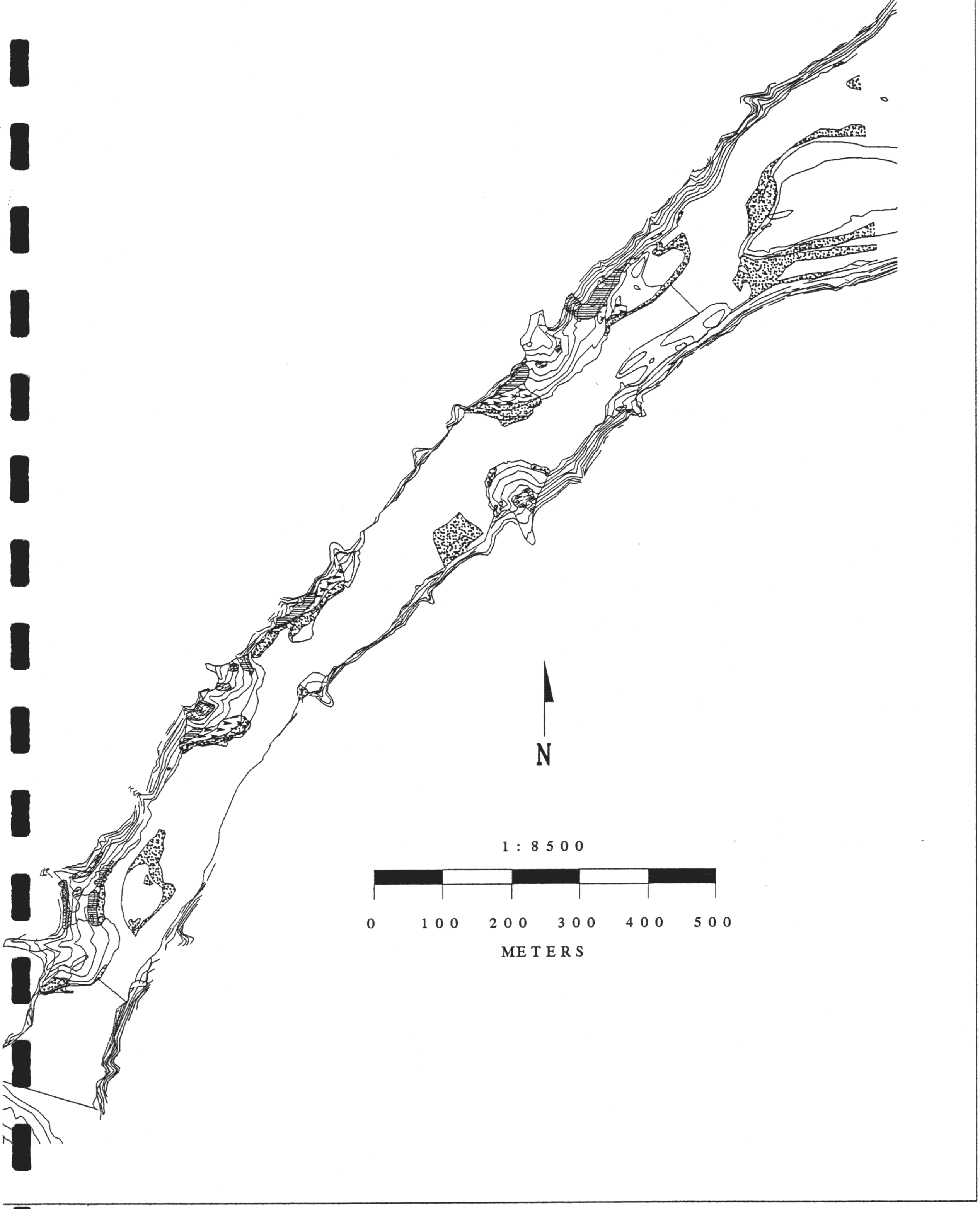


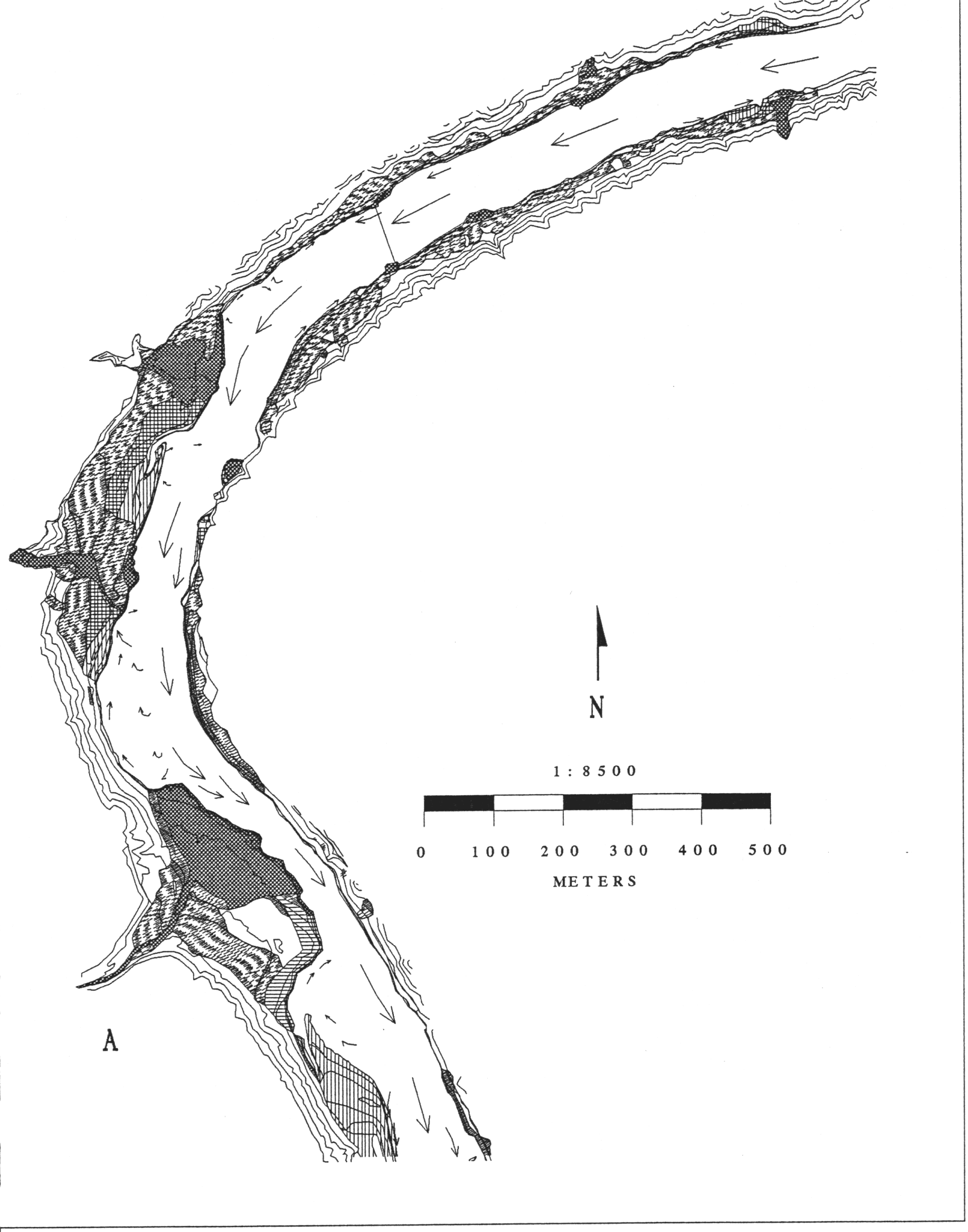
Legend
Debris Flows
Gravel Deposits
Contour Interval=5m
Scale=1:32,000
65
Lava Canyon
66
67
Espejo Creek
Comanche Creek
68
69
Basalt Canyon
Tanner Canyon
70
71
Cardenas Creek
N
1:32000
0 0.25 0.5 0.75 1
KILOMETERS

#10a

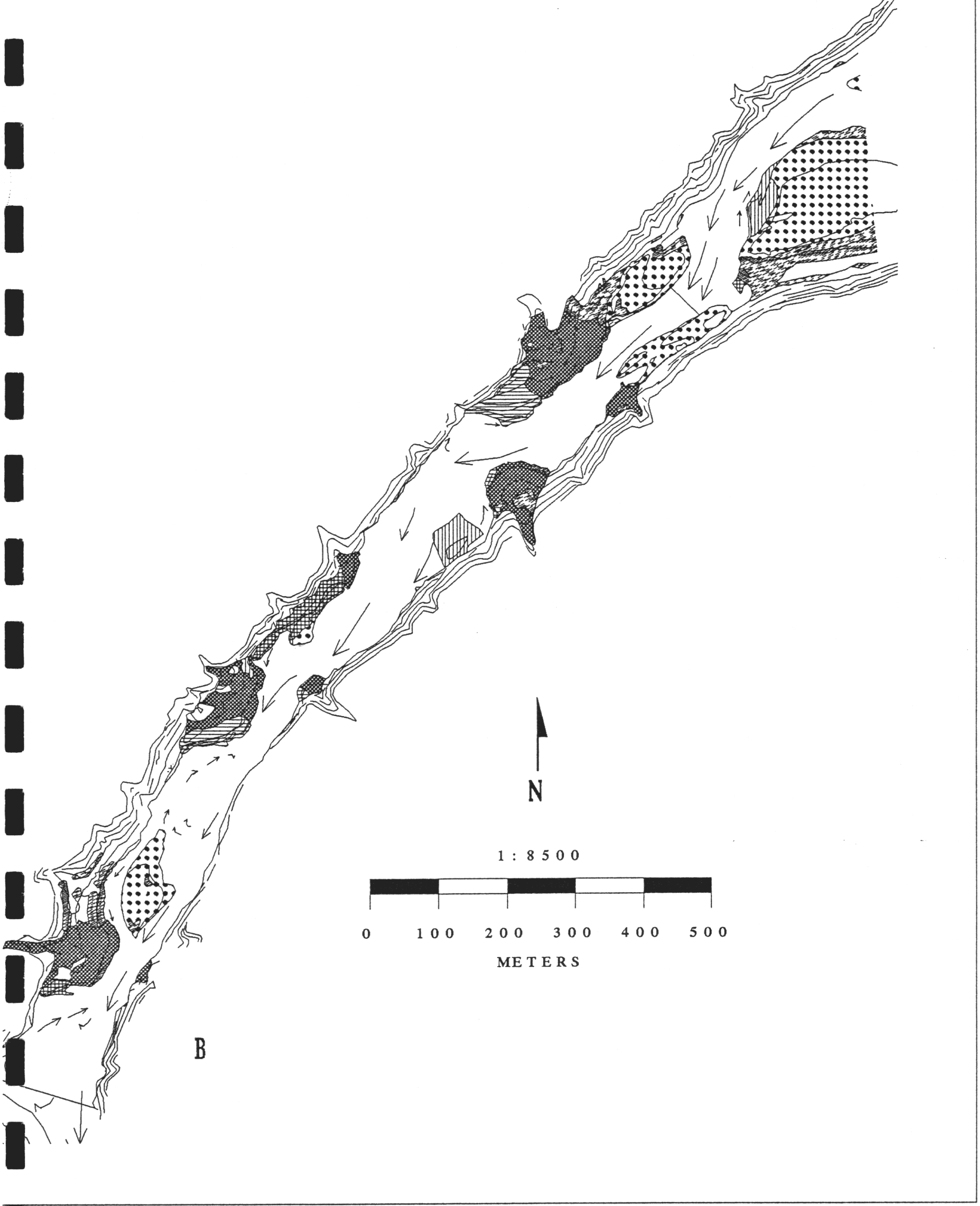


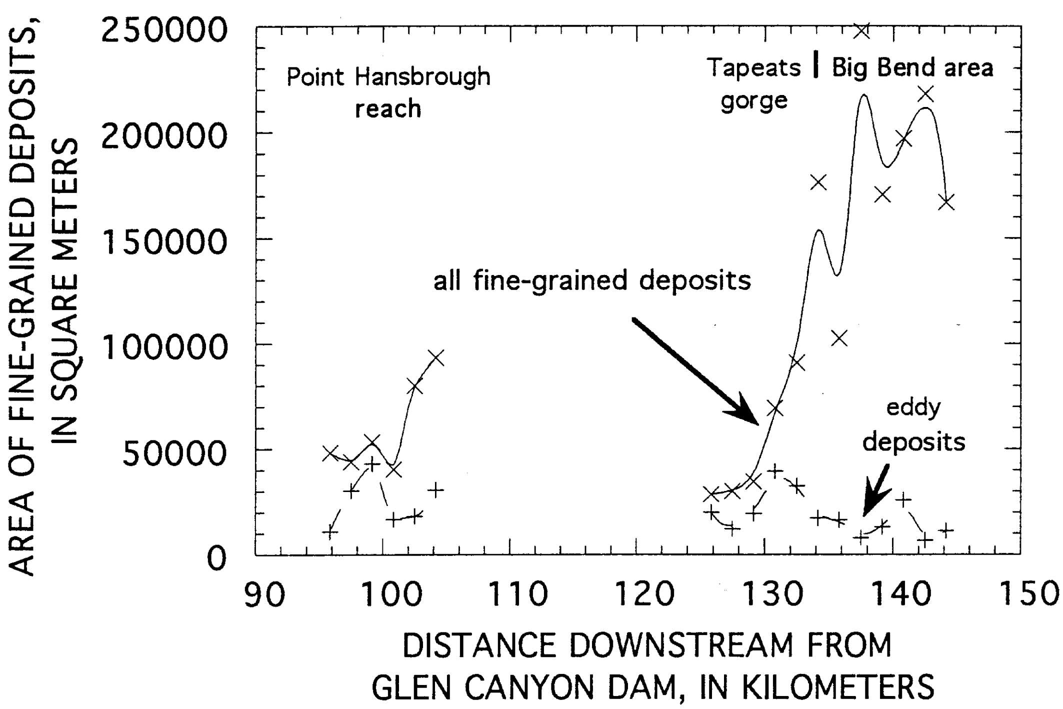
#106

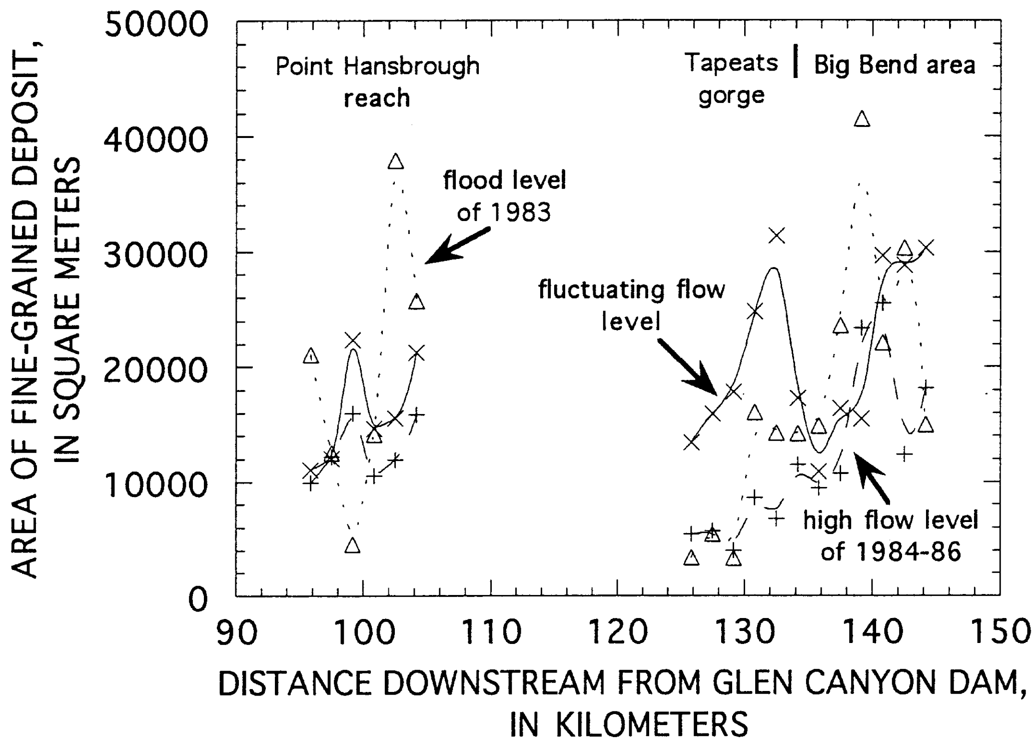



N
1 : 8500
0 100 200 300 400 500
METERS
A

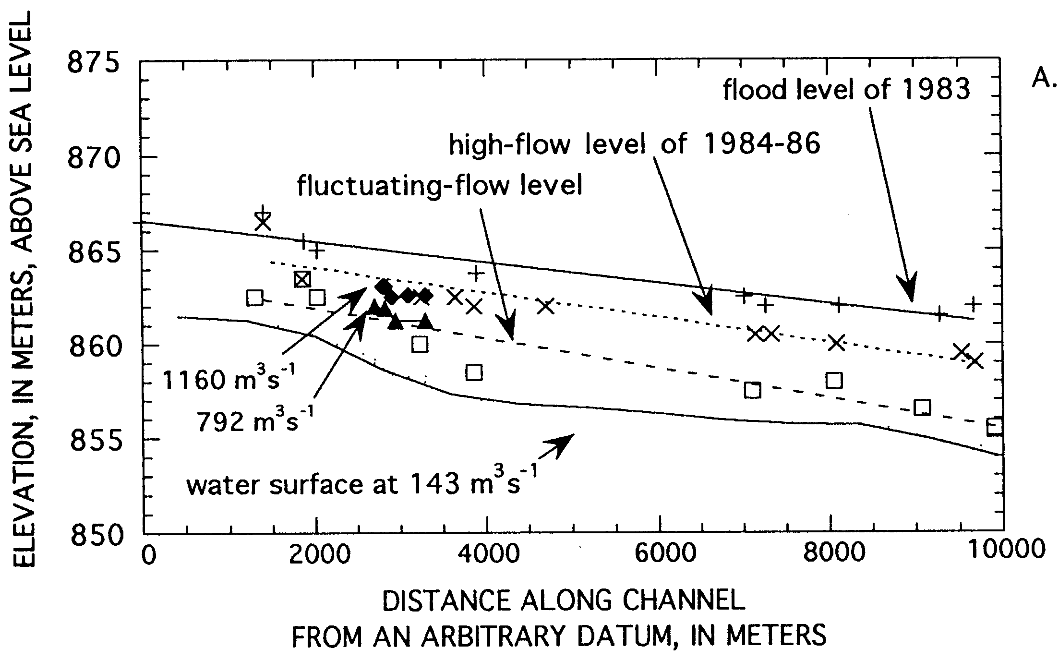
11b

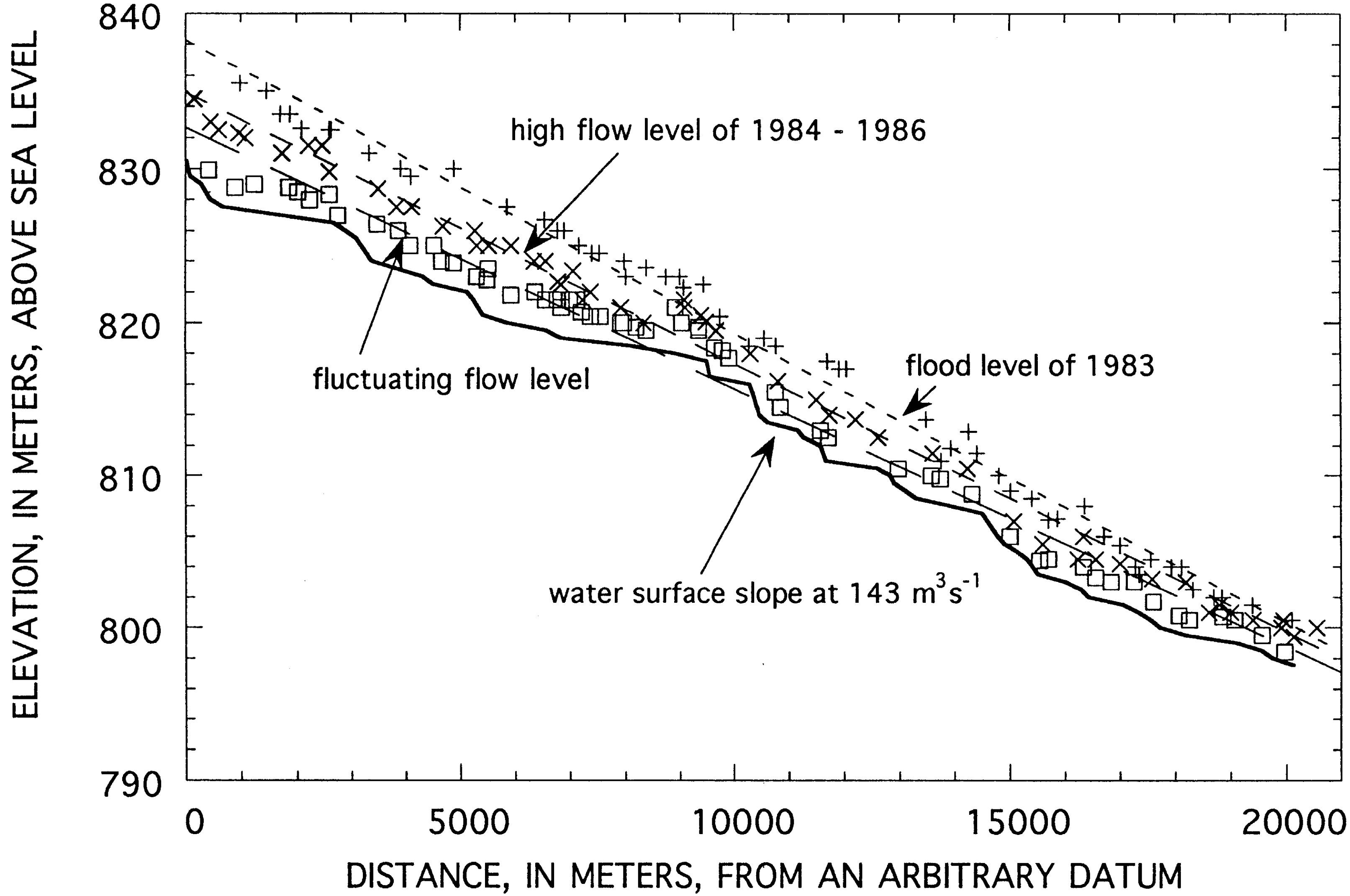



AREA OF FINE-GRAINED DEPOSITS, IN SQUARE METERS
250000
200000
150000
100000
50000
0
90
100
110
120
130
140
150
DISTANCE DOWNSTREAM FROM GLEN CANYON DAM, IN KILOMETERS
Point Hansbrough reach
Tapeats gorge
Big Bend area
all fine-grained deposits
eddy deposits



50000
40000
30000
20000
10000
0
90
100
110
120
130
140
150
AREA OF FINE-GRAINED DEPOSIT, IN SQUARE METERS
DISTANCE DOWNSTREAM FROM GLEN CANYON DAM, IN KILOMETERS
Point Hansbrough reach
Tapeats gorge
Big Bend area
flood level of 1983
fluctuating flow level
high flow level of 1984-86


A.
flood level of 1983
high-flow level of 1984-86
fluctuating-flow level
1160 m³s⁻¹
792 m³s⁻¹
water surface at 143 m³s⁻¹
ELEVATION, IN METERS, ABOVE SEA LEVEL
875
870
865
860
855
850
0
2000
4000
6000
8000
10000
DISTANCE ALONG CHANNEL
FROM AN ARBITRARY DATUM, IN METERS



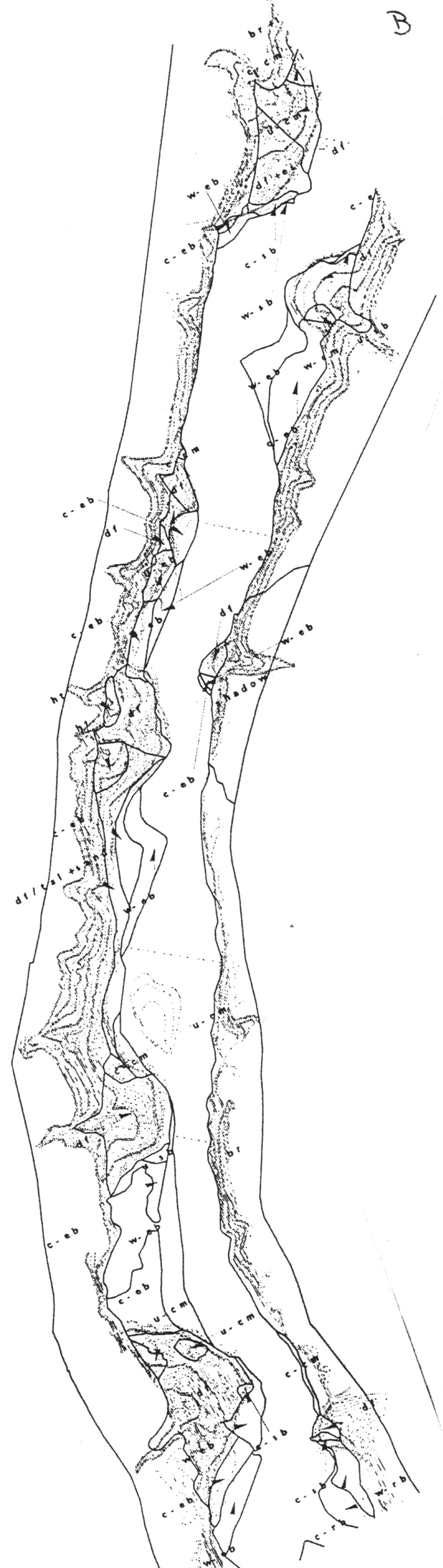
840
830
820
810
800
790
0
5000
10000
15000
20000
ELEVATION, IN METERS, ABOVE SEA LEVEL
DISTANCE, IN METERS, FROM AN ARBITRARY DATUM
high flow level of 1984 - 1986
flood level of 1983
fluctuating flow level
water surface slope at 143 m^{3}s^{-1}

14b

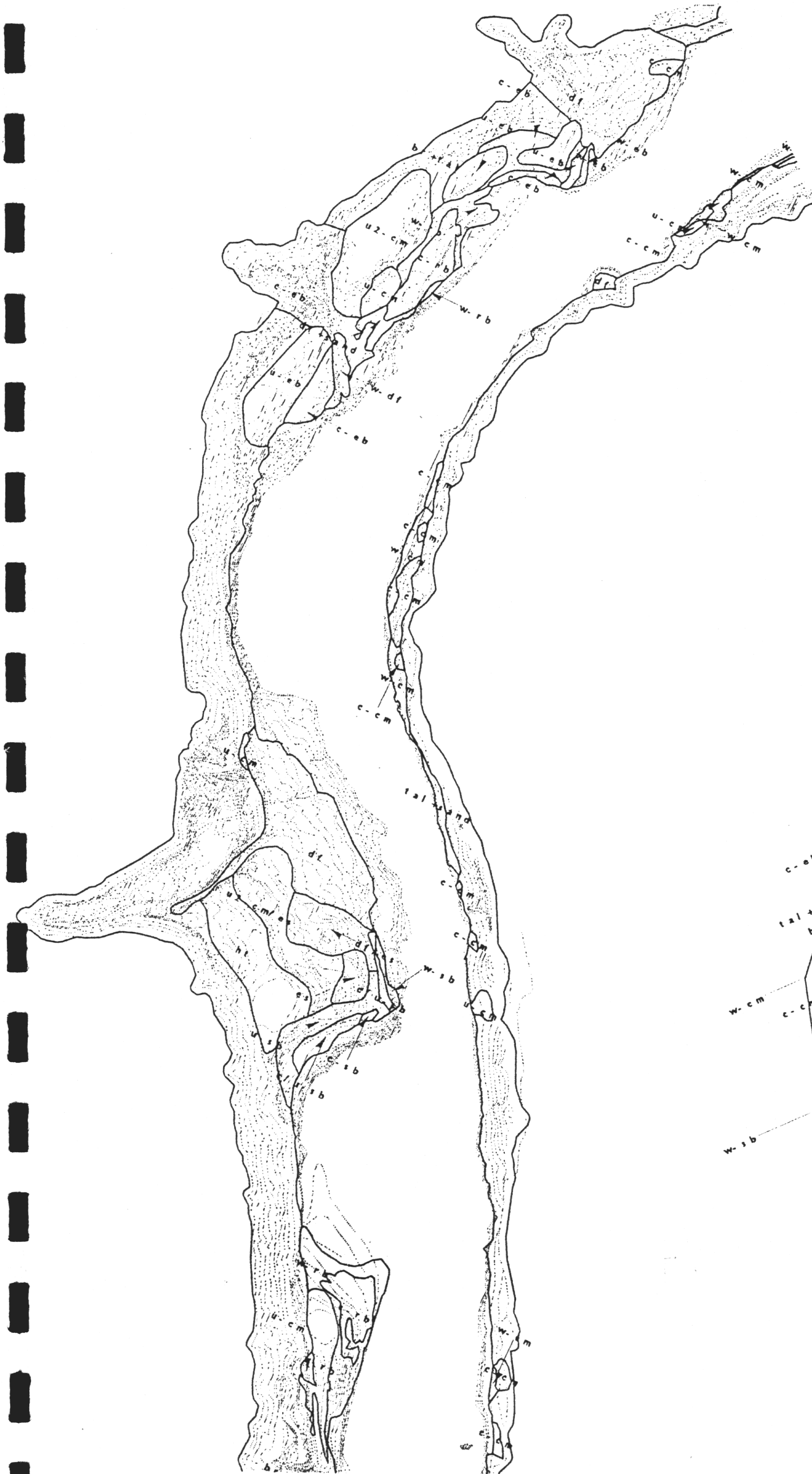
A


u-eb
w-eb
c-eb
u-cm
w-eb
br+tal
w/c/u-rb
obscured
c-rb
w-rb

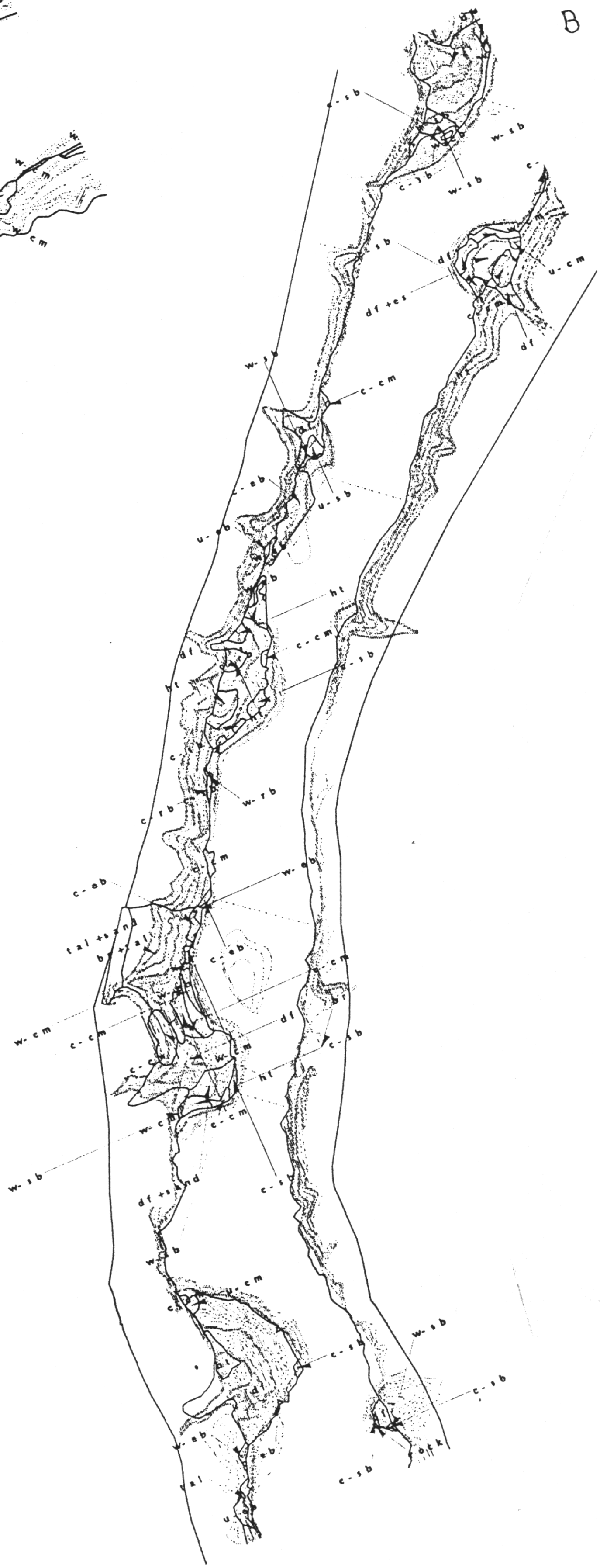
B

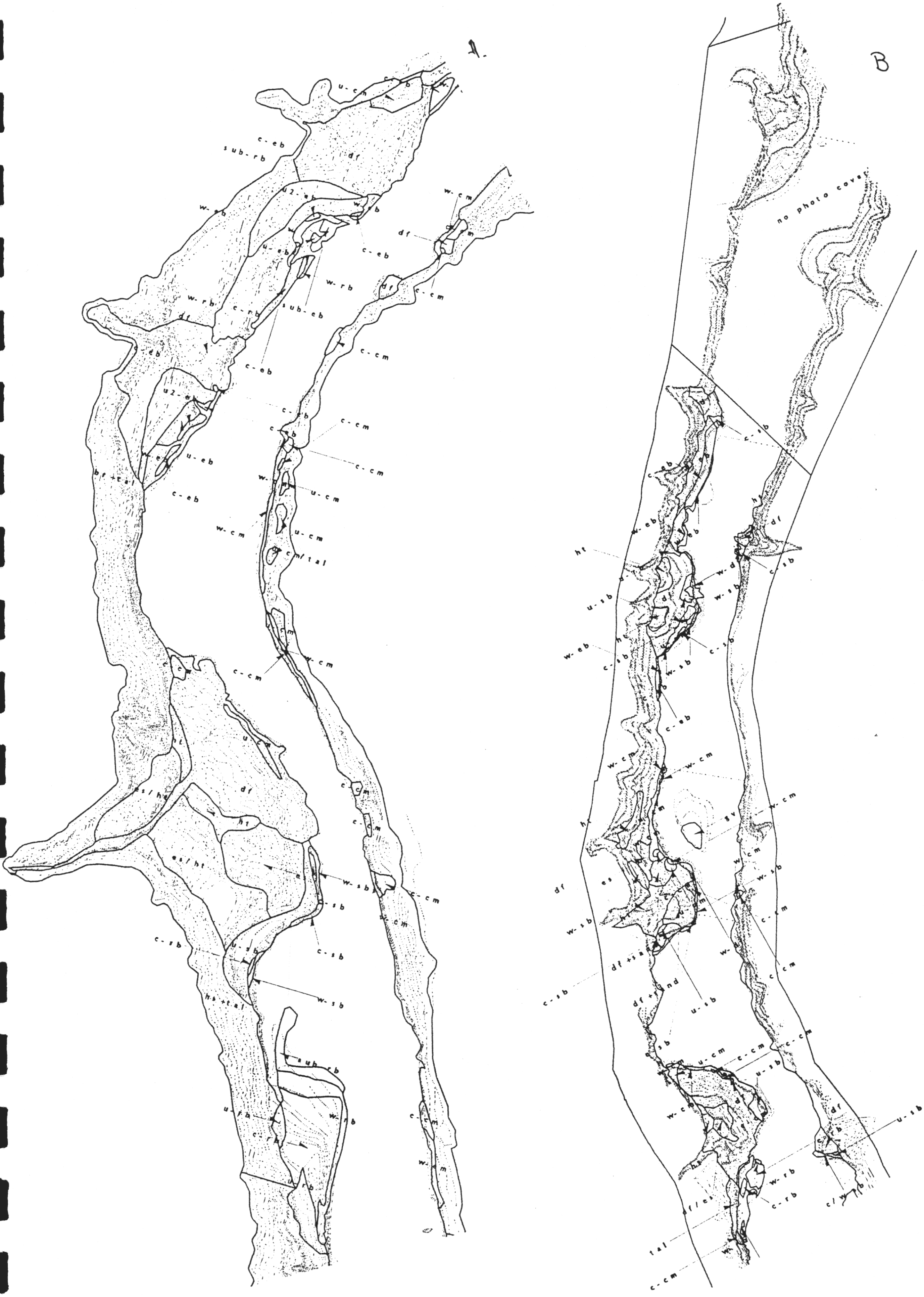

c-eb
c-sb
w-sb
w-eb
c-eb
u-cm
c-eb
u-cm

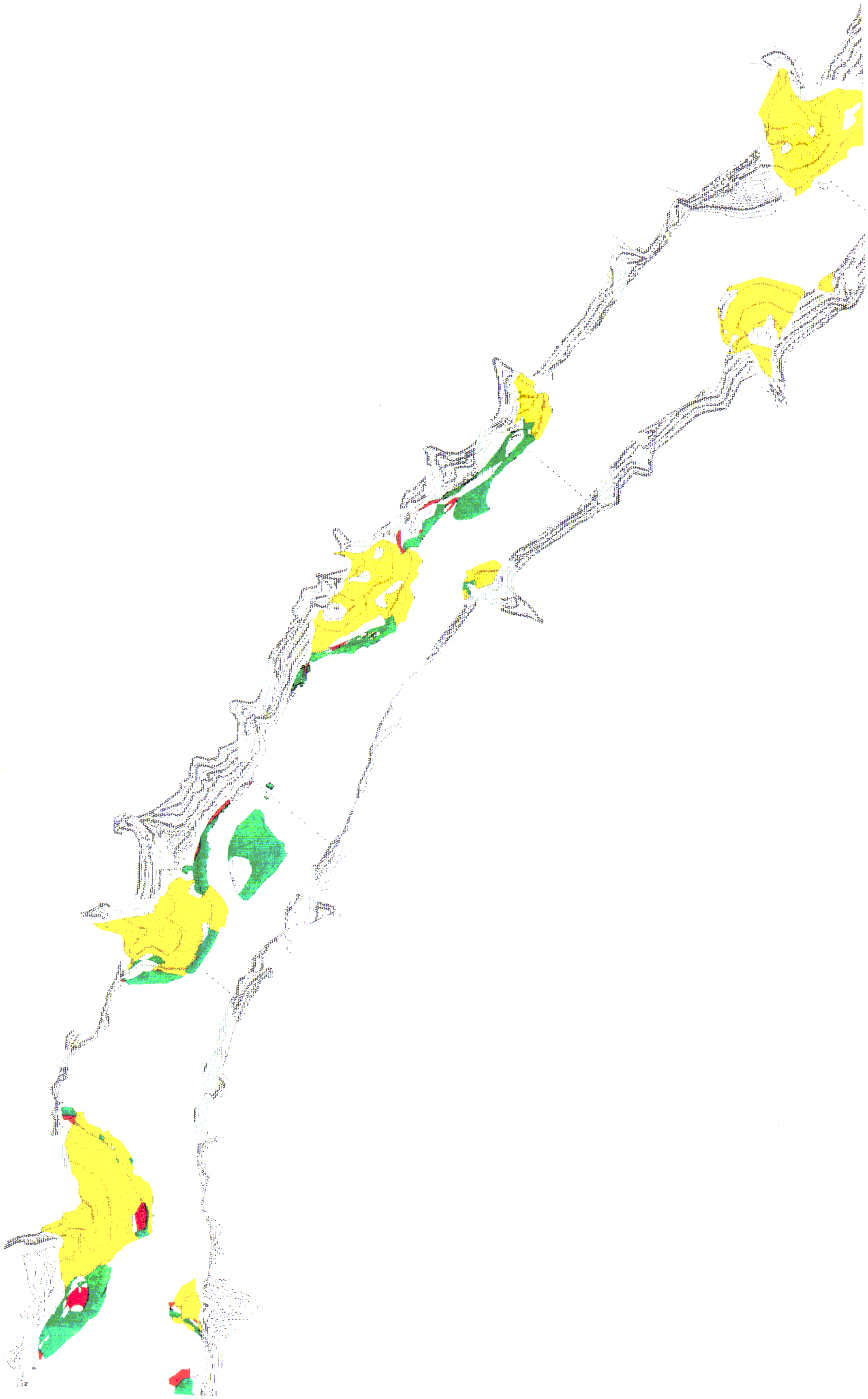
A.

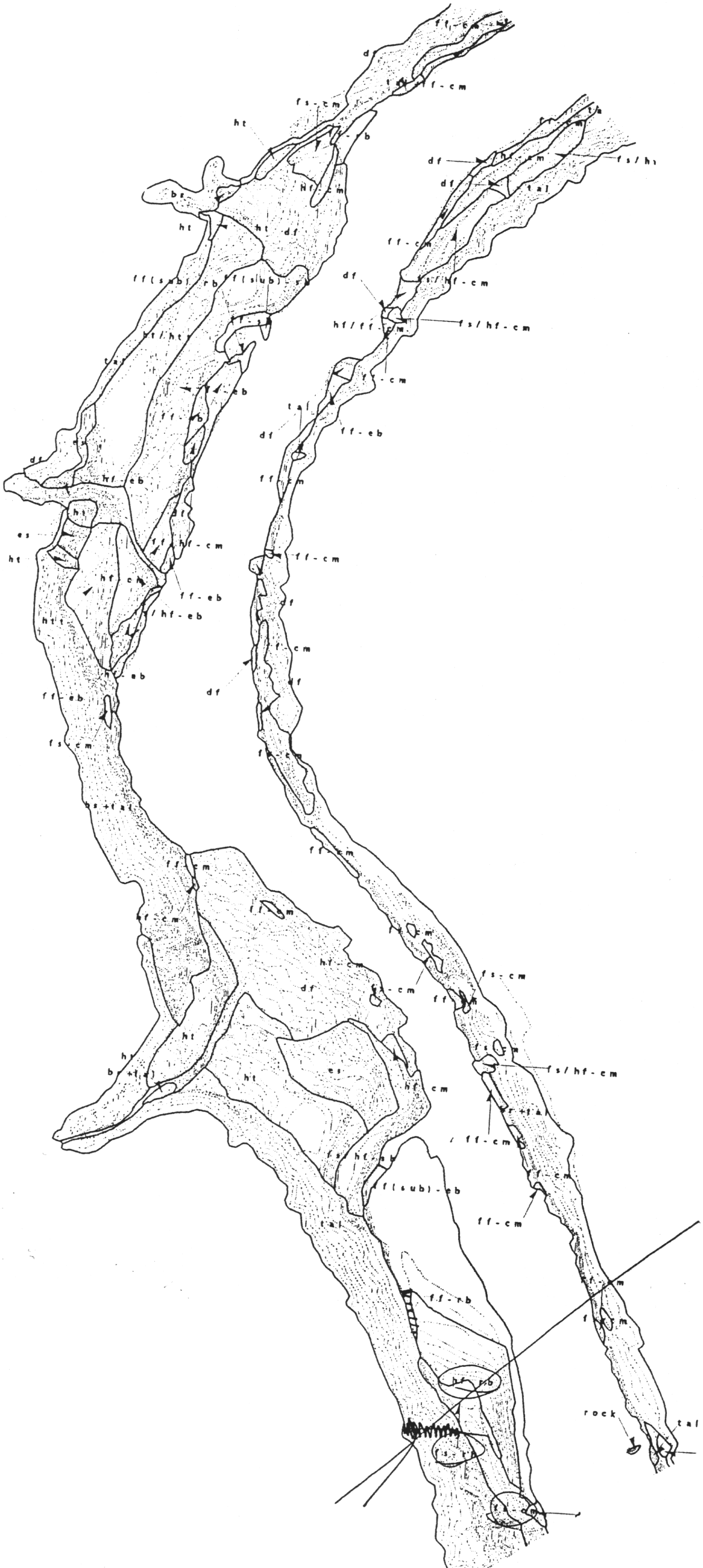

c-sb
df
u2-cm
c-eb
w-df
tal+sand
w-sb
ht
u-cm

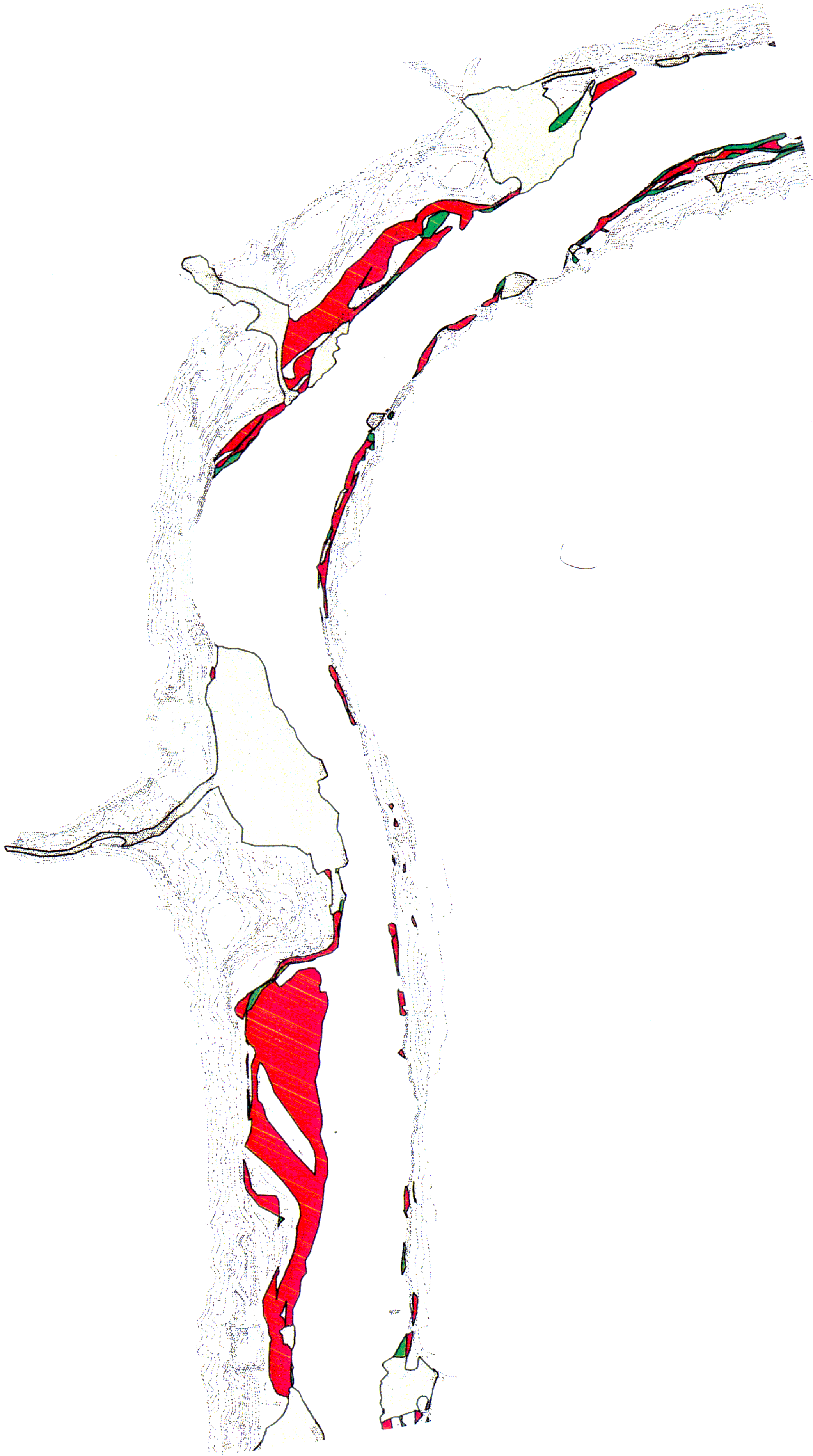
B

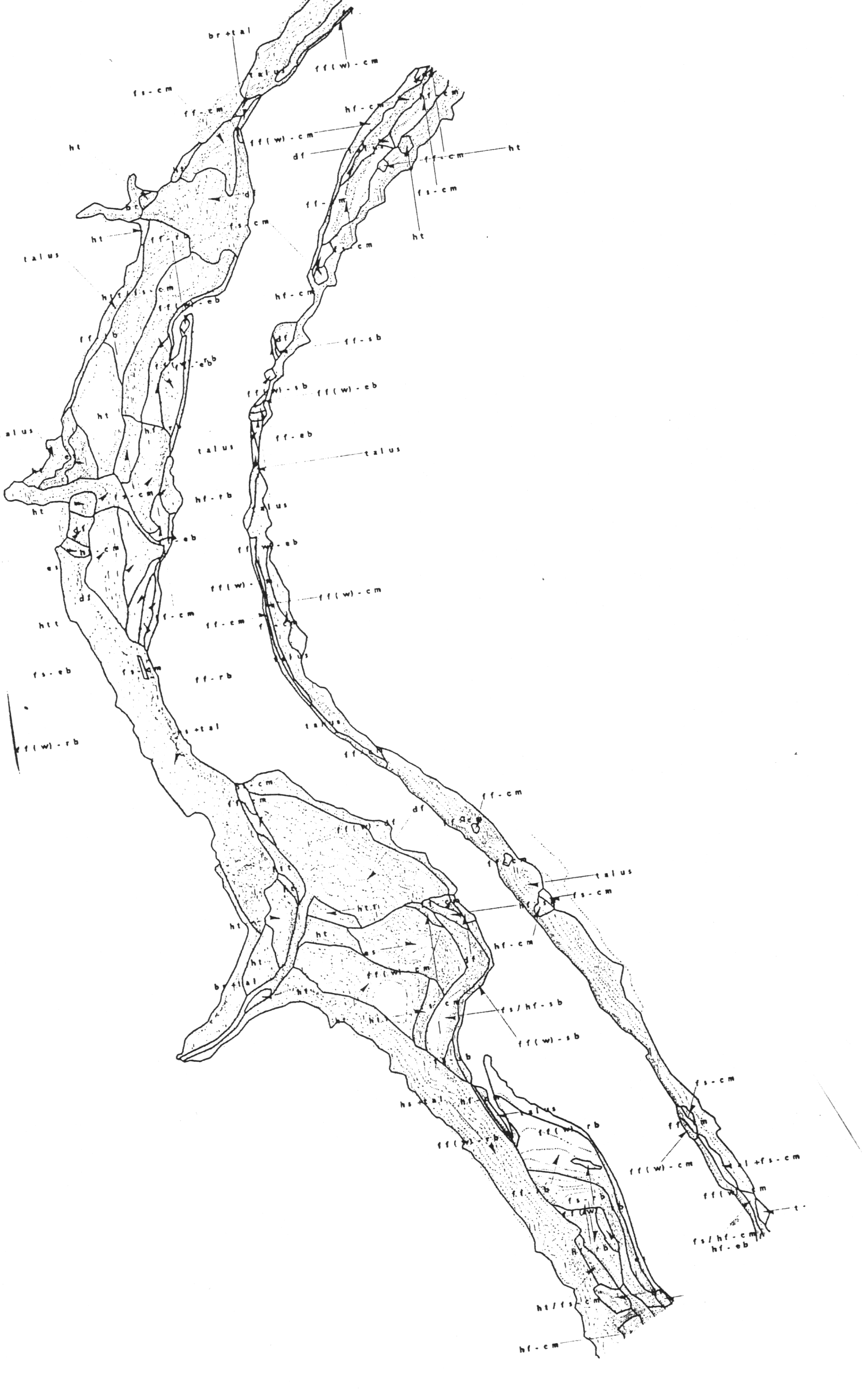

c-sb
w-sb
u-cm
df+es
c-cm
ht
w-rb
c-rb
c-eb
w-eb
tal+sand
w-cm
df+sand
c-sb

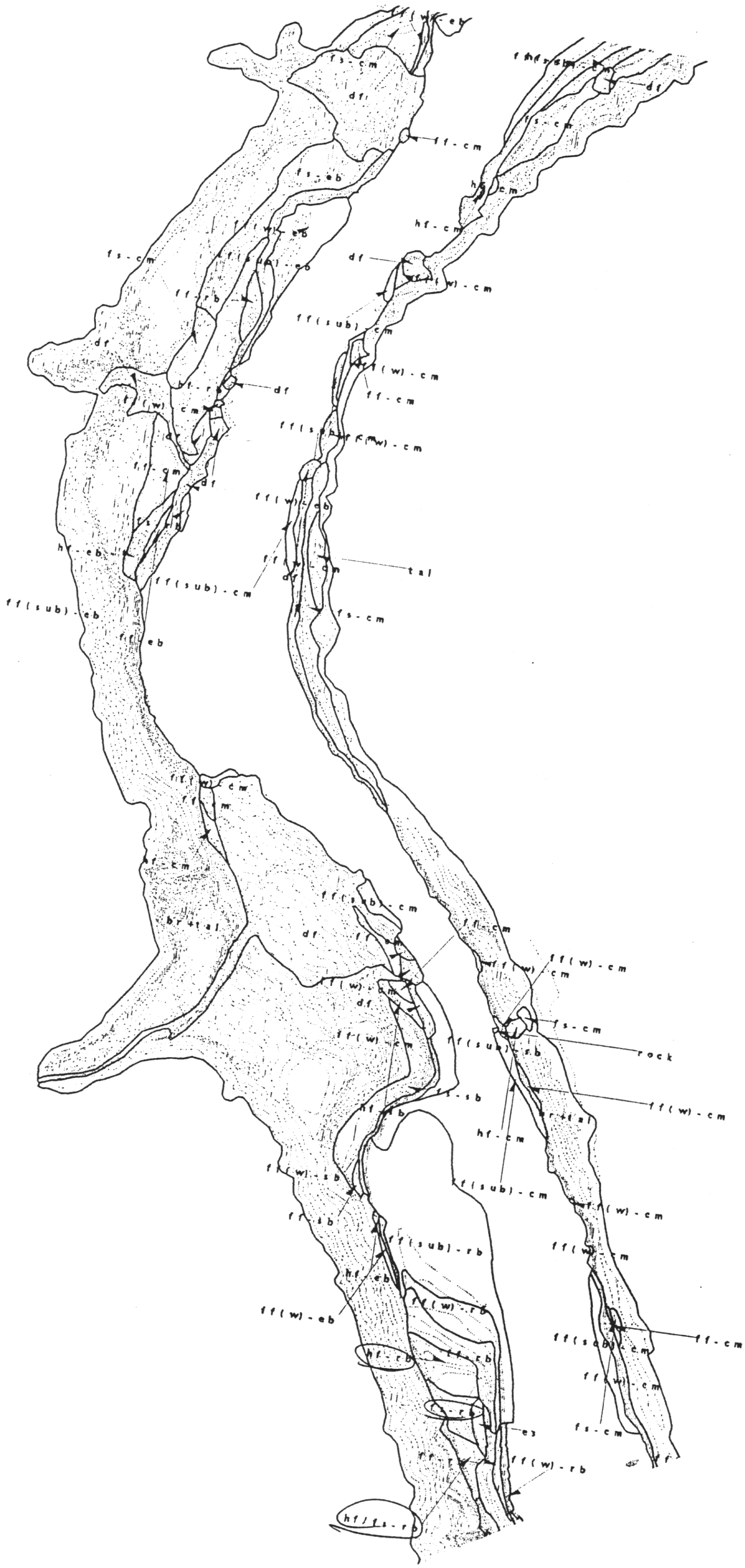

A.
B
u-cm
c-eb
sub-rb
df
u2-eb
w-b
w-eb
u-eb
c-eb
w-rb
w-rb
c-rb
sub-eb
c-eb
w-cm
df
df
c-cm
c-cm
u2-eb
u-eb
bf+tal
c-eb
c-cm
c-cm
u-cm
w-cm
u-cm
w-cm
c-cm
df
es/ht
ht
es/ht
w-sb
c-sb
c-sb
u-sb
w-sb
ht+tal
sub-rb
u-rb
w-rb
c-rb
u-rb
c-cm
w-cm
no photo cover
c-sb
ht
df
c-sb
ht
u-sb
w-sb
w-eb
c-sb
w-sb
c-eb
w-cm
w-cm
ht
w-cm
df
es
w-sb
c-cm
df+tal
c-sb
df+and
u-sb
u-cm
c-cm
c-cm
u-sb
df
u-sb
w-rb
c-rb
df/es
tal
c-cm



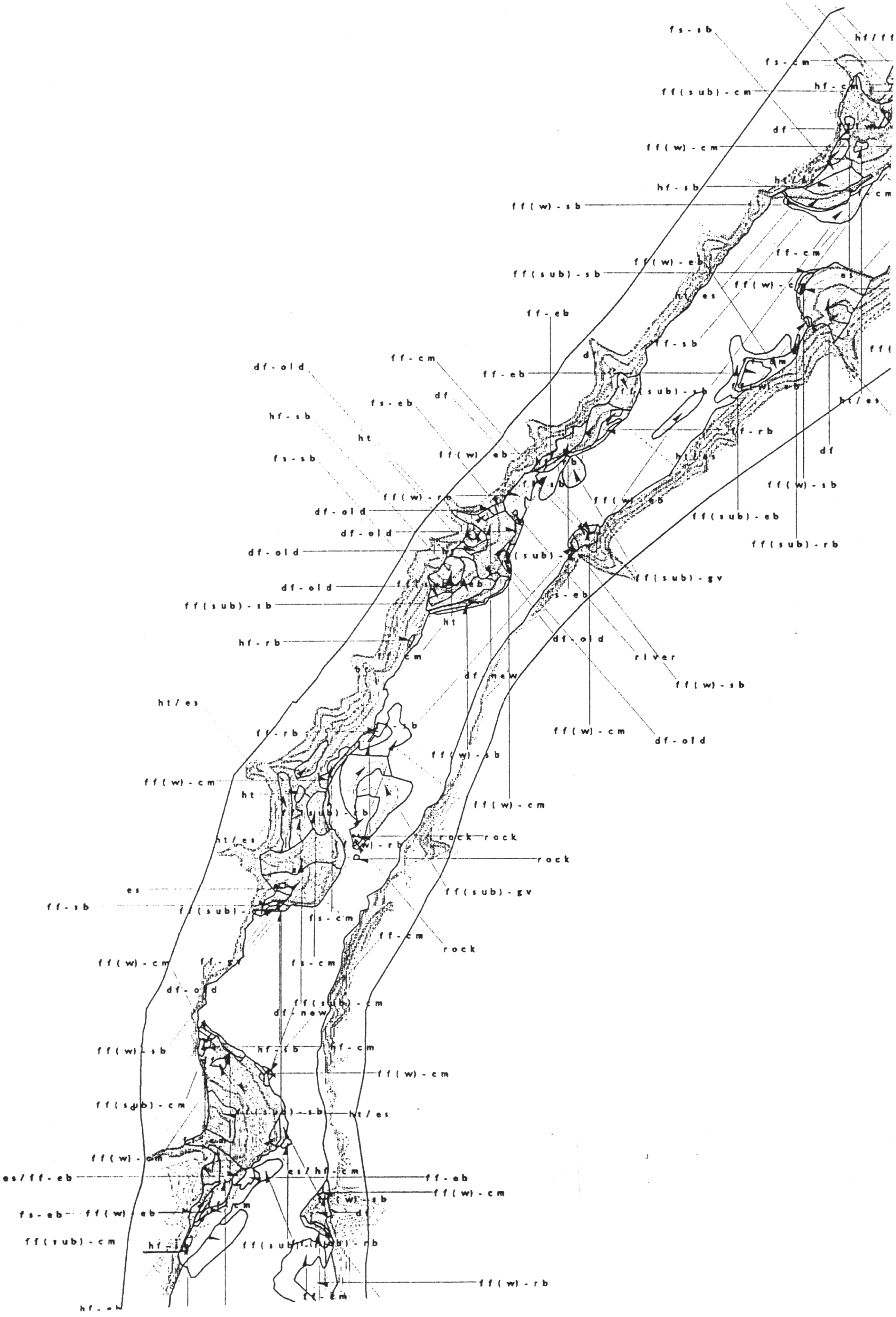

ff-cm
df
fs-cm
ht
hf-cm
bs
ht df
ff(sub)-rb
ff(sub)-sb
hf/ht
tal
ff-eb
hf-eb
es
ff/hf-cm
ff/hf-eb
fs-cm
bs+tal
df
fs/ht
fs/hf-cm
hf/ff-cm
ff-eb
ff(sub)-eb
ff-rb
rock
tal

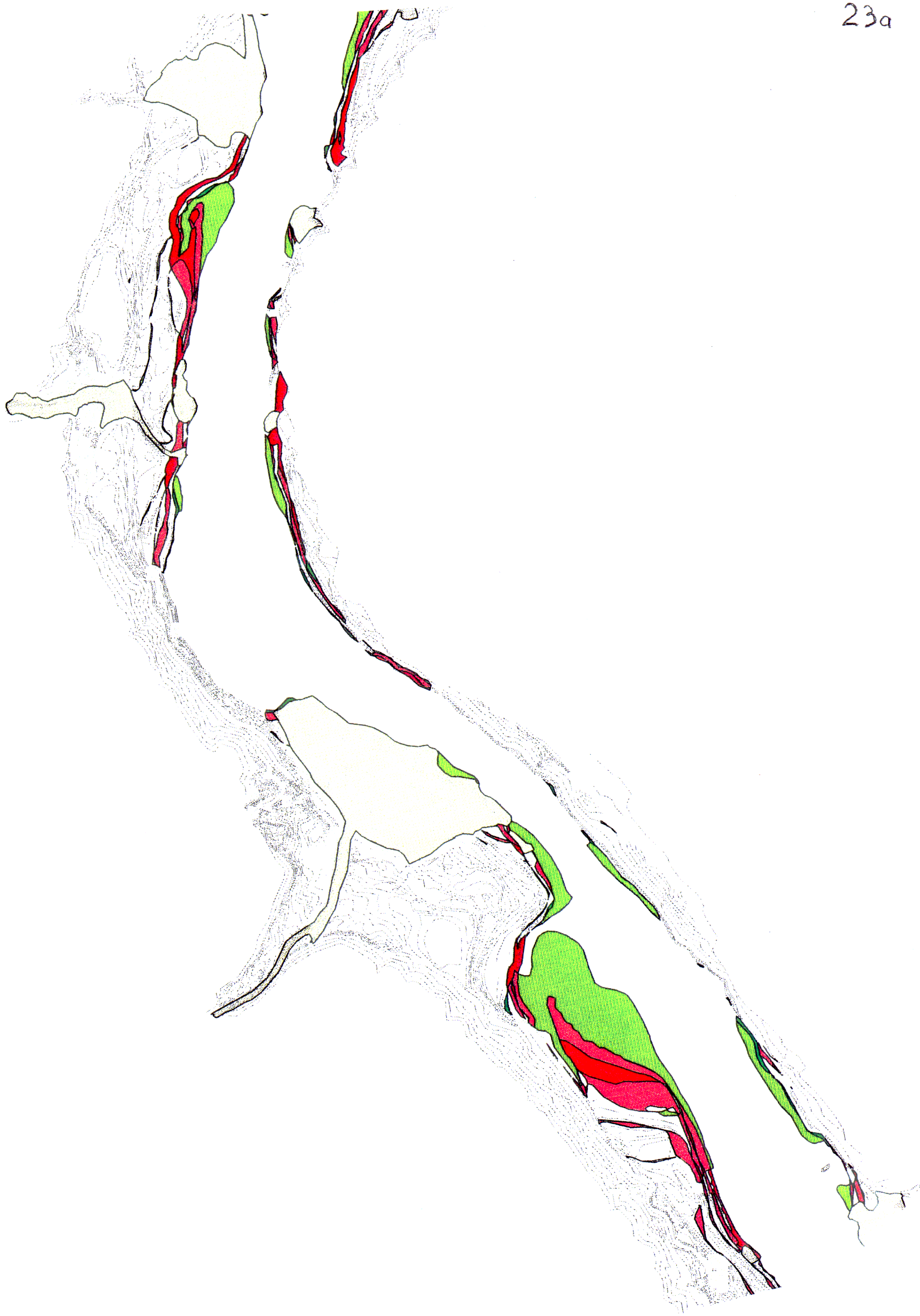


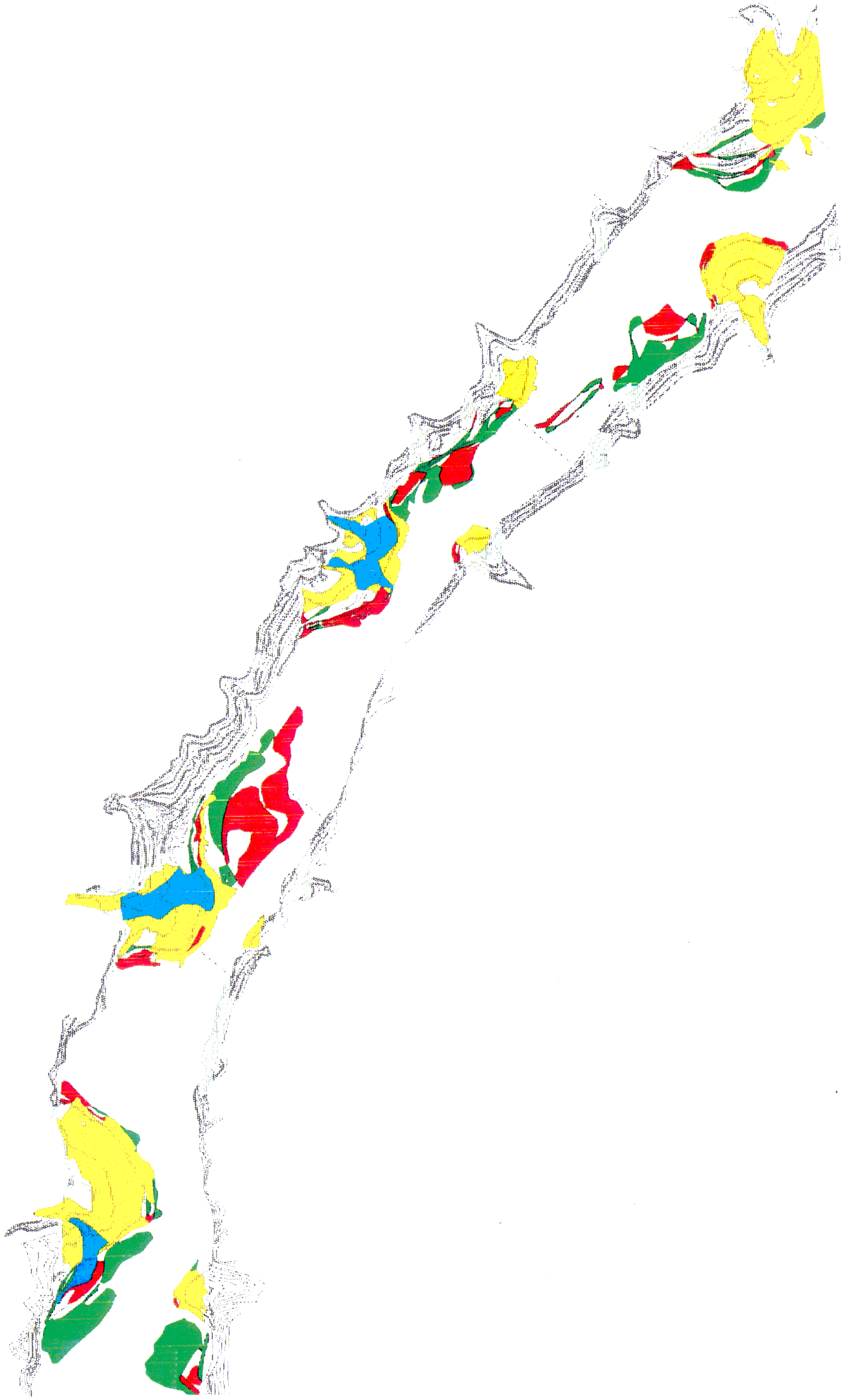

br+tal
talus
ff(w)-cm
fs-cm
ff-cm
hf-cm
ff(w)-cm
df
ht
fs-cm
ht
ht
talus
hf-cm
df
ff-sb
ff(w)-sb
ff(w)-eb
ff-eb
talus
talus
talus
hf-rb
ff(w)-eb
ff(w)-cm
ff-cm
ff-cm
ht
htt
fs-eb
ff-rb
ff(w)-rb
hs+tal
talus
ff-cm
df
talus
fs-cm
hf-cm
br+tal
fs/hf-sb
ff(w)-sb
hs+tal
talus
ff(w)-rb
fs-cm
ff(w)-cm
tal+fs-cm
fs/hf-cm
hf-eb
ht/fs-cm
hf-cm

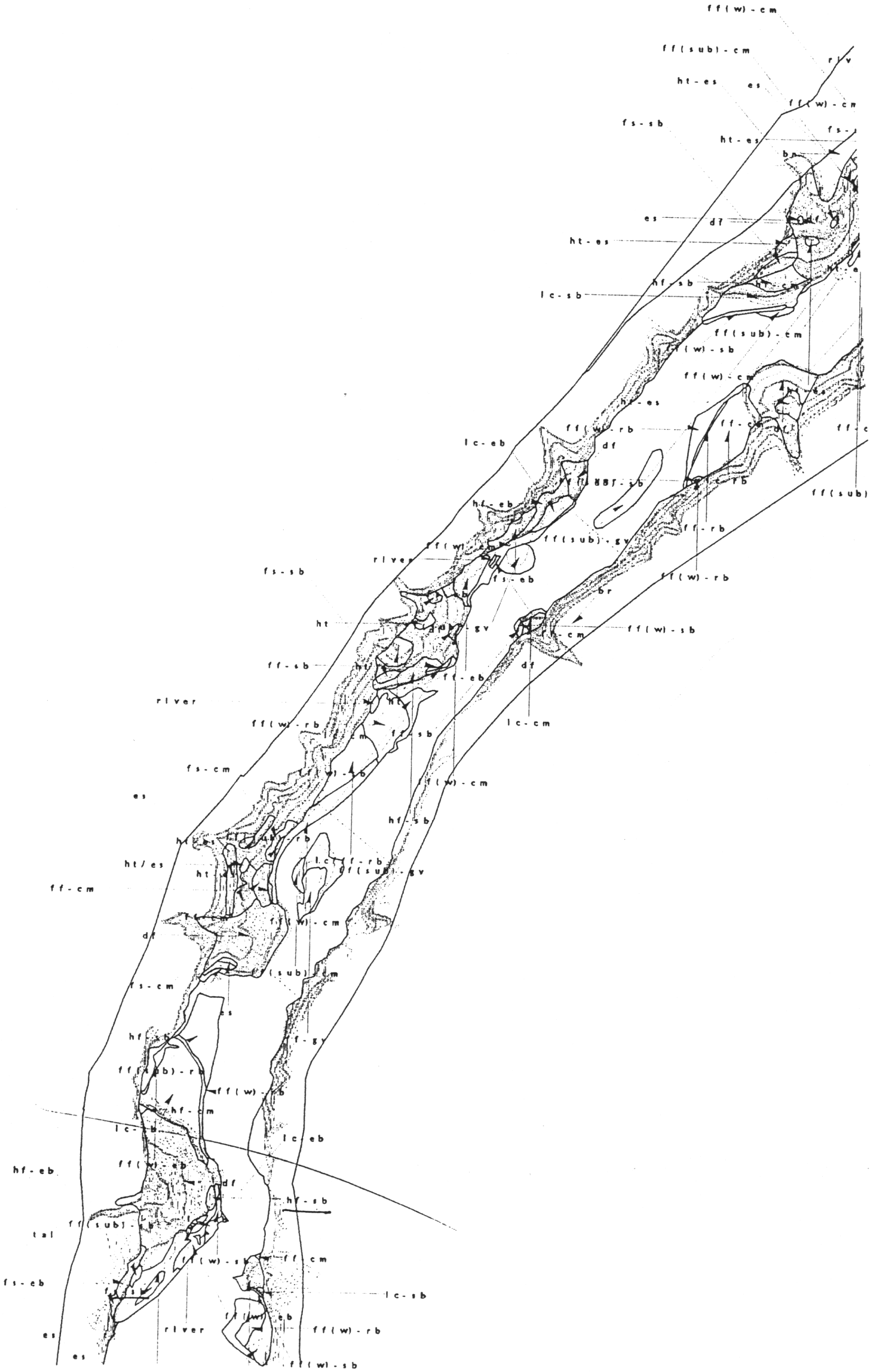

fs-cm
df
ff-cm
fs-eb
ff(w)-eb
ff(sub)-eb
ff-rb
hf-cm
ff(w)-cm
ff(sub)-cm
ff(w)-cm
ff-cm
tal
fs-cm
hf-eb
ff(sub)-cm
ff(sub)-eb
ff-eb
br+tal
ff(sub)-cm
fs-cm
rock
ff(w)-cm
ff(sub)-rb
hf-cm
ff(sub)-cm
ff(w)-sb
ff-sb
ff(sub)-rb
hf-eb
ff(w)-eb
ff(w)-rb
ff-rb
ff-cm
fs-cm
es
ff(w)-rb

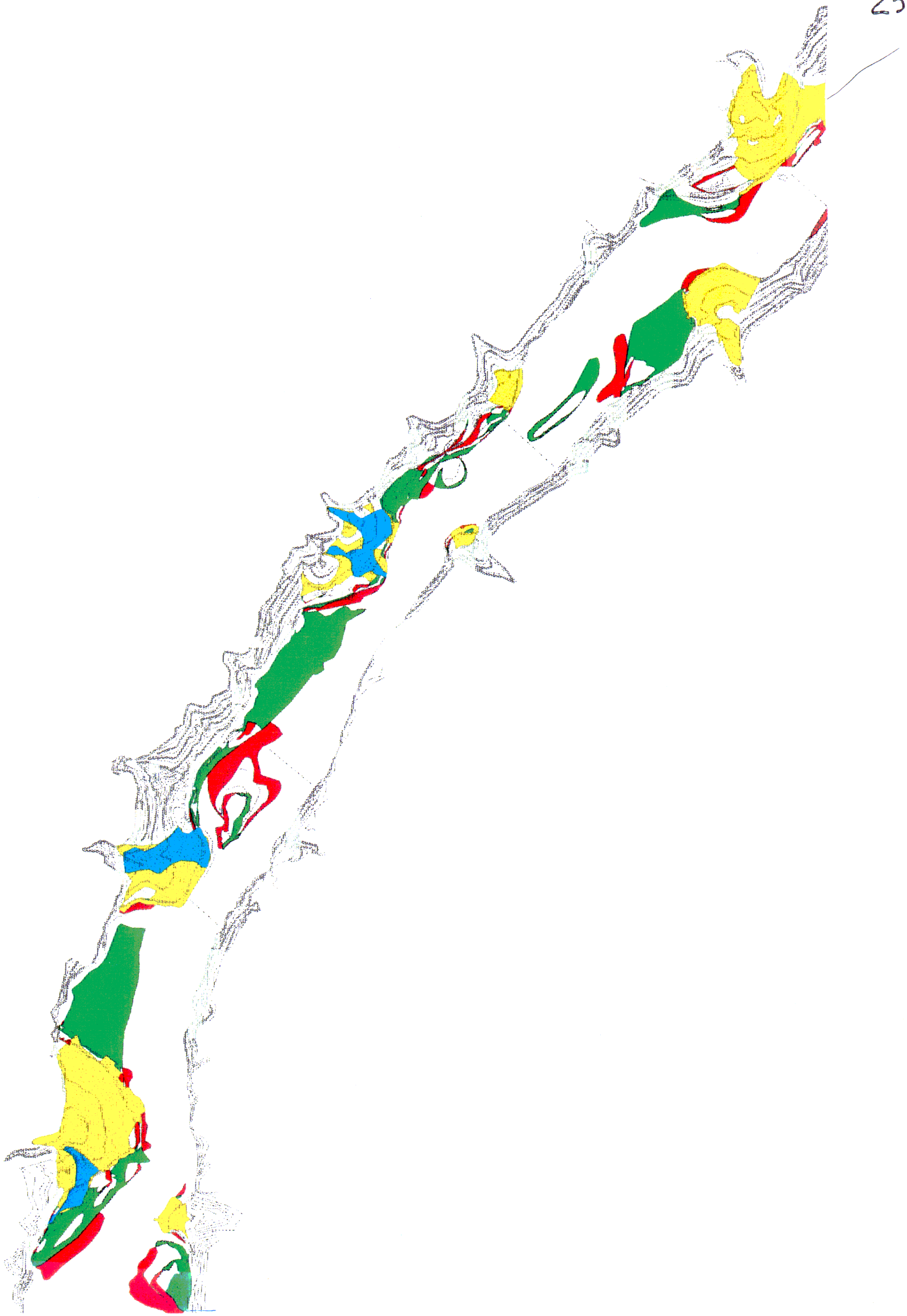
22b

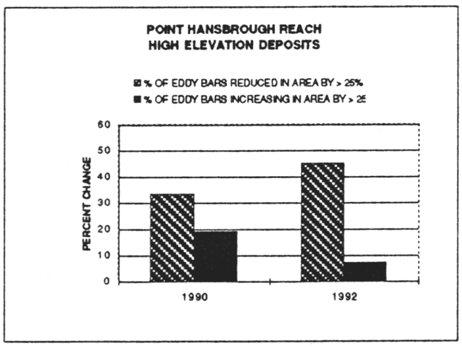

fs-sb
fs-cm
ff(sub)-cm
hf-cm
df
ff(w)-cm
hf-sb
ff(w)-sb
ff(w)-eb
ff(sub)-sb
ff-cm
ff-eb
df-old
ff-cm
ff-eb
df
fs-eb
hf-sb
ht
fs-sb
ff(w)-eb
ff(w)-rb
df-old
df-old
df-old
df-old
ff(sub)-sb
hf-rb
ff-rb
ht/es
df
ff(w)-sb
ff(sub)-eb
ff(sub)-rb
ff(sub)-gv
df-old
river
ff(w)-sb
df-new
ff(w)-cm
df-old
ht/es
ff-rb
ff(w)-cm
ht
ff(w)-sb
ff(w)-cm
ht/es
rock
rock
rock
ff(sub)-gv
es
ff-sb
fs-cm
ff-cm
rock
ff(w)-cm
fs-cm
df-old
ff(sub)-cm
df-new
ff(w)-sb
hf-sb
hf-cm
ff(w)-cm
ff(sub)-cm
ht/es
ff(w)-cm
es/ff-eb
es/hf-cm
ff-eb
ff(w)-cm
ff(w)-sb
fs-eb
ff(w)-eb
ff(sub)-cm
ff(w)-rb

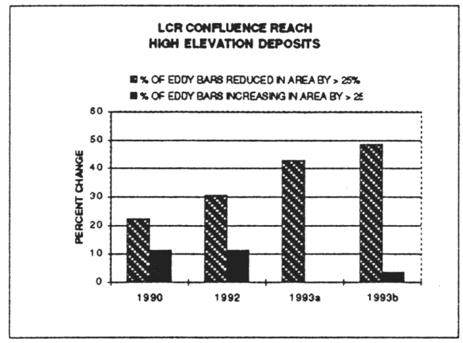


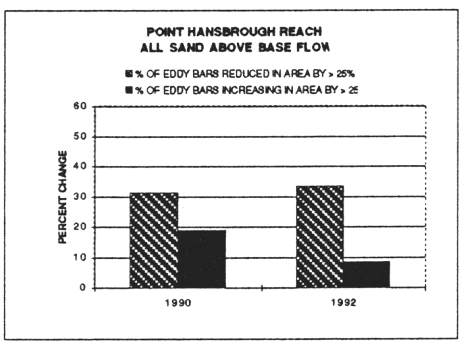


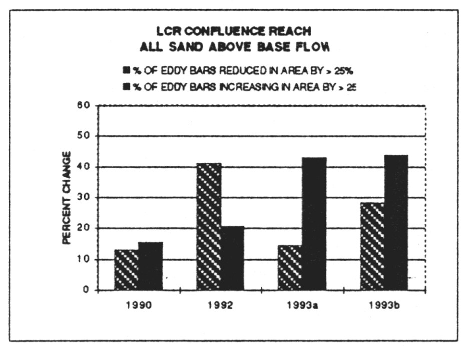

ff(w)-cm
ff(sub)-cm
ht-es
es
fs-sb
ht-es
es
df
ht-es
hf-sb
lc-sb
ff(sub)-cm
ff(w)-sb
ff(w)-cm
ht-es
lc-eb
ff(w)-rb
df
ff(sub)
hf-eb
ff(sub)-gv
ff-rb
river
fs-sb
fs-eb
br
ff(w)-rb
ht
ff(w)-sb
ff-sb
ff-eb
df
river
lc-cm
ff(w)-rb
fs-cm
ff(w)-cm
es
hf-sb
ht/es
ff(sub)-gv
ff-cm
df
ff(w)-cm
fs-cm
ff(sub)-cm
es
hf-cm
lc-eb
hf-eb
df
hf-sb
tal
ff(w)-sb
ff-cm
fs-eb
lc-sb
es
river
ff(w)-rb
es
ff(w)-sb

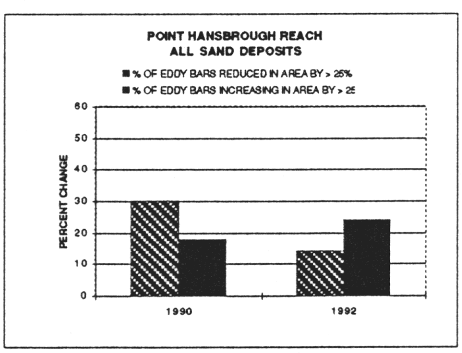


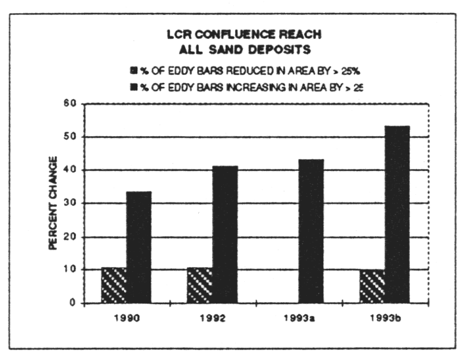

POINT HANSBROUGH REACH
HIGH ELEVATION DEPOSITS
% OF EDDY BARS REDUCED IN AREA BY > 25%
% OF EDDY BARS INCREASING IN AREA BY > 25
PERCENT CHANGE
1990
1992


LCR CONFLUENCE REACH
HIGH ELEVATION DEPOSITS
% OF EDDY BARS REDUCED IN AREA BY > 25%
% OF EDDY BARS INCREASING IN AREA BY > 25
PERCENT CHANGE
1990
1992
1993a
1993b


POINT HANSBROUGH REACH
ALL SAND ABOVE BASE FLOW
% OF EDDY BARS REDUCED IN AREA BY > 25%
% OF EDDY BARS INCREASING IN AREA BY > 25
PERCENT CHANGE
1990
1992


LCR CONFLUENCE REACH
ALL SAND ABOVE BASE FLOW
% OF EDDY BARS REDUCED IN AREA BY > 25%
% OF EDDY BARS INCREASING IN AREA BY > 25
PERCENT CHANGE
1990
1992
1993a
1993b


POINT HANSBROUGH REACH
ALL SAND DEPOSITS
% OF EDDY BARS REDUCED IN AREA BY > 25%
% OF EDDY BARS INCREASING IN AREA BY > 25
PERCENT CHANGE
1990
1992


LCR CONFLUENCE REACH
ALL SAND DEPOSITS
% OF EDDY BARS REDUCED IN AREA BY > 25%
% OF EDDY BARS INCREASING IN AREA BY > 25
PERCENT CHANGE
1990
1992
1993a
1993b

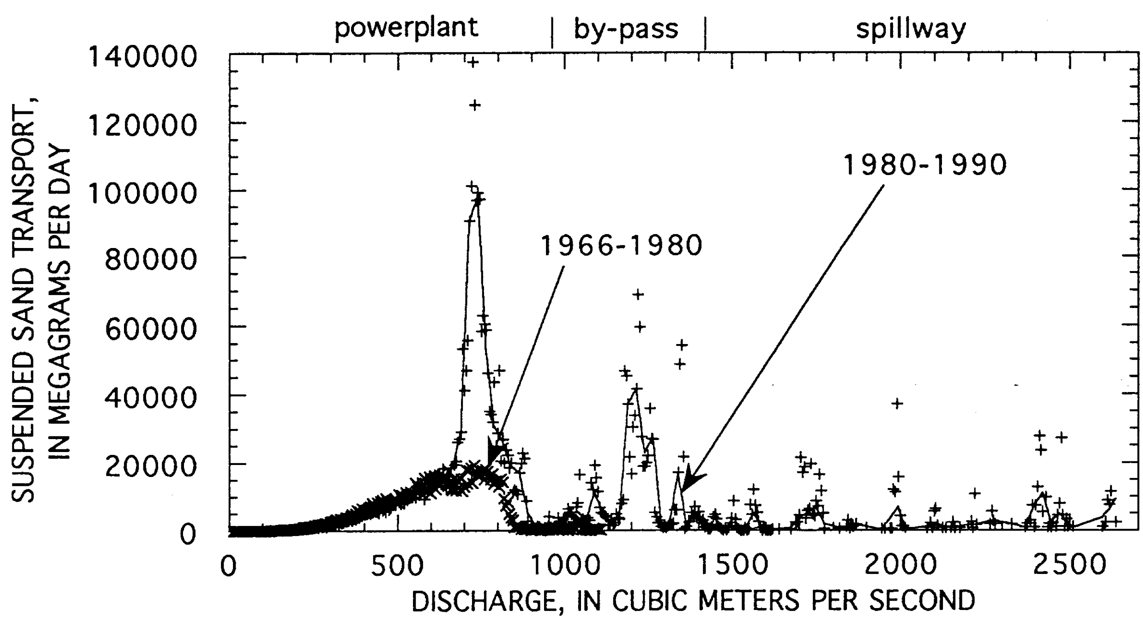

powerplant
by-pass
spillway
SUSPENDED SAND TRANSPORT, IN MEGAGRAMS PER DAY
140000
120000
100000
80000
60000
40000
20000
0
1980-1990
1966-1980
0
500
1000
1500
2000
2500
DISCHARGE, IN CUBIC METERS PER SECOND

Table 1. -- Aerial photograph information

Date and scale of photography	Agency and Photos	Discharge, in cubic meters per second
Point Hansbrough study reach		
December 31, 1935 (varies, approximately 1:30,000, 1:31,680, 1:35,000)	SCS 8433 - 8436	108
May 14, 1965 (1:12,000)	USGS 80 - 99	708 - 764
June 16, 1973 (1:14,400)	USGS 114 - 135	142 - 283
October 21, 1984 (1:3000)	GCES 2-176 to 2-221	141
June 30, 1990 (1:4800)	GCES 29-2 to 32-10	141
October 11, 1992 (1:4800)	GCES 34-4 to 37-9	226
May 30, 1993 (1:4800)	GCES 33-1 to 37-6	226
LCR confluence study reach		
December 31, 1935	SCS 100-107, 152-153	113
May 14, 1965	USGS 113 - 136	708 - 736
June 16, 1973	USGS 114 - 135	297 - 411
October 21, 1984	GCES 2-176 to 2-221	141
June 30, 1990	GCES 37-10 to 50-5	141
October 11, 1992	GCES 42-11 to 48-7	226
May 30, 1993	GCES 42-11 to 48-7	226

Table 2.--New debris flows occurring since June 1990, as determined from aerial photography[1]

Location in river miles and side of river	Did debris flow reach Colorado River?	Date of occurrence[2]
RM 62.3 R	yes	1990-1992
RM 62.3 R	yes	1990-1992
RM 62.5 R	yes	1990-1992
RM 62.7 R	yes	1990-1992
RM 62.9 R	yes	1990-1992
RM 63.2 R	yes	1990-1992
RM 63.5 L	yes	1990-1992
RM 63.7 L	no	1990-1992
RM 63.7 R	yes	1990-1992
RM 64.0 L	yes	1990-1992
RM 64.1 L	no	1990-1992
RM 64.3 L	yes	1990-1992
RM 65.0 L	yes	1990-1992
RM 65.0 L	no	1990-1992
RM 65.2 L	yes	1990-1992
RM 65.9 L	no	1990-1992
RM 66.0 L	no	1990-1992
RM 66.0 R	yes	1990-1992
RM 66.0 L	yes	1990-1992
RM 66.1 R	yes	1990-1992
RM 66.7 L	yes	1990-1992
RM 67.8 L	yes	1990-1992
RM 68.6 R	no	1990-1992
RM 70.3 L	yes	1990-1992
RM 70.4 L	yes	1990-1992
RM 59.8 R	yes	1992-1993
RM 64.0 L	yes	1992-1993
RM 65.2 R	yes	1992-1993

[1] no new debris flows observed in Point Hansbrough Reach

[2] see Table 1 for date of each year's photography

TABLE 3A. --Area of Map Units in Point Hansbrough Reach

Map Unit	Flow Level		Area of Deposit, in Square Meters, within Indicated River Miles					
			42-43	43-44	44-45	45-46	46-47	47-48
river			152833	152337	132313	133262	148485	166456
reattachment bars	fluctuating flow	sub	0	0	3660	0	0	0
		wet	0	2007	4142	2668	1628	3738
		dry	611	4674	7968	3236	3291	6816
	ff/hf		0	0	2316	0	0	0
	high flow sands		842	6488	5349	1528	2447	3689
	hf/fs		0	4037	0	577	0	0
	flood sands		0	1800	806	490	0	2663
	ht/fs		0	783	0	0	0	0
TOTAL			1453	19789	24241	8499	7366	16906
separation bars	fluctuating flow	wet	0	506	2256	1016	198	1061
		dry	195	608	2882	2900	45	391
	high flow sands		0	2063	8594	277	0	488
	fs/hf		573	741	0	0	0	3576
	flood sands		0	4045	1025	0	0	144
	htt/fs		664	0	4200	0	0	0
TOTAL			1432	7963	18957	4305.5	243	5660
eddy bar	fluctuating flow	wet	1122	389	0	616	943	1015
		dry	238	487	0	507	503	2147
	high flow sands		0	0	0	0	0	1812
	hf/fs		3547	0	0	226	0	1427
	flood sands		2992	1666	0	2556	9062	1725
TOTAL			7899	2542	0	3905	10508	8126
channel-margin deposits	fluctuating flow	wet	8124	1076	65	2368	6114	4241
		dry	742	2079	238	1209	2801	1832
	high flow sands		0	0	838	1641	8959	6175
	hf/fs		13712	1793	51	13012	1053	2340
	flood sands		0	48	567	2022	25388	16978
	fs and htt or ht		0	0	0	0	4994	746
	htt		0	0	1855	0	3996	2821
	high terrace		6061	6636	6184	1202	8230	27316
TOTAL			37568	13704	10036	23699	61979	62653
ff(w)-cm/df	wet		0	414	0	0	0	0
fs/hf-cm /df			446	1090	0	544	0	0
ff-sb/df			0	0	0	225	0	0
fs-cm or fs/hf-cm and tal			17263	1462	0	3164	888	408
hs/fs-cm			0	0	0	601	0	0
ht or htt/ eolian			0	814	0	0	0	0
ht/gv			0	0	476	0	0	0
TOTAL HIGH TERRACES			6393	7434.5	10377	1202	14723	30510
gravel bar	fluctuating flow	wet	0	4640	0	0	0	0
		dry	0	4640	0	0	0	922
TOTAL GRAVEL			0	9280	238	0	0	922
debris fans			1984.7	51368	21694	9506.83	15462	30685
TOTAL FINE SAND			48352	43998	53234	40409	80096	93345
TOTAL FINE SAND PER KM			30055	27349	33090	25118	49787	58022
TOTAL EDDY SAND			10784	30294	43198	16709.5	18117	30692
EDDY/TOTAL			0.223	0.689	0.811	0.414	0.226	0.329
EDDY/TOTAL BLW FS LEVEL			0.251	0.827	1.008	0.426	0.277	0.488
proportion gravel			0.000	0.174	0.004	0.000	0.000	0.010
TOTAL FINE-GRAINED DEPOSITS AT INDICATED LEVEL								
FF-LEVEL			11032	12033	22369	14632.5	15523	21241
HF-LEVEL			9906.7	12200	15964.5	10534.8	11933	15836
FS-LEVEL			21095	12512	4523.5	14130	37918	25759

TABLE 3B. --Area of Map Units in LCR confluence reach

Map Unit	Flow Level	60-61	61-62	62-63	63-64	64-65	65-66	66-67	67-68	68-69	69-70	70-71	71-72
		Area of Deposit, in Square Meters, within Indicated River Miles											
river		137028	114031	161551	176656	171316	136359	95210	139948	108796	185202	140348	162363
reattachment bars	fluctuating flow sub	1568	607	2560	7709	8805	2202	632	2053	0	880	2304	134
	wet	2594	1457	917	3704	4757	4313	80	20	1897	2313	489	1032
	dry	3202	1881	205	6444	6521	4682	70	0	4396	4466	366	1933
	ff/hf	0	0	0	0	401	0	0	0	0	0	0	0
	high flow sands	846	0	0	2623	1994	96	0	0	2122	2905	136	0
	hf/fs	0	0	0	0	0	0	0	0	455	0	0	0
	flood sands	894	0	0	4456	3080	0	6182	0	0	6769	0	0
TOTAL		9104	3945	3682	24936	25558	11293	6964	2073	8415	17333	3295	3099
separation bars	fluctuating flow sub	521	241	933	0	449	0	0	0	0	0	92	157
	wet	3442	127	1564	1151	1074	606	0	164	0	0	701	0
	dry	1417	539	2266	468	962	2678	0	245	0	0	620	553
	ff/hf	0	0	0	0	33	0	0	0	0	0	0	0
	high flow sands	1669	951	2219	2148	1262	0	0	789	0	0	423	0
	flood sands	1842	869	306	1695	1237	0	220	1524	0	0	198	0
	htt	0	0	0	0	0	0	0	1386	37	0	0	0
	high terrace	0	0	0	0	0	0	0	0	6	0	0	0
TOTAL		8891	2727	7288	5886.5	5017	3284	220	4108	43	0	2034	710
eddy bar	fluctuating flow sub	0	228	192	0	0	0	0	150	375	1651	0	0
	wet	361	1411	1939	699	0	257	1686	365	166	1157	1111	1565
	dry	96	344	3405	0	0	147	3103	381	456	531	226	0
	ff/hf	0	0	0	620	0	0	0	0	0	0	0	0
	high flow sands	1292	2171	1251	1407	755	0	4291	960	3216	542	0	2771
	hf/fs	0	0	0	0	0	0	0	0	0	948	8612	780
	flood sands	342	1359	1751	5308	1236	2198	68	0	282	4538	0	3097
TOTAL		2091	5513	8538	8034	1991	2602	9148	1856	4495	8419	1337	7433
channel-margin deposits	fluctuating flow sub	0	270	0	1348	2479	0	0	881	1695	3415	909	5667
	wet	120	1919	1446	1736	4106	758	1070	4888	2519	7072	2864	3433
	dry	111	6340	2251	1238	2002	1620	3604	5406	3662	2023	3994	2550
	ff/hf	0	0	0	0	0	0	0	0	303	1702	1545	16293
	ff/hf/fs	0	0	0	0	0	0	0	0	435	0	0	0
	high flow sands	1426	2010	528	2100	2511	11384	4985	5032	1395	9041	2340	4469
	hf/fs	331	0	0	0	0	0	241	0	9219	8786	8795	4684
	flood sands	112	2682	1158	4155	8696	12000	6191	18129	7431	0	12155	3259
	hf/fs/htt/ht	0	0	0	0	0	0	0	15699	37739	0	0	0
	fs/htt	0	0	0	0	0	0	3042	0	0	0	16063	11752
	htt	0	0	0	0	0	0	3813	20292	11752	6826	6735	19333
	htt/ht	0	0	0	0	0	0	592	1761	0	0	6955	2035
	high terrace	2693	1319	1005	3842	19339	29840	24814	28843	1050	3643	23466	17263
TOTAL		5270	16063	10262.5	20394.5	39133	92503	52458	145747.5	112448.5	112701	133936	105363.5
channel margin / debris fan		0	0	0	0	0	0	0	0	0	0	922	7377
es/fs-sb		0	0	0	849	0	0	0	0	0	0	0	0
es/fs-cm		0	0	180	0	0	0	1139	0	0	1242	2384	0
es/fs-cm (or ff/hf-cm)/gv		0	2687	0	0	0	0	0	0	0	2204	0	0
ht or htt/ eolian		954	1255	7359	11951	0	73802	5787	85996	27156	96224	64174	11605
ht/gv		0	0	0	0	0	0	0	0	37593	0	0	0
TOTAL HIGH TERRACES		3170	1946.5	4684.5	9817.5	19339	66741	33633.5	93894	45176.5	58581	77274.5	50309.5
gravel bar	fluctuating flow sub	633	5348	5183	8424	5486	3441	15551	11110	23178	5260	5541	8593
	wet	364	7101	0	0	1111	795	7978	2246	0	25498	9092	13182
	dry	7166	5872	5421	455	1086	5864	487	1887	1011	4124	4208	6172
	ff/hf	0	6998	0	0	0	0	0	5814	21182	3962	0	0
	ff/hf/fs	0	0	21835	0	0	0	3938	0	6362	0	0	0
	high flow	0	0	0	0	0	0	0	0	0	0	0	0
	hf/fs	0	0	0	0	0	0	0	0	11453	0	0	0
	flood sands	0	0	0	0	0	0	0	0	0	2182	0	0
	htt or ht	0	0	0	0	0	14203	3220	0	0	8898	0	0
	undifferentiated	0	0	0	0	0	0	0	0	0	21008	9292	0
channel margin / gravel bar	sub	0	0	210	0	0	0	1286	0	0	0	0	0
	fluctuating flow	0	0	0	0	0	0	0	3637	0	6897	28749	10269
	ff/hf	0	0	0	0	0	0	0	0	0	5592	0	0
	hf	0	0	0	0	0	0	0	0	2390	10925	0	0
	hf/fs	0	0	0	0	0	0	0	0	3358	0	0	0
	fs	0	0	0	0	0	0	0	0	0	5928	0	0
	htt	0	0	0	0	0	0	0	0	0	663	0	0
	hf/fs/htt	0	0	0	0	0	0	0	0	0	11445	0	0
	fs/htt/ht	0	0	0	0	0	0	0	0	111528	0	0	0
gv/es		0	29026	0	0	0	0	63981	0	113251	0	5416	0
TOTAL GRAVEL		8163	39832	32544	8879	7683	24303	63808	22876	121007	91657	45216	33082
debris fans		50061	22465	53634	43663	46157	72155	49434	82043	12427	52031	24476	22575.5
TOTAL FINE SAND		28526	30195	34455	69493	91038	176423	102423.5	247678.5	170578	197034	217876	166915
TOTAL FINE SAND PER KM		17732	18769	21417	43196	56588	109663	63666	153955	106030	122474	135430	103753
TOTAL EDDY SAND		20086	12185	19508	39281	32566	17179	16332	8037	12953	25752	6666	11242
EDDY/TOTAL		0.704	0.404	0.566	0.565	0.358	0.097	0.159	0.032	0.076	0.131	0.031	0.067
EDDY/TOTAL BLW FS LEVEL		0.905	0.463	0.781	0.786	0.622	0.400	0.473	0.131	0.216	0.357	0.214	0.190
proportion gravel		0.222	0.569	0.486	0.114	0.078	0.121	0.384	0.085	0.414996	0.329	0.243	0.221
TOTAL FINE-GRAINED DEPOSITS AT INDICATED LEVEL													
FF-LEVEL		13432	15901	17783	24807	31372	17263	10888	16371.5	15462.5	29646	28823	30305
HF-LEVEL		5398.5	5669.4	3998	8588	6739	11480	9396.5	10705.75	23335.75	25507	12375	18118.5
FS-LEVEL		3355.5	5447.4	3305	16038.5	14249	14198	14872	23577.75	41557.25	22107	30280	14964

Table 4.—Eddy Complex Change, 1973-1984

LCR Confluence Reach

	Mean area of deposition as proportion of total eddy complex area	Mean area of erosion as proportion of total eddy complex area
entire LCR reach	0.166	0.073
Tapeats gorge	0.160	0.062
Big Bend area	0.174	0.087
above Little Colorado River	0.122	0.062
below Little Colorado River	0.175	0.075

Eddy complexes where erosion proportion was greater than twice the mean response

Eddy complex number (proportion of change)
size class of eddy complex, in square meters

very small (<2500)	2500-5000	5000-10,000	10,000-20,000	20,000-40,000
15 (0.318)		40 (0.283)		65 (0.208)
19 (0.169)		43 (0.206)		95 (0.328)
35 (0.169)		89 (0.414)		
85 (0.454)				

Table 5.—Eddy Complex Change, 1984-1990

LCR Confluence Reach

	Mean area of deposition as proportion of total eddy complex area	Mean area of erosion as proportion of total eddy complex area
entire LCR reach	0.132	0.115
Tapeats gorge	0.130	0.127
Big Bend area	0.134	0.100
above Little Colorado River	0.145	0.079
below Little Colorado River	0.129	0.122

Eddy complexes where erosion proportion was greater than twice the mean response

Eddy complex number (proportion of change)
size class of eddy complex, in square meters

	very small (<2500)	2500-5000	5000-10,000	10,000-20,000	20,000-40,000
deposition	4 (0.315)	47 (0.481)		8 (0.267)	44 (0.277)
	15 (0.266)	74 (0.287)		80 (0.355)	65 (0.331)
	16 (0.333)				
	32 (0.302)				
	63 (0.348)				
	70 (0.326)				
	91 (0.361)				
	94 (0.783)				
erosion	15 (0.410)	2 (0.275)	18 (0.269)	62 (0.292)	42 (0.283)
	48 (0.445)		26 (0.243)		
	49 (0.335)		30 (0.317)		
	63 (0.282)		43 (0.242)		
	71 (0.268)				
	72 (0.381)				
	87 (0.235)				
	96 (0.257)				

Table 6.—Eddy Complex Change, 1990-1992

LCR Confluence Reach

	Mean area of deposition as proportion of total eddy complex area	Mean area of erosion as proportion of total eddy complex area
entire LCR reach	0.106	0.152
Tapeats gorge	0.121	0.156
Big Bend area	0.086	0.148
above Little Colorado River	0.103	0.108
below Little Colorado River	0.107	0.161

Eddy complexes where erosion proportion was greater than twice the mean response

Eddy complex number (proportion of change)
size class of eddy complex, in square meters

	very small (<2500)	2500-5000	5000-10,000	10,000-20,000	20,000-40,000
deposition	19 (0.826)	36 (0.470)	6 (0.214)		
	20 (0.443)	47 (0.513)	25 (0.240)		
	41 (0.315)		26 (0.246)		
	49 (0.307)		30 (0.356)		
	51 (0.237)		31 (0.540)		
	72 (0.483)		43 (0.323)		
	79 (0.957)		75 (0.241)		
	96 (0.521)				
erosion	4 (0.456)		67 (0.339)	46 (0.437)	42 (0.374)
	48 (0.876)				
	51 (0.367)				
	57 (0.598)				
	63 (0.386)				
	64 (0.573)				
	71 (0.344)				
	91 (0.547)				
	94 (0.304)				

Table 7.—Eddy Complex Change, 1992-1993

LCR Confluence Reach

	Mean area of deposition as proportion of total eddy complex area	Mean area of erosion as proportion of total eddy complex area
entire LCR reach	0.211	0.117
Tapeats gorge	0.254	0.129
Big Bend area	0.154	0.102
above Little Colorado River	0.070	0.121
below Little Colorado River	0.238	0.116

Eddy complexes where erosion proportion was greater than twice the mean response

Eddy complex number (proportion of change)
size class of eddy complex, in square meters

	very small (<2500)	2500-5000	5000-10,000	10,000-20,000	20,000-40,000
deposition	35 (0.525)	90 (0.425)	25 (0.489)	28 (0.545)	34 (0.704)
	57 (0.426)			29 (0.484)	
	64 (0.907)			50 (0.514)	
	78 (0.658)				
	81 (0.437)				
	85 (0.604)				
erosion	4 (0.405)	36 (0.352)	31 (0.332)		1 (0.243)
	15 (0.450)	47 (0.826)	43 (0.259)		
	19 (0.522)		45 (0.284)		
	20 (0.390)		67 (0.263)		
	48 (0.392)		75 (0.343)		
	51 (0.325)				
	72 (0.993)				
	87 (0.262)				
	91 (0.462)				
	94 (0.584)				
	96 (0.426)				
	98 (0.701)				

TABLE 8. --Number of Eddy Complexes that were smaller or larger than in 1984

Deposit level and eddy complex size	Number of eddy complexes in category	1990: less than 0.75 times of eddy complex size in 1984	1990: more than 1.25 times of eddy complex size in 1984	1992: less than 0.75 times of eddy complex size in 1984	1992: more than 1.25 times of eddy complex size in 1984	1993 above: Number of eddy complexes	1993 above: less than 0.75 times of eddy complex size in 1984	1993 above: more than 1.25 times of eddy complex size in 1984	1993 below: Number of eddy complexes	1993 below: less than 0.75 times of eddy complex size in 1984	1993 below: more than 1.25 times of eddy complex size in 1984
Point Hansbrough reach											
high elevation deposits[1]											
very small	21	11	5	15	2						
medium	9	1	1	2	0						
large	12	2	2	2	1						
TOTAL	42	14	8	19	3						
PERCENT CHANGE		*33*	*19*	*45*	*7*						
all sand above base flow											
very small	26	7	3	7	2						
medium	9	3	2	2	1						
large	13	5	4	7	1						
TOTAL	48	15	9	16	4						
PERCENT CHANGE		*31*	*19*	*33*	*8*						
all sand deposits											
very small	29	11	7	7	8						
medium	9	2	0	0	1						
large	12	2	2	0	3						
TOTAL	50	15	9	7	12						
PERCENT CHANGE		*30*	*18*	*14*	*24*						
LCR confluence reach											
high elevation deposits											
small	11	4	4	7	1	3	2	0	8	3	2
medium	14	5	2	7	2	3	2	0	11	6	1
large	13	2	2	2	2	3	1	0	10	2	0
very large	9	1	0	2	0	1	0	0	8	6	0
TOTAL	36	8	4	11	4	7	3	0	29	14	1
PERCENT CHANGE		*22*	*11*	*31*	*11*		*43*	*0*		*48*	*3*
all sand above base flow											
small	11	6	2	6	3	3	3	0	8	2	3
medium	17	3	2	3	4	3	1	1	14	4	6
large	13	1	2	10	4	3	0	2	10	2	5
very large	9	1	2	3	0	1	0	0	8	3	3
TOTAL	39	5	6	16	8	7	1	3	32	9	14
PERCENT CHANGE		*13*	*15*	*41*	*21*		*14*	*43*		*28*	*44*
all sand deposits											
small	11	6	3	4	5	3	3	0	8	2	4
medium	17	2	6	2	7	3	0	0	14	1	9
large	13	1	3	2	5	3	0	2	10	1	5
very large	9	1	4	0	4	1	0	1	8	1	3
TOTAL	39	4	13	4	16	7	0	3	32	3	17
PERCENT CHANGE		*10*	*33*	*10*	*41*		*0*	*43*		*9*	*53*

[1]formed in 1983-1986

APPENDIX A

ERROR ANALYSIS OF DATA TRANSFER METHODOLOGY

MEMORANDUM

To: Dr. Jack Schmidt
Department of Geography
Utah State University
Logan, UT

FROM: Patrick Wright
D.P. Associates Inc.
Contractor for B.O.R. Remote Sensing and GIS

SUBJECT: Accuracy assessment on data transfer work performed by USU for the Glen Canyon Environmental Studies geographic information system, (GCES/GIS).

An accuracy assessment was performed on the 1:2400 scale surficial geology map. This map is to be incorporated into the Glen Canyon Environmental Studies geographic information system data ~~base,~~ (GCES/GIS). The goal of the assessment is to apply an level of error to the USU data set to facilitate its use in the GCES/GIS.

The original mapping was done using a Bausch & Lomb Stereo Zoom Transfer Scope set on mono to transfer polygonal information representing surficial geology. The only map checked was the 1990 hard copy data set representing GCES site 3 map sheet 2.

The checks performed by the USBR Remote Sensing and Geographic Information section were based on a comparison of the location of common features found on both the data set developed on the aerial photography, and the transferred data set registered to a 1:2400 scale orthophoto map. An orthophoto is a photograph showing images of objects in their true orthographic positions.

The location of line intersections that could be photographically referenced to common features on both the aerial photography and orthophoto map were compared. The displacement on the 1:2400 scale data was measured. National Map Accuracy Standards states that " For maps on publication scales larger than 1:20,000 not more than 10 percent of the points tested shall be in error by more than 1/30th of an inch. " Out of the 16 points that could be compared two were off by 3/30th of an inch.

It must be noted at this point, to apply a valid National Map Accuracy Standard to a map product the check must be done by a conventional survey of higher accuracy. By definition this check does not comply with this standard, but to do so would have been too costly for our goals.

The maximum level of error of the 1:2400 scale data is estimated by adding the displacement error found in the check to the error that is inherent to the orthophoto base map. The orthophoto base map conforms with National Map Accuracy Standards for a 1:2400 scale map, thus the error associated with this product is plus or minus 6.6 feet.

The worst displacement found on the USU data was 3/30 of an inch at a scale of 1:2400 this translates to 20 feet. The best displacement found in the USU product was 1/30th of an inch at a scale of 1:2400 this translates to 6.6 feet. Therefore, the maximum level of error in the USU 1:2400 map depicting surficial geology is plus or minus 13.2 feet at best and 26.6 feet at worst. Given that 12.5 percent of the points tested were in error of 20 feet it is most probable that a maximum error of 13.2 feet would apply to the majority of the data set.

The USU transfer work was also checked by projecting the 1:4800 classified information onto the 1:2400 base map, emulating the original transfer process. One very evident discrepancy was discovered, not all the data depicted on the mylar developed on the 1990 aerial photography was transferred to the base map. It is understood that many classes up-slope from the rivers edge did not change significantly between the years they were mapped and therefore did not need to be re-mapped, but many classes at the rivers edge mapped on the 1:4800 data set were not transferred to the 1:2400 base map. Was this data interpolated during transfer?

Facts to note about this accuracy check:

1. The data set checked does not comply with National Map Accuracy Standards.

2. Only one base map was checked out of 55 base maps needed for the 1990 data set.

3. Only 16 common points could be found to test.

If their any questions I can answer this assessment please call.

cc: Dave Wegner
M. Pucherelli

Sincerely,

Patrick J. Wright

Patrick J. Wright

APPENDIX B

EDDY COMPLEX MAPS

(SEE PLATE)

Appendix B: plate

Geomorphology of Post-Glen Canyon Dam Fine-Grained Alluvial Deposits of the Colorado River in the Point Hansbrough and Little Colorado River Confluence Study Reaches in Grand Canyon National Park, Arizona

FINAL

by

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Glen Canyon Environmental Studies

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APPENDIX C

TABLES OF TOTAL AREA OF DEPOSITS IN EDDY COMPLEXES

Appendix C. Table 1a. --Total area of deposits, in square meters, in indicated eddy complex at indicated level, Point Hansbrough reach[1]

Eddy complex	High elevation deposits[2]			All sand above base level[3]			All sand deposits		
	1984	1990	1992	1984	1990	1992	1984	1990	1992
1	250	500	250	250	500	500	250	500	500
2	1000	750	500	1250	750	1000	1250	750	1000
3	2750	3250	2500	4250	4000	3250	4250	4000	3500
4	8750	9500	8250	12000	12500	11000	12250	12500	12500
5	nd[4]	5500	5000	nd	9250	9500	nd	9250	10250
6	nd	0	0	nd	250	0	nd	250	0
7	nd	250	0	nd	250	0	nd	250	0
8	2750	3250	2500	5000	5250	5000	5000	5250	5000
9	3750	3500	2750	4750	4750	4250	4750	4750	4250
10	0	0	0	0	0	0	0	0	0
11	11250	14500	12500	18750	21750	21000	19250	23750	31750
12	7500	7250	7000	16750	10750	9000	16750	12500	12750
13	5000	5000	4750	16750	13000	11000	17750	13000	16000
14	500	250	250	1000	750	750	1000	750	1250
15	1750	1750	1750	2500	2750	2500	2500	2750	2750
16	750	250	250	1250	1000	1000	1250	1000	1250
17	0	0	0	250	250	250	250	250	250
18	500	500	250	1250	1250	1250	1250	1250	1500
19	250	250	250	1250	1750	1500	1250	1750	1750
20	0	0	0	250	250	250	250	250	250
21	1000	250	250	2000	1250	1000	2000	1250	1500
22	1250	1250	1250	2250	1750	1750	2250	1750	1750
23	0	0	0	250	250	250	250	250	500
24	0	0	0	0	0	0	0	0	0
25	250	0	0	250	0	0	250	0	0
26	4000	2000	1000	5750	5500	4000	5750	5500	4500
27	0	0	0	500	250	250	500	250	1000
28	1000	1000	1000	1250	1500	1750	1250	1500	1750
29	1000	1500	1000	2000	2250	2000	2000	2250	2250
30	750	500	500	1250	1250	1250	1250	1250	1250
31	250	0	0	250	250	250	250	250	250
32	250	250	250	1000	1000	1000	1000	1000	1000
33	0	0	0	0	250	250	0	250	250
34	250	500	250	750	750	750	750	750	750
35	250	250	250	250	250	250	250	250	250
36	0	0	0	750	0	500	750	0	1500
37	12500	12000	10000	14750	15250	12750	15000	15250	16000
38	0	0	0	250	250	0	250	250	250
39	0	0	0	250	500	250	250	500	500
40	3750	3500	3250	4500	5250	5500	4500	5250	5750
41	16500	11000	10000	30250	21000	17250	30500	21000	32000
42	0	0	0	0	0	0	0	0	250
43	1500	1500	1500	3750	2750	2250	3750	2750	3750
44	2000	1500	1750	2750	3500	3250	2750	3500	3500
45	1000	500	500	4000	1500	1500	4250	1500	3250
46	500	750	250	500	750	250	500	750	500
47	4000	3500	2250	6250	5000	3250	6250	5000	5000
48	5250	5750	4750	7000	7250	6750	7000	7250	8250
49	7250	8750	8500	10000	12750	11750	10000	12750	13000
50	250	250	0	500	250	250	500	250	250
51	6000	4750	4500	8250	6000	5750	8250	6000	9500
52	1500	5250	3250	6000	9750	6500	6000	9750	9750
53	500	1000	1000	750	1750	1250	750	1750	1500

[1] areas as calculated from 1:2400 scale base maps from GIS

[2] formed in 1983-1986

[3] all deposits, excluding submerged

[4] no data

Appendix C. Table 1b. --Total area of deposits, in square meters, in indicated eddy complex at indicated level, LCR reach[1]

Eddy Complex	High elevation deposits[2]				All sand above base level[3]				All sand deposits			
	1984	1990	1992	1993	1984	1990	1992	1993	1984	1990	1992	1993
1	1500	1500	1500	1500	2750	4250	3000	2500	5000	8000	12000	7500
2	750	750	500	750	2000	1000	1000	1000	2250	1000	1750	1500
3	1750	500	500	250	2000	500	500	500	2000	500	500	500
4	0	0	0	0	750	750	500	250	750	1000	1000	750
5	0	0	0	0	0	0	0	0	0	0	0	0
6	250	0	0	0	1750	1500	2250	2250	2500	2250	3500	3000
7	1750	750	500	500	3250	1250	1250	1000	3250	1500	1500	1250
8	1750	1750	1500	1500	3500	5750	3750	4500	3750	6500	5500	5750
9	0	0	0	0	250	250	0	250	250	250	0	250
10	1750	1750	1500	1000	3750	4250	2750	2750	4000	4750	3750	3750
11	500	750	500	500	750	1000	750	500	750	1000	750	750
12	2000	2000	8500	1250	4250	3250	9500	3500	4250	3250	10250	4250
13	2250	2000	6000	2000	3000	2500	6500	2500	3000	2500	6500	2500
14	0	0	0	0	0	250	250	250	0	500	750	500
15	0	0	0	0	250	250	250	250	250	500	500	250
16	250	0	250	250	500	500	500	500	500	1000	750	500
17	1250	1000	1250	1000	1500	2250	2000	2500	1500	2250	2000	2500
18	1500	0	0	0	3250	2750	2500	2000	3250	2750	3500	4000
19	0	0	0	0	0	0	250	250	0	0	1250	750
20	0	0	0	0	500	0	500	250	500	250	1750	250
21	0	0	0	0	0	0	0	0	0	0	0	0
22	250	0	0	0	250	0	0	0	250	0	0	0
23	1250	2250	1750	2000	3250	4000	3250	5000	3250	4250	4750	5250
24	0	0	0	250	500	0	250	500	500	0	500	500
25	0	0	0	0	1500	750	2000	6250	1500	3500	4000	6250
26	2500	2250	2250	2000	5750	4500	4500	5500	5750	4500	5250	5500
27	0	0	0	0	250	250	250	250	250	250	250	250
28	1750	1750	1500	1500	3000	2500	2750	8500	3000	2750	4500	9500
29	250	250	250	250	1750	1500	1250	7000	1750	1500	1500	10000
30	2000	1000	1000	1250	4500	3000	3750	5250	4500	3000	5250	5500
31	0	0	0	0	750	750	2250	2000	750	750	4750	3250
32	0	0	0	0	1000	1000	1000	0	1000	1000	1000	0
33	0	0	0	0	750	500	750	1250	750	500	1000	1500
34	3500	250	250	250	8250	2000	4000	18500	8250	2500	9000	23000
35	0	250	250	250	250	250	250	1000	250	250	250	1250
36	1000	250	250	0	1500	750	750	250	1500	750	3250	250
37	750	500	250	250	1500	500	250	500	1500	500	500	1000
38	5250	7250	4500	6000	9250	10000	5750	8500	9250	10000	5750	8500
39	2500	2750	2250	2250	4250	4000	4250	8500	5750	6500	5500	9500
40	250	0	0	250	750	500	500	2750	1000	750	750	2750
41	250	0	0	0	500	250	250	250	500	250	500	500
42	12250	11250	10000	9250	24000	19250	13750	14250	24000	25000	21250	22250
43	1750	1500	2000	1500	3500	3000	3250	2750	3500	3500	3250	2750
44	3250	2500	1250	1250	7250	5750	3000	5000	7250	9500	6250	7250
45	3250	3500	3000	2500	4750	5000	4500	3500	4750	6250	5500	3750
46	2750	3500	2500	2500	12500	10750	8250	9000	12500	13500	13250	13750
47	0	0	0	0	500	1000	1750	500	500	1750	2500	500
48	0	0	0	0	250	250	0	0	250	250	250	0
49	250	250	250	250	750	500	500	500	750	500	750	750
50	4500	3250	3000	3250	9750	8750	6750	13500	9750	11500	10250	13750
51	250	250	250	0	500	500	500	250	500	500	500	500
52	1750	1750	1500	1000	9000	9750	10500	12000	9000	9750	14250	15000
53	0	0	0	0	0	0	0	0	0	0	0	0
54	750	0	0	0	2000	250	250	500	2000	500	500	500
55	11250	11750	10500	10000	16750	17000	14750	14250	16750	17000	18000	19250
56	250	0	0	250	250	0	250	250	250	0	250	250
57	0	0	0	0	0	250	0	0	0	250	0	0
58	250	250	250	250	250	250	250	250	250	250	250	250
59	250	250	0	0	250	250	0	0	250	250	0	0
60	250	250	250	250	250	250	250	250	250	250	250	250
61	0	0	0	0	0	0	0	0	0	0	0	0
62	9250	3000	2500	2250	9250	3500	4000	4000	9250	5500	5250	5000
63	250	0	0	0	250	250	0	0	250	500	0	250
64	0	0	0	0	0	0	0	500	0	250	0	750
65	6500	6500	5750	4750	11250	10750	11500	14750	11250	16250	14750	16750
66	0	250	0	0	250	250	250	0	250	250	250	0
67	3500	2500	2250	1250	6500	5750	5000	4750	6500	6750	6000	5500
68	750	750	1250	750	1000	1000	1500	1500	1000	1250	1500	1500
69	0	0	0	0	0	0	0	0	0	0	0	0
70	750	250	250	250	1000	500	250	250	1000	750	750	750
71	0	0	0	0	0	250	250	250	0	250	250	250
72	0	0	0	0	0	0	0	0	0	0	0	0
73	4000	4000	3750	3750	5000	5250	4750	5000	5000	5500	6000	5250
74	250	1250	1000	750	1500	2500	2500	3000	1500	2750	3250	4000
75	1250	1500	1250	1250	1750	3750	3500	2250	1750	5250	6750	5750
76	nd[4]	4750	4500	4250	nd	5000	5000	4750	nd	5000	5250	5500
77	0	0	0	0	0	0	0	0	0	0	0	0
78	0	0	0	0	250	0	250	0	250	0	250	1000
79	0	0	0	0	0	0	0	0	0	0	250	250
80	7250	8250	8750	7000	10500	12500	12500	9500	10500	13000	12500	9750
81	0	0	0	0	0	0	250	250	0	0	250	250
82	0	0	0	0	0	0	250	0	0	0	250	250
83	0	0	0	0	0	0	0	0	0	0	0	0
84	0	0	0	0	0	250	0	0	0	250	0	0
85	0	0	0	0	0	250	500	500	0	250	500	1000
86	3250	3250	3000	3250	3250	3250	3000	3250	3250	3250	3000	3250
87	500	250	250	250	500	500	500	500	500	500	500	750
88	750	750	750	750	1500	1500	2000	2250	1500	1500	2500	4000
89	1750	1750	500	250	4250	4250	2000	5000	4250	5750	4500	6750
90	500	750	750	500	1500	1250	1500	1750	1500	2000	2000	2750
91	250	250	250	0	500	750	750	500	500	750	750	750
92	11750	14500	14000	8250	15500	16500	16000	12250	15500	16500	21250	17250
93	0	0	0	0	0	0	0	0	0	0	0	0
94	0	0	0	0	0	0	0	0	0	0	0	0
95	7750	8000	6250	2750	9750	13000	9500	6500	9750	13000	11000	6500
96	0	0	0	0	500	250	250	500	500	250	750	500
97	250	250	0	0	500	250	250	1000	500	250	250	1000
98	0	0	0	0	250	0	250	0	250	0	250	0
99	0	250	250	0	4250	4500	4750	5500	4250	5500	6250	7000
100	250	0	0	0	750	500	500	750	750	500	750	1000
101	500	1000	1000	500	3500	4000	2750	5750	3500	5500	5000	8000
102	0	250	250	0	250	250	250	0	250	250	250	0

[1] areas as calculated from 1:2400 scale base maps from GIS
[2] formed in 1983-1986
[3] all deposits, excluding submerged
[4] no data