Magnitude and Frequency Data for Historic Debris Flows in Grand Canyon National Park and Vicinity, Arizona

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CONTENTS

FIGURES

TABLES

APPENDIXES

CONVERSION FACTORS

Multiply	By	To obtain
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.28	foot (ft)
square meter (m^2)	10.76	square foot (ft^2)
cubic meter (m^3)	35.31	cubic foot (ft^3)
kilometer (km)	0.6214	mile (mi)
square kilometer (km^2)	0.3861	square mile (mi^2)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
gram (g)	0.03527	ounce avoirdupois (oz avdp)
kilogram (kg)	2.205	pound avoirdupois (lb avdp)
megagram (Mg)	1.102	tons, short (2,000 pounds)

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

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By Theodore S. Melis, Robert H. Webb, Peter G. Griffiths, and Thomas W. Wise

Abstract

Debris flows occur in 529 tributaries of the Colorado River in Grand Canyon between Lees Ferry and Diamond Creek, Arizona (river miles 0 to 225). An episodic type of flash flood, debris flows transport poorly-sorted sediment ranging in size from clay to boulders into the Colorado River. Debris flows create and maintain debris fans and the hundreds of associated riffles and rapids that control the geomorphic framework of the Colorado River downstream from Glen Canyon Dam. Between 1984 and 1994, debris flows created 4 new rapids and enlarged 17 existing rapids and riffles.

Debris flows in Grand Canyon are initiated by slope failures that occur during intense rainfall. Three of these mechanisms of slope failure are documented. Failures in weathered bedrock, particularly in the Hermit Shale and Supai Group, have initiated many historic debris flows in Grand Canyon. A second mechanism, termed the fire-hose effect, occurs when runoff pours over cliffs onto unconsolidated colluvial wedges, triggering a failure. A third initiation mechanism occurs when intense precipitation causes failures in colluvium overlying bedrock. Multiple source areas and extreme topographic relief in Grand Canyon commonly result in combinations of these three initiation mechanisms. Interpretation of 1,107 historical photographs spanning 120 years, supplemented with aerial photography made between 1935 and 1994, yielded information on the frequency of debris flows in 168 of the 529 tributaries (32 percent) of the Colorado River in Grand Canyon. Of the 168 tributaries, 96 contain evidence of debris flows that have occurred since 1872, whereas 72 tributaries have not had a debris flow during the last century. The oldest debris flow we have documented in Grand Canyon occurred 5,400 years ago in an unnamed tributary at river mile 63.3-R. Our results indicate that the frequency of debris flows ranges from one every 10 to 15 years in certain eastern tributaries, to less than one per century in other drainage basins. On average, debris flows may recur approximately every 30 to 50 years in individual tributaries, although adjacent tributaries may have considerably different histories.

Peak discharges were estimated in 18 drainages for debris flows that occurred between 1939 and 1994. Typically, discharges range from about 100 to 300 cubic meters per second (m^3/s). The largest debris flow in Grand Canyon during the last century, which occurred in Prospect Canyon in 1939, had a peak discharge of about 1,000 m^3/s. Debris-flow deposits generally contain 15 to 30 percent sand-and-finer sediment; however, the variability of sand-and-finer sediment contained by recent debris flows is large. Reconstitution of debris-flow samples indicates a range in water content of 10 to 25 percent by weight.

Before flow regulation of the Colorado River began, debris fans aggraded by debris flows were periodically reworked by large river floods that may have been as large as 11,000 m^3/s.

Impoundment of the river by Glen Canyon Dam in 1963, and subsequent operation of the reservoir have reduced the magnitude of these floods. Flow releases from the dam since 1963 have only partly reworked recently-aggraded debris fans. Significant reworking of new debris-flow deposits now occurs only during river discharges higher than typical power plant releases, which currently range between 142 and 510 m^3/s.

INTRODUCTION

Debris flows are an important sediment-transport process in at least 529 tributaries of the Colorado River in Grand Canyon between Lees Ferry and Diamond Creek, Arizona (river miles 0 to 225; see Webb and others, 1989; Melis and Webb, 1993). Debris flows are one source of fine sediment in the now-regulated river system downstream from Glen Canyon Dam. However, debris flows also deposit large boulders in the Colorado River that create and maintain debris fans and rapids, directly influencing the storage of fine sediment in the river channel (Hamblin and Rigby, 1968; Dolan and others, 1974; Howard and Dolan, 1981; Kieffer, 1985; Webb and others, 1989; Schmidt and Graf, 1990; Melis and Webb, 1993). By supplying boulders that exceed the competence of regulated discharges in the river, debris flows also directly control the navigability of the Colorado River, affecting the more than 20,000 whitewater enthusiasts who use the Colorado River for recreation each year (Stevens, 1990).

Understanding the frequency and magnitude of debris flows over long and short periods of time is important to future adaptive management of the riparian ecosystems and recreational resources of Grand Canyon. Debris flows periodically contribute large volumes of fine sediment and large boulders to the river. The hundreds of debris fans that have accumulated along the Colorado River directly control the formation and stability of most sand bars (Rubin and others, 1990; Schmidt, 1990; Schmidt and Graf, 1990; Schmidt and others, 1993). These debris fans and sand bars provide valuable substrates for riparian ecosystems (Stevens, 1989). Debris flows also can severely disrupt plant communities living in tributary channels and on debris fans along the river channel (Stevens, 1989). Sand bars deposited on debris fans are also used as campsites by thousands of river-runners who boat on the Colorado River annually. Fluctuating releases from Glen Canyon Dam since 1963 have eroded many of these sand bars (U.S. Department of the Interior, 1989; Schmidt and Graf, 1990). The geometry of river-constricting debris fans, as well as the morphology of the channel, influence the size, shape, and volume of fine sediment deposits stored along the river channel. Therefore, a greater understanding of debris flows and their effect on the formation and stability of sand bars is necessary to predict future trends in the sediment budget under flow regulation.

Development of a sediment budget for the Colorado River through Grand Canyon requires an estimate of long-term sediment yields from hundreds of ungaged tributaries. Estimating long-term sediment yields from these tributaries depends on estimates of debris-flow frequency and magnitude for as many tributaries as possible. In addition, these estimates require knowledge of the particle-size distributions, as well as water content, of debris flows that reach the river. Increased knowledge of debris flow and mainstem processes in Grand Canyon will contribute to future efforts to manage Glen Canyon Dam in ways that minimize downstream impacts on ecological resources.

Historical data on the occurrence of debris flows in Grand Canyon are limited and difficult to obtain because of the isolated setting and inaccessibility of many of the rivers tributaries. Accessing these tributaries by boat, we examined the potential for debris flows in hundreds of tributaries and studied the effects of historic debris flows in 39 tributaries that occurred between 1939 and 1994 (fig. 1). In many cases, it was possible to examine sites of recent debris flows within weeks of their occurrence. This report includes all data collected concerning the frequency and magnitude of historic debris flows in tributaries of the Colorado River in Grand Canyon National Park and vicinity. This study was funded in cooperation with the U.S. Bureau of Reclamation as part of a larger study entitled "Glen Canyon Environmental Studies," which began in 1982 (Wegner, 1991).

Purpose and Scope

This report provides data on the magnitude and frequency of historic debris flows in Grand Canyon National Park and vicinity. We emphasize data on the amount of sand-and-finer sediment transported into the Colorado River by this process, and the effects of debris flows on debris fans, rapids, and sand bars. The data presented here will be used as the basis for development of sediment-yield estimates from ungaged tributaries of the Colorado River, which are one aspect of the sediment budget for Grand Canyon. Calculation of the sediment budget is one means of evaluating the effects of the operation of Glen Canyon Dam on sediment storage along the Colorado Rivers channel. Because rapids and debris fans may be enlarged as a result of deposition by debris flows, releases higher than present peak-power plant discharges (142 to 510 m^3/s) from Glen Canyon Dam may be desirable to rework newly-aggraded debris fans and to mitigate the direct, erosional impacts of debris flows on existing sand bars.

This report supplements existing information on debris flow frequency and magnitude in Grand Canyon (Cooley and others, 1977; Webb and others, 1989; Melis and Webb, 1993). The study area includes all geomorphically significant tributaries of the Colorado River between Lees Ferry and Diamond Creek, Arizona (river miles 0 to 225), excluding the Paria and Little Colorado Rivers and Kanab and Havasu Creeks. We define and list the names of these tributaries, their drainage areas, and the rapids that have formed at their junctures with the Colorado River. Three mechanisms of debris-flow initiation are identified and studies of magnitude and frequency in 39 tributaries of the Colorado River are presented. The study area is isolated and little historical documentation exists for most of these tributaries; consequently, the type and amount of information known for each tributary varies greatly. However, all information presented here is useful for the development of a model of total sediment yield from ungaged, ephemeral, and perennial streams in the Grand Canyon region. The study also documents the effects of debris flows in Grand Canyon National Park on the downstream resources of the Colorado River.

Units and Place Names

In this report, we use the inch-pound unit of mile to describe location of tributaries along the Colorado River, and the unit of feet for elevation on location maps; metric units are used for all other measures. Use of river mile has considerable historical precedent and provides a reproducible method of describing the location of tributaries with respect to the Colorado River. The location of tributaries was determined using the most recent edition of a well-known river guide (Stevens, 1990) in river miles downstream from Lees Ferry, Arizona, and a descriptor of "L" for river-left and "R" for river-right. The left and right sides of the Colorado River are determined as one faces downstream.

Names of tributaries and other significant features were obtained from two sources. Published U.S. Geological Survey 7.5-minute quadrangle maps are the source for most names of tributaries. For tributaries without names on 7.5-minute quadrangle maps, we used either informal names, which are designated in quotation marks and are typically obtained from Stevens (1990), or we refer to the tributary as an unnamed tributary at a specified river mile and side. In addition, we also refer to E-Areas, which are smaller drainages that may have debris flow and flash-flood potential, but did not meet all of the criteria for our category of geomorphically significant tributaries.

We typically refer to "Grand Canyon" in broad reference to both Marble and Grand Canyons. "Marble Canyon" is the canyon reach of the Colorado River between Lees Ferry, Arizona and the juncture with the Little Colorado River (river miles 0 to 61.5); we refer to Marble Canyon only for specific tributaries in that reach. Grand Canyon, which is formally designated between the juncture with the Little Colorado River and the Grand Wash Cliffs (river miles 61.5 to about 280), is considerably larger and better known than Marble Canyon. We refer informally to the first reach of Grand Canyon proper (designated study-reach five in this report) as Furnace Flats (between river miles 61.5 and 78.0).

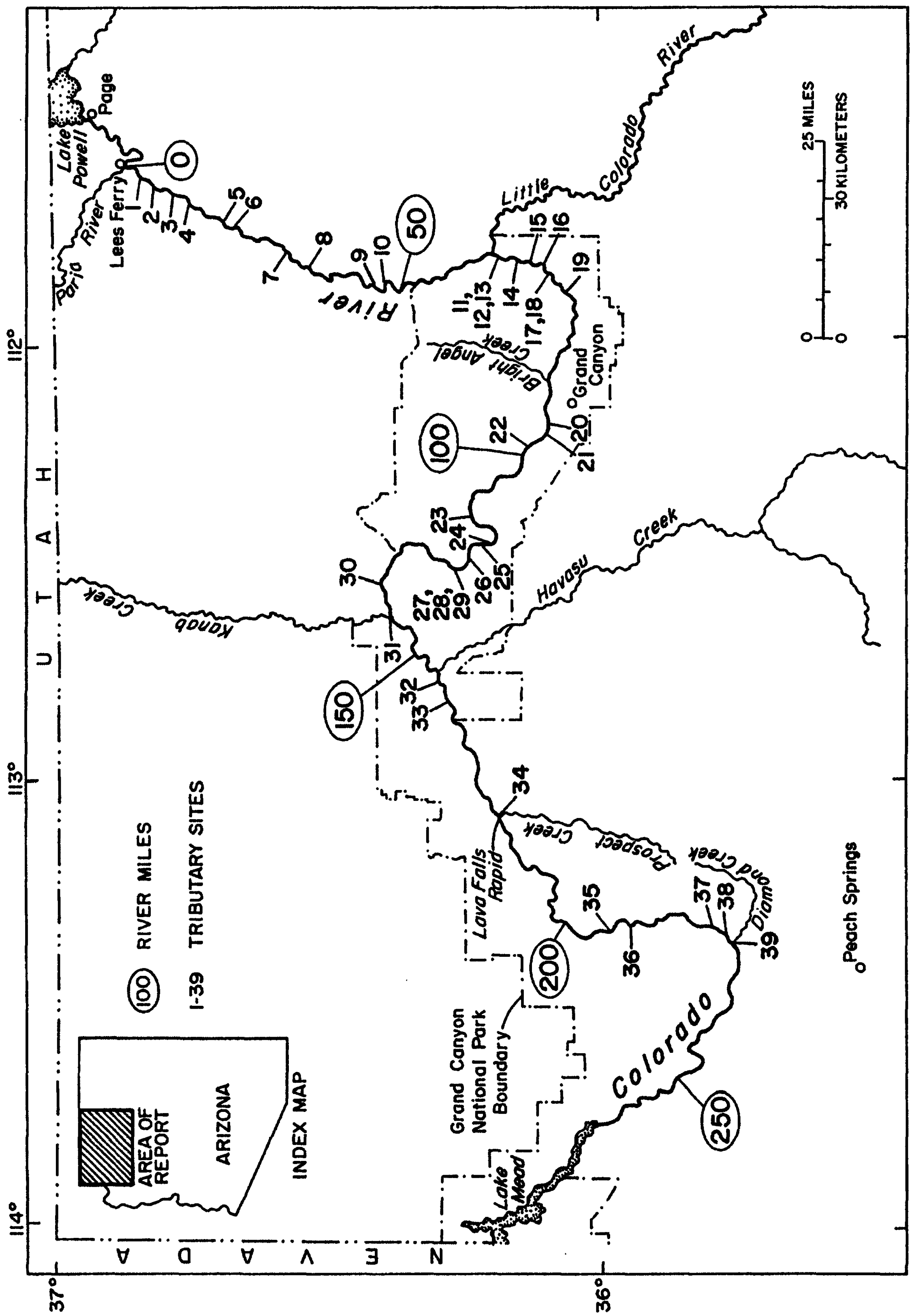

Figure 1. Locations of debris-flow study sites along the Colorado River in Marble and Grand Canyons, Arizona.

1 CATHEDRAL WASH (MILE 2.8-R)
2 BADGER CANYON (MILE 7.9-R)
3 SOAP CREEK (MILE 11.2-R)
4 HOUSE ROCK WASH (MILE 16.8-R)
5 18-MILE WASH (MILE 18.0-L)
6 MILE 19.1-L
7 MILE 30.5-R
8 NANTILOID CANYON (MILE 34.7-L)
9 MILE 42.9-L
10 TATAHOYSA WASH (MILE 43.2-L)
11 MILE 62.5-R
12 CRASH CANYON (MILE 62.6-R)
13 MILE 63.3-R
14 LAVA CANYON (MILE 65.5-R)
15 TANNER CANYON (MILE 68.5-L)
16 CARDENAS CREEK (MILE 70.9-L)
17 MILE 71.2-R
18 MILE 72.1-R
19 75-MILE CANYON (MILE 75.5-L)
20 MONUMENT CREEK (MILE 93.5-L)
21 BOUCHER CREEK (MILE 96.7-L)
22 CRYSTAL CREEK (MILE 98.2-R)
23 WALTENBURG CANYON (MILE 112.2-R)
24 119-MILE CREEK (MILE 119.0-R)
25 FORSTER CANYON (MILE 122.7-L)
26 FOSSIL CANYON (MILE 125.0-L)
27 MILE 126.9-L
28 MILE 127.3-L
29 127.6-MILE CANYON (MILE 127.6-L)
30 140-MILE CANYON (MILE 139.9-L)
31 KANAB CREEK (MILE 143.5-R)
32 MILE 157.6-R
33 MILE 160.8-R
34 PROSPECT CANYON (MILE 179.4-L)
35 MILE 207.6-L
36 209-MILE CANYON (MILE 208.6-R)
37 MILE 222.6-L
38 MILE 224.5-L
39 DIAMOND CREEK (MILE 225.8-L)

Figure 1. Continued.

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DEBRIS FLOWS IN GRAND CANYON NATIONAL PARK

Debris flows are an important sediment-transport process in a variety of geomorphic settings throughout the world. Costa (1984) described debris flows as water-based slurries of poorly sorted material ranging in size from clay to boulders. Debris flows occur in arid, semiarid, tropical, and montane environments (Brunsden and Prior, 1984). In these settings, they are typically called mudflows, debris slides, and debris torrents, to name a few of the more common terms

(Blackwelder, 1928; Sharp and Nobles, 1953; Johnson and Rodine, 1984; Pierson, 1984; Pierson and Costa, 1987). When this type of flash-flood results from a volcanic eruption, it is termed a lahar. Debris flows frequently have devastating effects on populated areas (Pierson and others, 1990), but damage can be severe even in sparsely populated areas of the southwestern United States (*e.g.*, Glancy and Harmsen, 1975).

Debris flows commonly contain 70 to 90 percent sediment by volume, making them an extremely significant sediment-transport process. The complex flow properties associated with debris flows, including their ability to transport large boulders long distances on relatively gentle gradients (Rodine and Johnson, 1976; Johnson and Rodine, 1984), continue to intrigue and challenge our understanding of this fluvial process. Although much remains to be learned about debris flows, their general effects on the Colorado River have already been established (Webb and others, 1988, 1989; Melis and Webb, 1993).

Debris-Flow Transport of Sediment to the Colorado River

Three previous studies have addressed the magnitude and frequency of debris flows in Grand Canyon. Cooley and others (1977) examined debris flows that occurred in 1966 in several tributaries of the Colorado River, including Lava Canyon and Crystal Creek (river miles 65.5-R and 98.2-R). They estimated the magnitude of the debris flow in Dragon Creek, a tributary of Crystal Creek (river mile 98.2-R), and inferred some frequency information from damage to archaeological sites. In an examination of aerial photography, Howard and Dolan (1981) reported that 25 percent of all debris fans in Grand Canyon had been affected by tributary floods between 1965 and 1973. In addition, Webb and others (1989) reported magnitude and frequency information for three tributaries of the Colorado River. As part of this study, 37 debris flows that had a significant effect on the Colorado River were identified (Table 1). In addition, a list of recent debris flows and streamflow floods in Grand Canyon that originally appeared in Webb and others (1989) has been updated (appendix 1).

As early as 1869, the significance of tributary flooding in Grand Canyon, and its impact on the Colorado River corridor, were recognized by John Wesley Powell (1875) during the first scientific exploration of Grand Canyon. Powell realized the potential of the Canyons small but steep tributaries to control the rivers character as his expedition faced continual hardship while lining and portaging their boats through and around the rivers many large rapids. Powell, and those that followed, greatly respected the rapids of Grand Canyon, although they may not have fully understood the role that debris flows played in transporting the large boulders that created them. Only today are we beginning to realize the full implications of debris flows and their ability to continually shape Grand Canyon and the Colorado River (fig. 2).

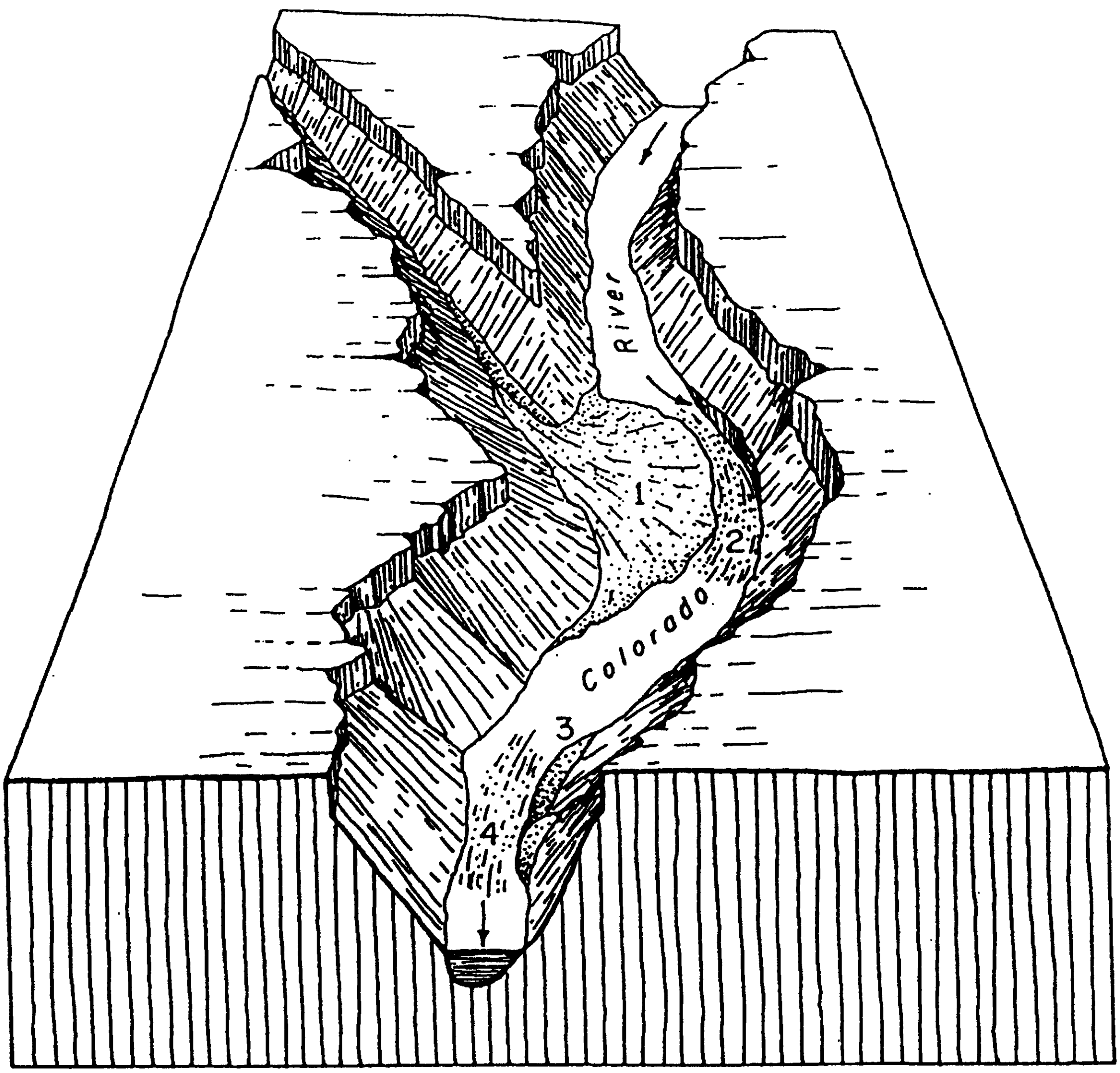
Many researchers have described the rapids that dominate the river corridor of Grand Canyon (Leopold, 1969; Cooley and others, 1977; Graf, 1979; Howard and Dolan, 1981; Webb and others, 1988, 1989; Melis and Webb, 1993). The infrequent and episodic nature of debris flows in Grand Canyons tributaries results in catastrophic modifications to alluvial debris fans and associated rapids over very short time periods; in most cases minutes to hours (Webb and others, 1988, 1989). Similarly, debris flows are capable of altering sand bars, commonly termed beaches, through burial and (or) erosion when they issue from tributaries into the river channel. Debris flows also influence the net volume of fine sediment stored in the river channel by forming low-velocity sediment traps, commonly referred to as eddy-complexes upstream and downstream of debris fans. Eddies are very effective traps for fine sediment entering the river channel from tributaries (Schmidt and Graf, 1990).

Howard and Dolan (1981) attributed aggradation on debris fans between 1965 and 1973 to tributary flooding, but only generally referred to debris flows as a sediment-transport process. Other researchers have more-fully documented the role of debris flows in the creation and maintenance of debris fans and rapids in Grand Canyon (Cooley and others, 1977; Webb, in press; Webb and others, 1988, 1989; Melis and Webb, 1993). On the Green River, Graf (1979) studied the effects of regulated discharges released from Flaming Gorge Reservoir on downstream rapids. He reported a significant increase in the stability of rapids, and predicted a

Table 1. Locations of major debris flows that have occurred during the last century in Grand Canyon

Name of Tributary canyon	Name of Rapid	River Mile	Side	Year(s) of debris flow(s) or range
Jackass Canyon	Badger Creek	7.9	L	1994
Badger Canyon	Badger Creek	7.9	R	*1897 to 1909
Soap Creek	Soap Creek	11.2	R	*1923 to 1934
House Rock Canyon	House Rock	16.8	R	11966
Unnamed canyon	Unnamed riffle	18.0	L	1987
Unnamed canyon	Unnamed riffle	21.5	L	*1890 to 1990
Unnamed canyon	24-Mile	24.2	L	1989
Tiger Wash	Tiger Wash	26.6	L	*1890 to 1990
Unnamed canyon	No rapid exists	30.2	R	1989
South Canyon	Unnamed riffle	31.6	R	*1940 to 1965
Unnamed canyon	Unnamed riffle	42.9	L	1983
Tatahoysa Wash	President Harding	43.2	L	1983
Unnamed canyon	New rapid	62.5	R	1990
Unnamed canyon	Unnamed riffle	63.3	R	1990
Lava Canyon	Lava Canyon	65.5	R	1966
Palisades Creek	Lava Canyon	65.5	L	1966, 1984, 1987, 1990
Tanner Canyon	Tanner	68.5	L	1993
Unnamed canyon	No rapid exists	71.2	R	1984
Unnamed canyon	Unnamed riffle	72.1	R	1984
75-Mile Creek	Nevills	75.5	L	1959, 1987, 1990
Hance Creek	Sockdolager	78.7	L	*1890 to 1990
Monument Creek	Granite	93.5	L	*1960s, 1984
Boucher Creek	Boucher	96.7	L	*1935 to 1965
Crystal Creek	Crystal	98.2	R	1966, 1995
Waltenberg Canyon	Waltenberg	112.2	R	*1938 to 1987
Unnamed canyon	New rapid	127.6	L	1989
128-Mile Creek	128-Mile	128.5	R	*1890 to 1923
Specter Chasm	Specter	129.0	L	1989
Bedrock Canyon	Bedrock	130.5	R	1989
Unnamed canyon	Unnamed riffle	130.9	L	*1890 to 1991
Unnamed canyon	Unnamed riffle	133.0	L	*1890 to 1923
Kanab Canyon	Kanab	143.5	R	*1923 to 1942
Unnamed canyon	New rapid	160.8	R	1993
Prospect Canyon	Lava Falls	179.4	L	1939, 1954, 1955, 1963, 1995
205-Mile Canyon	205-Mile	205.5	L	*1937 to 1956
Unnamed canyon	Unnamed riffle	222.6	L	*1890 to 1990
Diamond Creek	Diamond Creek	225.8	L	1984

*The exact year of the flood is uncertain.



(Modified from Hamblin and Rigby, 1968)

Explanation

1. Tributary debris fan
2. Rapid controlled by large immobile boulders
3. Debris bar (synonymous with "island" or "rock garden")
4. Riffle or rapid caused by debris bar

Figure 2. The morphology of a typical debris fan and rapid of the Colorado River in Grand Canyon, Arizona.

trend of continuing aggradation at those sites because of reduced mean-annual discharges in the river.

Before regulation of flow began in 1963, the Colorado River in Grand Canyon was known for its high inter-annual variability of flooding. Periodic, large floods on the river worked together with tributary rockfalls and debris flows to form one of the worlds most spectacular erosional features. The reduction of the size of the annual flood on the Colorado River since 1963 now limits the river's competence to completely erode newly-deposited debris that continues to accumulate on debris fans. Howard and Dolan (1981) report that this decrease in the size of flood flows represented a fourfold decrease in the sediment-transport potential of the river. Tributaries downstream from Glen Canyon Dam remain unregulated, and their continuing debris flows remain an effective agent of change to the river corridor (Howard and Dolan, 1981; Webb, 1987). As a result, the quasi-equilibrium conditions (Langbein and Leopold, 1964) that must have existed between the river and its canyons in the pre-dam era have been perturbed in favor of the canyon's tributaries since 1963. Anticipated changes, such as locally-increased flow gradients and navigational hazards in rapids, are only the most obvious consequences to be expected from continuing debris flows.

Debris flows can modify the river corridor in a number of ways. Debris flows can cause 1) aggradation of debris fans, 2) erosion of debris fans, 3) increased constriction of the river channel, 4) an increase or decrease in the severity of rapids, 5) disturbance of existing vegetation on debris fans and along tributary channels, 6) erosion or burial of existing sand bars, and 7) changed patterns of deposition and erosion of sand bars caused by altered flow patterns around recently-aggraded debris fans. Predicting the impacts of debris flows on the river channel is extremely difficult because of the complex characteristics of eddies relative to the geometry of debris fans and the width and general slope of the reach. In most cases, lower discharges in the river have allowed more frequent, small debris flows to increase the severity of rapids.

Effects of Debris Flows on Rapids

Debris flows control the formation and evolution of rapids in Grand Canyon by depositing large boulders and finer sediment in the Colorado River at hundreds of locations. In minutes, a debris flow can transport enough sediment to the river to change a mild riffle into a severe rapid; an example of this occurred at Crystal Rapid (river mile 98.2-R) in December 1966 (Cooley and others, 1977; Webb and others, 1989). More recently, debris flows have created or enlarged riffles and (or) rapids at 54 sites since 1872 between Lees Ferry and Diamond Creek (Table 2). In most cases, these changes resulted in

Table 2. Historic changes to rapids of the Colorado River in Grand Canyon interpreted from repeat photography
[Summary of changes, describes the physical changes that have occurred in the rapid and describes which geomorphic processes have caused them based on evidence seen in matched photographs, such as the appearance of debris levees (debris flow), and deposition of large, angular rocks in the river channel (rockfall). Reduced hydraulic hazards may result when debris flows deposit large boulders in rapids that fill-in standing waves, or by large-magnitude river flows which can remove debris from rapids; evaluation of change in rapids and their cause, is subjective]

River mile	Rapid name	Summary of changes
7.9	Badger	Debris flow from Badger Canyon deposited rocks at upper right
11.2	Soap Creek	Flood or debris flow from Soap Creek in the 1930s decreased the severity of waves in the rapid
14.3	Sheer Wall	Debris flow from Tanner Canyon; fan eroded and rocks moved
16.8	House Rock	Debris flow from House Rock Canyon in 1966
18.0	Unnamed	Debris flow from 18-Mile Wash constricted the river channel
21.4	Unnamed	Debris flow added new boulders to river channel
24.2	24-Mile	Debris flows from both sides in 1989
26.6	Tiger Wash	Debris flows from both sides of river
26.8	MNA	Rockfall from high-angle chute in 1974
43.2	"Boulder"	Debris fan eroded, left run enlarged
62.5	Unnamed	Debris flow from unnamed tributary created new rapid

Table 2. Historic changes to rapids of the Colorado River in Grand Canyon interpreted from repeat photography—Continued

River mile	Rapid name	Summary of changes
63.3	Unnamed	Debris flow from unnamed tributary enlarged existing riffle
65.5	Lava Creek	Multiple debris flows from Palisades and Lava Creeks
68.5	Tanner	Debris flow in 1993 constricted the channel
71.2	Unnamed	Debris flow from unnamed tributary deposited boulder island in the center of river channel
72.1	Unnamed	Debris flow from unnamed tributary created new riffle
75.5	Nevills	Multiple debris flows from 75-Mile Canyon, but little effect
76.8	Hance	Few changes
78.7	Sockdolager	Debris flow from Hance Creek deposited new rocks on left
81.5	Grapevine	Rocks moved from center of channel
87.9	Bright Angel	Debris fan eroded at lower right
88.9	Pipe Springs	Few changes
90.2	Horn Creek	Few changes
93.5	Granite	Multiple debris flows from Monument Creek have constricted the top of the rapid on river left
95.0	Hermit	Tailwaves drowned-out owing to debris flow at Boucher Canyon
98.2	Crystal	Debris flow from Crystal Creek in 1966 created severe, new rapid now considered one of the worst in the western U.S.
99.3	Tuna Creek	Few changes
101.3	Sapphire	Few changes
103.9	104-Mile	Few changes
104.6	Ruby	Few changes
106.0	Serpentine	Few changes
107.6	Bass	Few changes
108.6	Shinumo	Few changes
112.2	Waltenberg	Aggradation on right, boulders moved from left
119.0	119-Mile	Few changes
122.7	Forster	Debris flow in 1991 increased constriction through the rapid
125.0	Fossil	Debris flow in 1989 deposited new boulders in the channel
127.6	Unnamed	Debris flow from unnamed tributary created new rapid
128.5	128-Mile	Debris fan reworked, decreasing the constriction of rapid
129.0	Specter	Debris flow in 1989 increased constriction through rapid
131.7	Dubendorff	New rock garden at lower left
133.8	Tapeats	Few changes
143.5	Kanab	Debris flow from Kanab Creek, but few changes to rapid
160.8	Unnamed	Debris flow from unnamed tributary created new riffle
164.5	164-Mile	Few changes
179.4	Lava Falls	Multiple debris flows from Prospect Creek since 1939 have radically altered the existing rapid
205.5	205-Mile	Rockfall from right; debris flow from 205-Mile Creek
208.6	209-Mile	Rockfall created major hydraulic wave in 1978
212.2	Little Bastard	Few changes
215.7	Three Springs	Few changes
217.4	217-Mile	Few changes
220.4	Granite Springs	Few changes
225.8	Diamond Creek	Pre-1883 debris flow constricted river, 1984 debris flow deposited new debris bars
230.9	231-Mile	Debris flow and river erosion has changed rapid

an increased water-surface slope through the rapid and (or) the addition of boulders to the river channel that created new navigational hazards, such as standing waves (for a detailed description of this process, see Kieffer, 1985).

In general, most debris flows that reach the Colorado River in Grand Canyon aggrade debris fans and increase the severity of rapids. In many cases, the river becomes more constricted at the debris fan, leading to increased flow velocities through the rapids. The increase in velocity at the constriction will normally result in greater reworking of coarse sediments at the toe, or distal edge of the debris fan, but this reworking is now greatly restricted by the regulated flows released from Glen Canyon Dam. Very large boulders resist transport by the river except at higher discharges. River discharges as high as 11,000 m^3/s have been estimated for prehistoric floods (O'Connor and others, 1994); however, since 1963 the peak discharge has not exceeded about 2,700 m^3/s. Changes to rapids caused by debris flows can greatly increase navigational hazards for the more than 20,000 whitewater enthusiasts who use the river annually (Stevens, 1990). An increased number of hydraulic features, known as holes, or standing waves caused by rapid flow over boulders in rapids, increased flow velocities, and narrower routes through rapids commonly result when debris flows reach the Colorado River. To what extent a given debris flow alters the river depends on the duration, instantaneous peak discharge, and particle-size distribution of sediments transported by the debris flow and deposited in the river channel. Site-specific channel morphology in the vicinity of the river and tributary confluence, the discharge of the river at the time of the debris flow, and the size and style of the existing debris fan at the site, also influence the relative impacts that debris flows have on the rivers channel. These factors also influence reworking of debris flow sediments by mainstem flows.

Before construction of Glen Canyon Dam, occasional large floods on the river transported most sediment from newly-aggraded debris fans downstream; typically, the largest particles were deposited immediately downstream in the rapid. With repeated reworking, this process resulted in sorting of particles to form stable debris fans comprised of large boulders and downstream deposits comprised mainly of cobbles and small boulders. These downstream deposits are commonly termed debris bars, and are also termed channel bars, rock gardens, and islands. Since construction of Glen Canyon Dam, the quasi-equilibrium conditions existing between fluvial processes of the Colorado River, and its tributaries have been altered in favor of debris-flow deposition of sediments by tributaries. One result of this change is increased aggradation of the river channel at many tributary mouths.

Some debris flows may change rapids in ways that make them less severe. Debris flows are generally the only type of flash floods in Grand Canyon tributaries capable of transporting large boulders from distant tributary source areas into the river. Newly deposited boulders may smooth out bed irregularities caused by surrounding larger boulders that protrude from the bed. Hydraulic features, such as holes and standing waves in the rapids, may be reduced in severity, or the deposition of new debris may cause the flow to impinge on and remove other boulders. Before regulation of the river, sediment smaller than boulders with b-axis diameters of about 512 mm were periodically removed from debris fans and rapids by large, infrequent annual floods that usually occurred in late spring and early summer. With repeated reworking, most debris fans and rapids developed coarse, residual bouldery textures; only boulders that exceeded the competence of the river under the pre-dam flow regime (generally particles with b-axis diameters larger than about 512 to 1,024 mm) could remain in rapids.

Effects of Debris Flows on Sand Bars

Sand and finer sediments are mainly stored as sand bars within debris-fan controlled eddy complexes along the Colorado River (Schmidt and Graf, 1990). In most alluvial rivers, sand bars migrate along the channel. In contrast, the locations of sand bars in Grand Canyon are controlled by eddies that form upstream and downstream from constrictions that are relatively immobile over decades or even centuries. Most of these constrictions are caused by debris fans and their associated downstream debris bars (Webb and others, 1989; Schmidt and Graf, 1990). Sand bars most commonly form downstream from these constrictions in zones of flow separation, or eddies. According to Schmidt and Graf (1990), "When flow separation occurs, the main downstream current becomes separated from the channel banks, and areas of recirculating flow exist between the downstream current and the banks." This phenomenon creates rotational flow patterns in the eddy, termed recirculating flow, which result in a marked stagnation of downstream flow velocity. Flow stagnation commonly results in the deposition of fine sediment suspended in the mainstem current.

The geometry of a debris fan greatly affects flow separation and recirculating flow. Debris-fan morphology itself is strongly influenced by the cumulative interactions of the frequency and magnitude of debris flows, the frequency and magnitude of large floods in the Colorado River, the particle-size distribution of debris fans, and the local river-channel morphology.

Debris flows affect sand bars directly through burial and (or) erosion. Separation bars can be particularly affected by debris flows or channel avulsion. At least 22 sand bars have been buried and (or) eroded by recent debris flows at sites along the Colorado River (Table 3). Indirect effects result from the aggradation of debris fans which control: 1) the locations where sand bars will form and the river discharges at which deposition of sand will occur; 2) the length of the flow-separation zone; 3) the size of the sand bar relative to the size of the constriction; and 4) the direction in which flow exits the constriction and enters the flow separation zone. These relations are a function of discharge, and a debris fan's size, shape, and height, and directly control the range of discharges at which recirculating flow and deposition of fine sediment can occur upstream and downstream from the constriction. Because debris-fan shapes, and the morphology of the river channel vary greatly throughout the river corridor, different discharges may have very different effects on the erosion and deposition of both sand bars and debris fans. This is especially true in the first 125 km downstream from Glen Canyon Dam, where the bedrock geology of the river channel and its morphology varies considerably.

Before closure of Glen Canyon Dam, the variability of fine sediment stored in flow separation zones was related mainly to the variability of sediment transported through Grand Canyon, and to the local changes in flow patterns caused by periodic debris flow activity and river-reworking of debris fans. Pre-dam floods on the Colorado River annually rebuilt sand bars that had been buried and (or) eroded by debris flows. Reworking of new, poorly-sorted debris-fan sediments occurred during mainstem flood peaks, whereas sand bars were probably redeposited on debris fans during the recessional flood stages. During pre-dam floods, many debris fans, particularly in narrow reaches, were completely inundated. Evidence of these floods, such as driftwood, remain on and above many debris fans. Sand bars were also eroded during these floods as constricting debris fans were overtopped, and their associated recirculating zones were washed-out. However, recirculating-flow zones would reform downstream from stable, reworked fans as the floodwater receded. This would allow redeposition of transported sand along the flanks of the constriction in the vicinity of the eddy.

Since 1963, most fine sediment transported from the upper Colorado River drainage has been trapped in Lake Powell (fig. 1). Large, clearwater releases from Glen Canyon Dam overtopped many debris fans between 1985 and 1986, and resulted in erosion of sand bars, specifically in geomorphically-sensitive reaches (Schmidt and Graf, 1990). Many debris fans and sand bars in Marble Canyon were inundated almost daily between 1984 and 1986 by clearwater releases from the reservoir. Clearwater floods did not carry enough sediment for significant deposition to occur once the recirculating zones returned at lower discharges during fluctuating cycles during that time period. Consequently, many pre-dam era sand bars were eroded between 1984 and 1986 and have not been redeposited. This erosion occurred particularly where geomorphic controls for deposition of sand bars were weakest (*i.e.*, low-

Table 3. Sand bars in the Colorado River eroded or buried by tributary debris flows and (or) streamflow floods between 1939 and 1994

[Name of tributary, official names taken from USGS 7.5-minute quadrangle maps; unofficial, but commonly used names are given in quotation marks]

River mile	River side	Name of tributary	Year(s) of debris flow(s) or flood(s)
18.0	L	"18-Mile Wash"	1987
19.9	L	Unnamed tributary	1987
34.7	L	Nautiloid Canyon	[1]1980 to 1984
41.0	R	Buck Farm Canyon	1992
42.9	L	Unnamed tributary	1983
43.2	L	Tatahoysa Wash	1983
62.5	R	Unnamed tributary	1990
62.6	R	"Crash Canyon"	1990
63.3	R	Unnamed tributary	1990
68.5	L	Tanner Canyon	1993
71.2	R	Unnamed tributary	1984
72.1	R	Unnamed tributary	1984
112.2	R	Waltenberg Canyon	[1]1973 to 1984
122.7	L	Forster Canyon	1991
127.3	L	Unnamed tributary	1989
127.6	L	"127.6-Mile Canyon"	1989
129.0	L	Specter Chasm	1989
130.5	R	Bedrock Canyon	1989
157.6	R	Unnamed tributary	1993
160.8	R	Unnamed tributary	1993
166.4	L	National Canyon	[1,2]1965 to 1992
207.8	L	Unnamed tributary	1991

[1]The exact year that the flood impacted the sand bar is uncertain.

[2]Several flash floods were responsible for degrading sand bars during the time period specified

elevation debris fans without downstream controls).

Erosion of sand bars since closure of Glen Canyon Dam has been attributed mostly to a combination of widely fluctuating daily flows released from the dam's power plant and, more importantly, occasional large, clearwater releases during years of heavy, upper-basin snowpack and runoff. Many sand bars have also been eroded by other natural geomorphic processes in Grand Canyon. These include tributary debris flows (mainly burial of sand bars), tributary flash floods (mainly erosion of sand bars), wind erosion, and human use. An almost 90-percent reduction in suspended sediment load occurred immediately after closure of the dam (Laursen and others, 1976). As a consequence of reduced discharges in the Colorado River, most sand bars buried and (or) eroded by debris flows will probably not be redepo sited under powerplant releases. This has been true for the low, seasonally adjusted dischargges (between 142 and 510 m^3/s), referred to as "interim flows", that have occurred since August 1, 1991. The stages of these releases do not completely inundate most sand bars and debris fans.

METHODS OF STUDY

Delineation of Geomorphically-Significant Tributaries of the Colorado River

Selection Criteria for Tributaries

We identified and designated geomorphically significant tributaries between Lees Ferry and Diamond Creek (appendix 2). Our definition of geomorphically significant tributaries includes numerous small drainages that have potential to produce debris flows that affect the geomorphology of the river channel. The criteria for designating drainages were determined from analysis of 38 U.S. Geological Survey 7.5-minute quadrangle maps of the river corridor, and 106 maps of the Grand Canyon region. Included were all tributaries that: 1) have drainage areas larger than 0.01 km^2; 2) are mapped as having perennial or ephemeral streams; 3) were previously designated with an official name; 4) clearly terminate at the Colorado River in a single channel; and 5) contribute to formation of obvious debris fans and (or) rapids.

Designation of these tributaries is partly subjective and was based on our field experience in evaluating drainages for debris-flow potential. One of the main purposes of this study is to develop a better sediment budget for the Colorado River downstream from Glen Canyon Dam. Therefore, we have concentrated our attention mainly on tributaries for which little is currently known regarding sediment input to the Colorado River. We excluded the Paria River, the Little Colorado River, Kanab Creek, and Havasu Creek from our delineation and study of tributaries because they have gaging stations and their sediment-transport histories and drainage characteristics have already been documented by the U.S. Geological Survey. All four of these drainages exhibit evidence of past debris flows. However, only Kanab Creek (river mile 143.5-R) is included in this assessment of debris-flow frequency. Appendix 2 lists the significant tributary canyons of the Colorado River in Grand Canyon, including information on drainage areas, reference maps, rapid ratings (see Stevens, 1990), locations, as well as official and unofficial place names assigned. Additional drainage characteristics for these tributaries are given in appendix 3.

Areas Not Assigned to Tributaries

Many areas that could not be designated using the criteria outlined above were designated as "E" or extra drainage areas. This type of drainage area also contributes sediment to the Colorado River and typically consists of steep slopes with no identifiable channel on 7.5-minute quadrangle maps. Sediment contributed from these drainages is usually delivered to the Colorado River by overland sheetflow or is transported by small debris flows originating as slope failures near the river. In addition, these smaller areas do not form obvious basins with terminal flow channels. Drainages that were identified, but previously unnamed were given river mile designations based on published river miles commonly in use (Stevens, 1990).

Estimation of Drainage Areas

Drainage areas of geomorphically-significant tributaries were estimated by hand from hand-drawn outlines digitized on 7.5-minute quadrangle topographic maps as noted in appendix 2.

Delineation of Eleven Study Reaches of the Colorado River

The Colorado River in Grand Canyon has been previously subdivided into 11 study reaches between river miles 0 and 225 on the basis of the type of bedrock at river level and general characteristics of the river channel (U.S. Department of Interior, 1989; Schmidt and Graf, 1990). We generally retained the previous geomorphic classification of the Colorado River established (Schmidt and Graf, 1990) during phase I of the Glen Canyon Environmental Studies. However, we did slightly modify some of the beginning and ending points of some reaches in order to refine them; the river-mile designations for these modified study reaches are given in appendix 2. We examined 79 drainages in these eleven study reaches for recent or ancient evidence of debris flow processes (Table 4). On the basis of these field studies, we conclude that debris flows have occurred in all of Schmidt and Graf's (1990) original study reaches downstream from Glen Canyon Dam.

Determination of Frequency for Debris Flows

Repeat Photography

Repeat photography has been used successfully in previous geological and biological studies in Grand Canyon and throughout the western U.S. (Hastings and Turner, 1965; Turner and Karpiscak, 1980; Stephens and Shoemaker, 1987; Webb and others, 1989; Webb and others, 1991; Webb, in press). Most of our frequency information for historic debris flows (1872 to 1994) used during this study was obtained from systematic, repeat photography and interpretation of historical photographs. Abundant historical photographs of the Colorado River corridor, dating as far back as 1872, allowed us to study many different debris fans for changes caused by debris flows, river-reworking associated with mainstem floods, and other geomorphic processes such as rockfall. During our study, we matched and interpreted 1,107 historic photographs of the river corridor to determine significant changes to tributary channels, debris fans, rapids, sand bars, and riparian vegetation (appendixes 4, 5, and 6). The photographs were studied and detailed notes were recorded both in the field and office in an attempt to extract the maximum amount of information available. By using historical photographs showing specific debris fans at different times, we were able to bracket when debris flows occurred in selected tributaries. For some tributaries, the dates of debris flows could be determined to within 1 year.

A collection of photographs made by Franklin A. Nims and Robert Brewster Stanton between 1889 and 1890 consists of 445 views of the river at approximately 2-km intervals downstream (appendix 4). This remarkable collection served our study as an excellent baseline for estimating the frequency of changes occurring on debris fans and in rapids during the last century. A second set of 171 photographs was taken during the U.S. Geological Survey expeditions of 1921 and 1923. These mostly panoramic views, made by Eugene C. LaRue, mainly show potential dam sites and scenery in Grand Canyon (appendix 5). A total of 491 other photographs taken by many photographers at various times were also examined to obtain temporal coverage of specific debris fans in Grand Canyon (appendix 6). Including the Nims-Stanton and LaRue photographic collections, and other photographs not replicated by us, nearly 1,200 historical photographs were examined as part of this study.

We also examined several sets of low-elevation aerial photographs taken between 1935 and 1994 for evidence of the occurrence of debris flows. In 1935, the Soil Conservation Service took black and white aerial photographs of Marble Canyon (river miles 0 to 61) and Diamond Creek to Lake Mead (river miles 225 to 280) at a scale of 1:31,800; these photographs are stored at the National Archives in Arlington, Virginia. Another set of photographs, taken in November 1935 under the direction of John Maxon of the California Institute of Technology, recorded parts of the Inner Gorge from the vicinity of Bright Angel Creek to Specter Chasm (river miles 87 to 129) and western Grand Canyon from about river mile 211 to Lake Mead (river mile 280) in 1938. The scale of these photographs is unknown (probably about 1:20,000). The 1965 aerial photography is available from the EROS Data Center in Sioux Falls, South Dakota, and 1973 aerial photography is stored at the U.S. Geological Survey in Tucson, Arizona. Aerial photography flown on many dates between 1980 and 1994 are stored at the Glen Canyon Environmental Studies office in Flagstaff, Arizona.

Radiometric Dating Techniques

Radiocarbon analysis was used to determine ages for debris flows that predate historical photographs (Webb and others, 1989). Where organic materials, such as wood and charcoal, were found in massive debris-flow deposits such as debris levees, they were extracted from the deposits. These types of samples are usually interpreted as maximum ages for deposition of the deposits owing to the possibility of long residence times for charcoal in arid, fluvial environments.

However, datable organic material is scarce or lacking in most massive debris-flow deposits. As an alternative, we extracted fine-grained organic material from mudcoats (interpreted as being debris-flow matrix) preserved under overhanging walls to obtain our most reliable radiocarbon ages; these normally consisted of small, shredded twigs. This method provided us with additional debris flow frequency data, but it was not always possible to associate preserved mudcoats with debris levees or debris fans. Owing to the delicate nature and small size of the preserved wood samples found in the mudcoats, we propose that this organic material did not have a long residence time in the drainage prior to the debris flow's date. We assume that such samples probably reflect the remains of small woody plants that were growing in the channel at the time the debris flow occurred and were entrained in the flow.

Organic materials were analyzed for ^{14}C activity and calibrated to an age in years before present (yrs BP); present is defined as 1950. At several sites, organic materials in debris-flow deposits had significantly-elevated activities of ^{14}C, which indicates that the organic material grew after the advent of above-ground nuclear testing in 1950. Radiocarbon ages that predate 1950 were converted to calendric dates using a decadal-scale calibration (Stuiver and Becker, 1986) applied using a standard computer program (Stuiver and Reimer, 1986). Calibrations for ^{14}C dates older than 4,000 yrs BP relied on the data-sets of Pearson and others (1986) for calibration. We report the maximum range for the radiocarbon date at one standard deviation (appendix 7). Post-1950 radiocarbon dates were converted using the post-bomb ^{14}C relation (Ely and others, 1993). A complete list of radiocarbon dates used in this study is given in appendix 7.

Frequency data for recent debris flows were also obtained by the analysis of debris-flow sediments for their ^{137}Cs activity. A by-product of fallout from above-ground nuclear testing, the detection of ^{137}Cs activity in debris-flow deposits should indicate a post-1952 deposition; this is most-probable in arid environments where soil leaching is minimal. This technique is useful for delineating the time range of historic floods (Ely and others, 1993). For example, in cases where change was caused by a debris flow that occurred since 1890 (based on the original photograph), ^{137}Cs analysis was used to establish whether the debris flow occurred between 1890 and 1952 or between 1952 and the date of sampling. The interior sediments of pre-1950 debris flow deposits should not give a detect for ^{137}Cs if leaching is not a factor, however, surface samples collected from such deposits should give a positive detection result. Ely and others (1993) found that leaching of radionuclides from the surface to interior sediments was not a significant contamination problem in fine-grained flood deposits. Sediments analyzed for ^{137}Cs were sand-size-or finer; in several cases, we analyzed concentrated silt and clay fractions separated by dry sieving.

Measurement of Sediment Characteristics

Debris flows commonly are poorly-sorted mixtures of sediment containing particles ranging from clay to boulders. To account for boulder-size sediment, accurate sampling of the particle-size distribution of a debris flow deposit is essential, but problematic owing to the size of the samples required to determine accurate size distributions. Representative samples of Grand Canyon debris-flow deposits for laboratory sieving cannot be easily collected because a prohibitively large sample weight is necessary to accurately account for boulders. Collection of such large samples is normally impossible owing to the isolated nature of the study areas and the limitations of transporting heavy samples out of Grand Canyon. Therefore, we used several methods in combination with limited sample collection to estimate the particle-size distribution of Grand Canyon debris flow deposits.

Point Counts

Point counts were made in the field on debris flow deposits containing particles that are too large to easily transport to the laboratory for standard dry-sieve analysis (Wolman, 1954). For deposits judged to be representative, 50 to 100-m measuring tapes were stretched over the surface of the deposit at parallel intervals to form a transect sampling grid. The length of the transect was variable but typically ranged from 10 to 100 m, and the distance between adjacent tapes was generally 0.25 to 0.50

Table 4. List of tributaries of the Colorado River in Grand Canyon that have been examined as part of this study
[(X), indicates that the attribute listed in the column was either observed or measured in the drainage. Tributary names are taken directly from U.S. Geological Survey 7.5-minute quadrangle maps in all cases where the name does not appear in quotation marks. Names in quotations indicate that we used informal names]]

Tributary name	Colorado River Mile	Ancient debris flow evidence	Recent debris flow evidence	Stratigraphy analyzed	Discharges estimated	Recent stream flooding evidence	Particle size measured
Cathedral Wash	2.8R	X				X	
Badger Canyon	7.9R	X				X	
Jackass Creek	7.9L	X				X	
Soap Creek	11.2L	X	X			X	
House Rock Wash	16.8R	X	X		X		
"18 Mile Wash"	18.0L	X	X	X	X		
"19 Mile Canyon"	19.0R	X					
Unnamed tributary	19.9L	X	X			X	
Sheep Spring Wash	24.4L	X	X	X			
Shinumo Wash	29.2L	X	X				
Unnamed tributary	30.5R	X	X				X
Nautiloid Canyon	34.7L	X	X	X		X	
Buck Farm Canyon	41.0R	X	X				
Unnamed tributary	42.9L	X	X			X	
Tatahoysa Wash	43.2L	X	X				
Unnamed tributary	43.7L	X	X				
Saddle Canyon	47.0R	X					
Unnamed tributary	49.8R	X					
Nankoweap Canyon	52.2R	X	X			X	
Kwagunt Canyon	56.0R	X					
Unnamed tributary	61.1R	X	X				
Unnamed tributary	62.5R	X	X		X		X
"Crash Canyon"	62.6R	X	X	X	X		X
Unnamed tributary	63.3L	X	X	X	X		X
Lava Canyon	65.5R	X	X	X	X	X	X
Palisades Creek	65.5L	X	X	X		X	
Unnamed tributary	66.3L	X	X				
Espejo Creek	66.8L	X	X	X			
Comanche Creek	67.2L	X	X				
Tanner Canyon	68.5L	X	X		X	X	X
Cardenas Creek	70.9L	X	X		X	X	X
Unnamed tributary	71.2R	X	X	X	X		X
Unnamed tributary	72.1R	X	X	X	X		X
Unkar Creek	72.6R	X					
75-Mile Creek	75.5L	X	X	X	X	X	X
Red Canyon	76.7L	X	X				
Hance Creek	78.7L	X	X			X	
Clear Creek	84.1R	X	X				

Table 4. List of tributaries of the Colorado River in Grand Canyon that have been examined as part of this study—Continued

Tributary name	Colorado River Mile	Ancient debris flow evidence	Recent debris flow evidence	Stratigraphy analyzed	Discharges estimated	Recent stream flooding evidence	Particle size measured
Bright Angel Creek	87.8R	X				X	
Monument Creek	93.5L	X	X	X	X	X	X
Hermit Creek	95.0L	X	X			X	
Boucher Creek	96.7L	X	X	X		X	X
Crystal Creek	98.2R	X	X	X	X		X
Tuna Creek	99.3R	X				X	
Shinumo Creek	108.6R	X					
Waltenberg Canyon	112.2R	X					
Unnamed tributary	116.8L	X	X				
Unnamed tributary	119.0R	X				X	X
Blacktail Canyon	120.1R	X					
Forster Canyon	122.7L	X	X	X	X		
Fossil Canyon	125.0L	X	X			X	
Unnamed tributary	126.9L	X	X				
Unnamed tributary	127.3L	X	X	X	X		X
"127.6-Mile Canyon"	127.6L	X	X		X		X
Specter Chasm	129.0L	X	X				
Bedrock Canyon	130.5R	X	X			X	
Galloway Canyon	131.7R	X				X	
Stone Canyon	131.9R	X					
Unnamed tributary	133.0L	X	X			X	X
Tapeats Creek	133.8R	X	X			X	
Deer Creek	136.2R	X				X	
140-Mile Canyon	139.9L	X	X			X	X
Olo Canyon	145.6L	X					
Matkatimiba Creek	147.9L	X				X	
Unnamed tributary	157.8R	X	X			X	X
Unnamed tributary	160.8R	X	X			X	X
National Canyon	166.4L	X				X	X
Fern Glen Canyon	168.0R	X	X			X	
Prospect Canyon	179.4L	X	X	X	X	X	X
Whitmore Wash	188.1R	X		X		X	X
Parashant Wash	198.5R	X		X		X	
205-Mile Creek	205.5L	X		X		X	X
Indian Canyon	206.5R	X		X			
Unnamed tributary	207.8L	X	X	X	X	X	X
209-Mile Canyon	208.6R	X	X	X		X	
220-Mile Canyon	220.0R	X		X			
"222.6-Mile Canyon"	222.6L	X					X
"224.5-Mile Canyon"	224.5L	X					X
Diamond Creek	225.8L	X	X			X	

m. At this interval, any large particle directly beneath the tape mark (at 0.25-m intervals) was selected and measured; particles smaller than gravel were selected by their closest proximity to the mark when choice was required. The standard unit of measurement of particles is ϕ, defined as

$$D = 2^{-\phi}, \quad (1)$$

where D = the diameter, in millimeters, of the intermediate (b-axis) of the particle. During point counts, the b-axes were measured and aggregated into one of the ϕ categories for particles >2 mm in diameter. For example, a fine-grained deposit might have particles in the categories of 2 to 4 mm (-1 to -2 ϕ), 4 to 8 mm (-2 to -3 ϕ), 8 to 16 mm (-3 to -4 ϕ), and larger (Folk, 1974). Typically, 100 to 400 particles were measured during each point count.

Sources of Particles >2 mm

We also recorded the formations that yielded particles >2 mm in diameter to determine relations among sediment source areas and material deposited during debris flows. Identifying the source of gravel in the field (2 to 16 mm in diameter) is typically difficult; many particles were recorded as "unknown" source because of small size. We used the source classes of Kaibab Limestone (including Toroweap Limestone), Coconino Sandstone, Hermit Shale, Supai Group (including four individual Formations), Redwall Limestone (including Temple Butte Limestone and rocks of the Surprise Valley Formation), Muav Limestone, Bright Angel Shale, Tapeats Sandstone, younger Proterozoic rocks (including Galeros Formation, Nankoweap Sandstone, Dox Sandstone, Cardenas Lavas and Shinumo Quartzite), and older Proterozoic rocks (including schists, pegmatites, granites, and amphibolites). Because all source identifications were made using hand specimens, they are subject to some unknown degree of error. Huntoon and others (1986) contains detailed geologic descriptions of these rocks and the areas where they outcrop in Grand Canyon. A stratigraphic column of these units, as they occur in Grand Canyon and appear at river level is shown in figure 3.

Largest Boulders

In addition to point counts, we commonly measured the ten largest boulders that were obviously transported by recent debris flows. We determined whether large boulders that could have been present in the channel before the debris flow were transported by the debris flow by examining aerial or oblique photography whenever possible. We also examined boulders for fresh percussion marks on their downstream sides and recently killed organic debris pinned beneath them. The a- (long), b- (intermediate), and c- (short) axes of the boulders were measured and their lithologies and shapes were recorded. The boulder volumes were estimated using equations for variously shaped solids. Typically, boulders were either shaped as rectangular solids, right-triangular solids, cylinders or ellipsoids. In estimating the weight of measured boulders, we assumed an average density of 2.6 g/cm^3 regardless of source. Dimensions, volumes, lithologies, shapes, and estimated weights of many large boulders transported by several recent debris flows are listed by drainage (river mile) in appendix 8. These data show great variability in the size and source of boulders delivered to the Colorado River throughout Grand Canyon by recent debris flows.

Dry-Sieve Analysis

We collected large, intact debris-flow samples for sieve analysis at sites where deposits appeared to be representative of the contents of a debris flow. Typically, samples were collected from preserved, lateral debris levees deposited along channel margins or lobate deposits on debris fans at the Colorado River. It is difficult to find deposits that accurately represent the particle-size distribution of a debris flow because many sites are severely reworked by recessional hyperconcentrated flow and (or) streamflow. As a result, considerable effort was expended in locating sites for sample collection. Once a representative deposit was located, a volume of sediment was excavated and

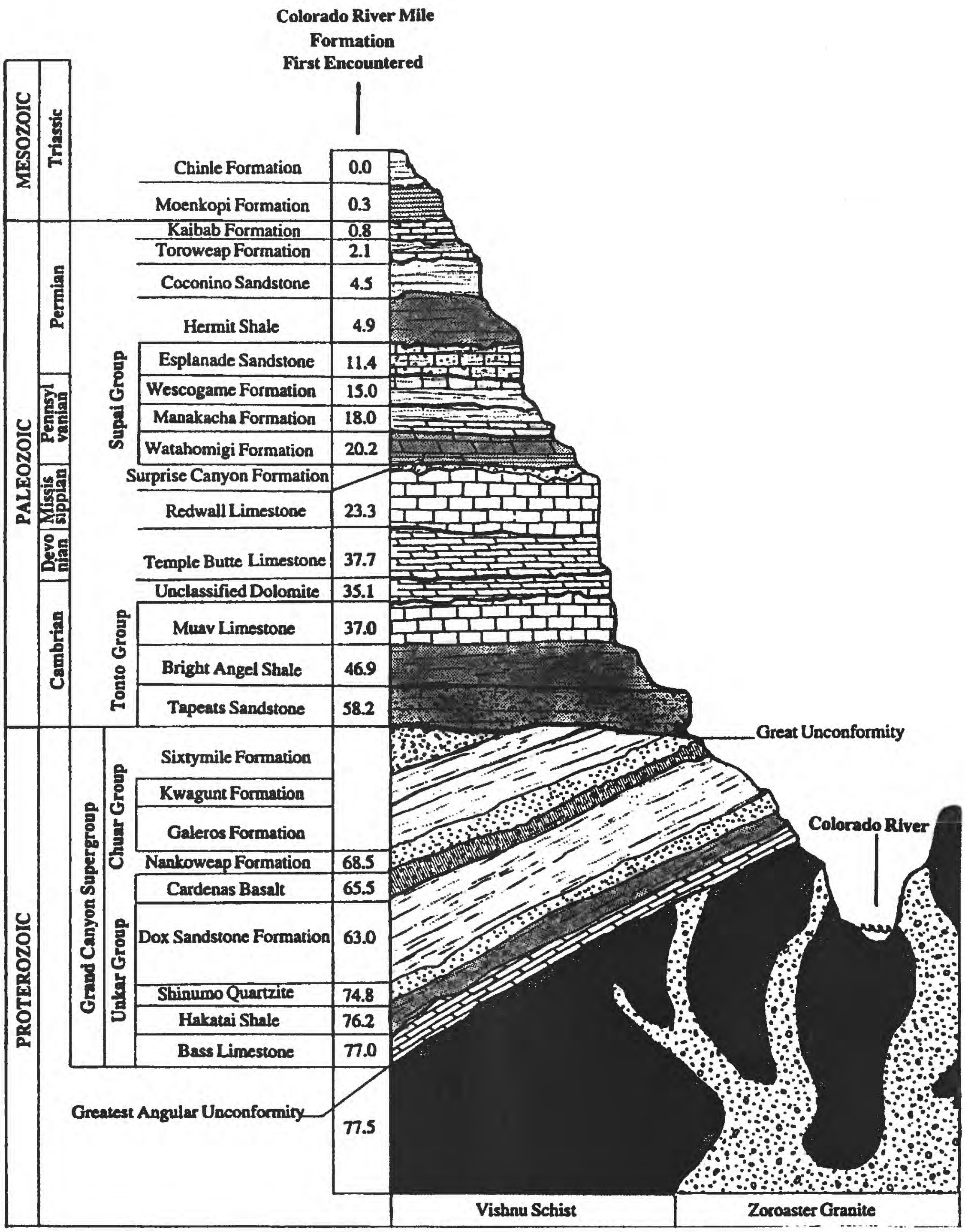


Figure 3. A stratigraphic column showing rocks exposed in Grand Canyon, Arizona, and the distances in river miles downstream from Lees Ferry, Arizona where they first appear along the Colorado River.

collected. The largest sediment sample we collected (390 kg) was from the 1990 debris-flow deposit at the mouth of Crash Canyon (river mile 62.6-R). That sample contained all particles (including 23 boulders) found in a 1-m square area of the deposit. Because of the large weight and logistical complications of collecting and transporting such samples from remote areas of Grand Canyon to the laboratory, we typically collected smaller samples and measured and discarded particles >64 mm in the field. We calculated the weight of ejected particles by assuming that the particle was shaped like an ellipsoid with measured a-, b-, and c-axis diameters; we again assumed an average density of 2.6 g/cm^3.

We analyzed particle-size distribution using standard techniques (Kellerhals and Bray, 1971; Folk, 1974). Samples were air dried, then dried again in laboratory ovens overnight at 50 to 100° C. All particles >64 mm were removed from the sample after carefully retaining finer particles. The b-axes of these particles were measured, their individual weights were recorded and segregated by ϕ class, and, in most cases, their lithologies were also identified. The particle-size distribution for samples with particles <64 mm and >0.063 mm in diameter were determined using standard, brass sieves in sets with 1 ϕ intervals between sieves. Particles with b-axis diameters between 16 mm and 64 mm were removed by hand sieving the sample through 16 and 32 mm sieves and the retained particles were weighed. The total sample weight was calculated as the sum of the weights of particles >64 mm, particles between 16 and 64 mm, and particles <16 mm. The sample with particles <16 mm was then split into manageable subsamples of a maximum of 400 g for standard dry-sieve analysis. We used a mechanical shaker for 15 minutes to segregate particles on sets of sieves. The sets had sieves with meshes of 0.063, 0.125, 0.25, 0.5, 1.0, 2.0, 4, 8, and 16 mm. Particles retained on each sieve were weighed and the percent of the subsample in each ϕ class was determined.

The particle-size distribution was then determined by reconstructing the percentage of particles in each ϕ class on the basis of sample weight or by occurrence in point counts. If particle diameters were measured in the field, the particle-size distribution determined using sieve analysis was adjusted for these particles after the particle weight was calculated. If point counts also were made on the surface of the deposit from which the sample was collected, the two types of data were combined. Although point counts are made using surface exposure and dry-sieve analyses are based on weight percent of a sample, the order of magnitude of the resulting percentages is similar (Kellerhals and Bray, 1971). We assumed that point counts accurately measure particles in excess of 64 mm; therefore, the particle-size distribution >64 mm was determined using point counts, whereas the particle-size distribution <64 mm was determined by combining point count and dry-sieve data. The percentage of particles <64 mm determined by point count was adjusted by the particle-size distribution of the collected sample.

Clay Mineralogy

The clay mineralogy of source sediments is likely an important contributor to initiation of debris flows in Grand Canyon. Little information is available on the clay mineralogy of bedrock, particularly shales, exposed in Grand Canyon's walls (Blakey, 1990, p. 161). Layers with large amounts of smectites, particularly montmorillonite, may act as potential slip surfaces and promote slope failures. Alternatively, other clays minerals, particularly kaolinite, may be dispersive and aid in the rapid disintegration of cohesive sediments during intense rainfall.

We analyzed clay particles finer-than 2 µm for mineralogy using a common technique (D.M. Hendricks, University of Arizona, written commun., 1988). Representative samples extracted using the pipet method were saturated with magnesium (Mg) and potassium (K), respectively, and mounted on glass slides. X-ray diffraction scans were made of the Mg-saturated samples following equilibrium at 54 percent relative humidity and solvating with ethylene glycol. Similar scans were made of the K-saturated samples after heating to 300° and 500° C. The clay mineralogy was interpreted qualitatively and semi-quantitatively from the relative intensities and positions of the peaks obtained from X-ray diffraction.

Reconstitution of Water Content

The water content of recent Grand Canyon debris flows at the time they occurred was estimated using dry-sieved samples weighing 5 to 8 kg. All particles with b-axis diameters >16 mm were removed using standard sieves. In a plastic mixing tray, water was added in small increments to the sample (typically less than 100 ml) and mixed well; between additions, the mixture was qualitatively examined for properties similar to those of debris flow. These properties include the ability to flow as a plug, to form lateral levees (indicating internal shear), and to support particles >16 mm. When the mixture first exhibited these properties, the water content was calculated to reflect the driest possible debris-flow mixture. We continued to add water until the mixture no longer had clearly observable debris-flow properties, particularly the ability to support large particles. This water content, the probable upper limit of hyperconcentrated flow (Beverage and Culbertson, 1964; Pierson and Costa, 1987), typically occurs at a water content of 40 to 70 percent by weight. We report the range in possible water content at which the debris-flow sediment samples first exhibited debris-flow characteristics.

Peak-Discharge Estimates

Grand Canyon tributaries produce three distinct types of floods. These types, as defined by Pierson and Costa (1987), are streamflow (<40 percent solids), hyperconcentrated flow (40-80 percent solids), and debris flow (>80 percent solids). Although determination of the magnitude and frequency of debris flows is the primary concern of this study, we also estimated discharges for streamflow and hyperconcentrated flow floods.

Streamflow

Tributary streamflows and debris flows are commonly associated with one-another in Grand Canyon. Streamflow typically constitutes the recessional phase of Grand Canyon debris flows, although such floods may also precede debris flows in some cases (Cooley and others, 1977). Evidence of streamflow includes deposition of well-sorted sediment on channel margins and in the bed, and the presence of well-delineated zones of organic debris along high-water lines.

Peak discharges of streamflow were estimated using the slope-area technique (Dalrymple and Benson, 1967). Mean velocity, V, of streamflow was estimated using Mannings equation,

$$V = 1/n \cdot R^{0.67} \cdot S^{0.5}, \qquad (2)$$

where R = hydraulic radius, S = the friction slope, and n = a roughness coefficient called Mannings n. Discharge is calculated using

$$Q = A \cdot V, \qquad (3)$$

where Q = discharge and A = the cross-sectional area. A relatively-uniform channel-reach was selected whenever possible that had continuous high-water marks on both channel sides. Two to three cross sections were normally surveyed and Manning-n values were visually estimated on site.

Evidence of Debris-Flow Process and Peak-Discharge Stage

Four types of evidence of debris flows are commonly preserved in tributaries of the Colorado River. These types of evidence consist of: 1) debris levees composed of poorly-sorted sediments deposited along channel margins; 2) continuous or discontinuous mudlines preserved on overhanging walls; 3) damaged plants on the sides of the channel that are scarred, buried, or surrounded by poorly-sorted sediment; and 4) continuous or discontinuous muddy scour lines preserved on hillslope channel margins, channel walls or terraces. Evidence of debris flow may be difficult to discern from streamflow scour except when the top of the scour zone is associated with freshly-deposited cobbles and boulders. Intact debris-flow levees containing fine-grained matrix sediment or debris levees reworked into lines of boulders are the most reliable indication of a recent debris flow. Evidence of ancient debris flows typically consists of levee deposits from which the original matrix sediment has been removed by rainfall, fluvial reworking by streamflows, and (or) weathering of boulder surfaces (Bull, 1991, p. 116-118). The presence of a bouldery, poorly-sorted debris fan is an almost certain sign that a debris flow has occurred in a tributary; deltaic deposits resulting from streamflow floods are typically finer and graded. In addition, badly-damaged trees, which in many cases have been sheared-off at ground level, also usually indicate that debris flows have recently occurred in a tributary.

Sediment-Yield Estimates

We estimated the amount of sediment eroded from initiation points in four drainage basins (river miles 62.5-R, 62.6-R, 127.3-L, and 127.6-L) where debris flows had recently occurred. We measured the depth of scour and width of channels near the head of the drainages examined. In some cases, it was obvious that part of the sediment from the eroded hillslope was deposited locally in the tributary channel; therefore, not all sediment eroded from the initiation point was deposited in the debris fan. We documented the depth of sediment that aggraded the channel wherever possible. Freshly-exposed roots and incised colluvial deposits commonly provided the best evidence for scouring of source sediments. Such estimates were made only in drainages smaller than 2 km^2, where debris flows had been initiated by fire-hose effects in colluvial deposits at the base of near-vertical bedrock walls.

Indirect Estimates of Debris-Flow Peak Discharge

The opportunity and likelihood of directly measuring the velocity and discharge of a debris flow in Grand Canyon is very limited. Debris flows occur infrequently in most tributaries and are seldom witnessed. Because of this, peak discharges of debris flows were indirectly estimated during this study. High-water marks of debris flows typically are mudlines preserved under overhanging cliffs; the arid climate of Grand Canyon allows for long-term preservation of these mudlines making the estimation of peak discharge for prehistoric debris flows possible in some cases. Scour lines also provide evidence for high-water marks where debris flows have occurred. Plants, particularly cacti, at the maximum-flow elevation frequently preserve mud, gravel, and other types of debris that can be used to reconstruct the maximum stage of the debris flow. Exposed roots and freshly abraded tree trunks are commonly found in channels through which debris flows have passed. These types of flow elevation evidence provide data for the estimation of a debris flows peak discharge.

Tributary canyons of the Colorado River in Grand Canyon are characteristically well-suited to estimating peak discharges of debris flows. These tributaries typically have more than one channel bend along their course where evidence of superelevation and runup are preserved. This makes it possible to compare several sites for consistency of estimates and (or) changes in flow characteristics. Ideal sites have had minimal scour during debris flows, such as bedrock-controlled channels with relatively uniform reaches in which continuous mudlines are preserved on both sides of the channel.

Because the mechanics of debris flow are complicated, standard methods used to estimate peak discharge for streamflows are not applicable to debris flows. Mannings equation (eq. 2) is inappropriate for estimating peak discharges of debris flows because it was developed only for Newtonian fluids; debris flows behave as non-Newtonian fluids (Costa and Jarrett, 1981). Mannings *n* (a frictional coefficient) does not adequately reflect energy losses in debris flow associated with channel roughness (Antonious Laenen, U.S. Geological Survey, written commun., 1986; Laenen and others, 1987). Debris flows have complex interactions among particles that create internal shear-strength, cause energy losses, and support large particles in suspension.

Debris flows are mixtures of clay- to boulder-sized sediments and water; typically, the volumetric water concentration ranges from about 10 to 30 percent (Pierson and Costa, 1987; Major and Pierson, 1992). A variety of classifications have been proposed for distinguishing debris flows, hyperconcentrated flows, and streamflows (Beverage and Culbertson, 1964); recent work has focused on rheological properties (Pierson and Costa, 1987). Debris flows are characterized by cohesive properties that are probably related to clay content, sand content, grain-particle interactions which result in shear strength, and the ability to transport large boulders (Rodine and Johnson, 1976; Johnson and Rodine, 1984; Costa, 1984). Source lithologies, which strongly affect particle-size distributions and, therefore, flow rheology in debris flows, vary greatly in and between individual drainages in Grand Canyon. The properties of debris flow are contrasted by those of hyperconcentrated flow, which also has been documented in Grand Canyon (Webb and others, 1989).

Hyperconcentrated flows contain between 20 and 60 percent water by volume (Beverage and Culbertson, 1964; Pierson and Costa, 1987). These flows deposit faint but distinctive sedimentary structures (mostly faint, laminar bedding) with unique sorting characteristics (coarsening-upward). Some researchers believe hyperconcentrated flows behave as quasi-Newtonian fluids (Pierson and Scott, 1985). The sedimentological criteria used to define transitions between streamflow, hyperconcentrated flow, and debris flow are based on differences in particle-size distribution, sedimentary structures such as slight laminar bedding, and an overall coarse-sand, upward-coarsening texture commonly containing erratic cobbles and boulders (Pierson and Costa, 1987). Commonly, debris-flow deposits are characterized by the complete absence of sedimentary structures, very poor sorting, and massive appearance. Debris flows are thought to move as laminar flowing plugs (Enos, 1977; Johnson and Rodine, 1984) and under certain conditions (*i.e.*, in steep channels) may be highly erosive (Pierson, 1980). In low-gradient channels, debris flows typically are non-erosional and depositional; however, all of these types of floods can cause erosion in steep channels.

Superelevation and Runup Estimates

During flow through channel bends, the surface of a flowing fluid typically rises on the outside of the bend and drops on the inside of the bend (Apmann, 1973). The difference in flow elevation between the inside and outside of bends is termed superelevation (Apmann, 1973). Superelevated flow is caused by centrifugal forces being exerted on the flowing fluid mass as it moves around the bend (fig. 4A). The mean fluid-flow velocity determined using the superelevation method (V_s) is related to the difference between the raised elevation of flow on the outside of the bend and the lower elevation of flow on the inside of the bend (fig. 4B) by

$$V_s = (g \cdot R_c \cdot \Delta H_s / W)^{0.5} \qquad (4)$$

where g = acceleration due to gravity (9.8 m/s^2), R_c = the radius of bend curvature along the channels centerline, H_s = the difference in cross-channel surface elevation at the point of maximum superelevation, and W = the channels top width at the point of maximum superelevation. Use of equation (4) requires the assumption be made that the flow is steady, uniform, and that all flow lines are parallel to one another as flow proceeds through the bend. Because debris flows are viscous-type fluids, this assumption may be justified.

When a flowing fluid encounters a stationary obstruction in its flow path (typically a tree trunk, vertical wall, bridge pier, etc.), the momentum of the fluid forces it to runup the immovable object. The height of runup is related to the flow velocity using a method similar to that of superelevation. In both cases, we assume that the peak velocity at a point on the bedrock wall is close to the mean velocity of the flow, which is a tenuous assumption. Many of the sites where we identified debris-flow runup occurred in tight corners (nearly 90-degree bends) where the flow encountered the channel wall nearly straight-on.

The mean velocity of flow at a runup site (V_r) is estimated using

$$V_r = (2 \cdot g \cdot \Delta H_r)^{0.5}, \qquad (5)$$

where H_r = the difference between the maximum runup and unobstructed flow-surface elevation (usually a continuous mudline up and downstream from the runup obstruction). Evidence of runup typically is also found at a superelevation site, allowing for estimates of debris flow velocity by both methods (eqs. 4 and 5). In Grand Canyon tributaries, evidence of runup is usually preserved in tight corners of bedrock channels, or on rock buttresses protruding into the channel. As a result, many locations preserve evidence of superelevation and runup in close proximity to one another. In many cases, the peak-flow velocities estimated using superelevation and runup evidence were quite similar (Webb and others, 1989). Pierson (1985) compared measured surface velocities with indirect estimates of mean velocity. These velocities presumably are similar if plug flow exists; he found that mean velocities estimated using indirect

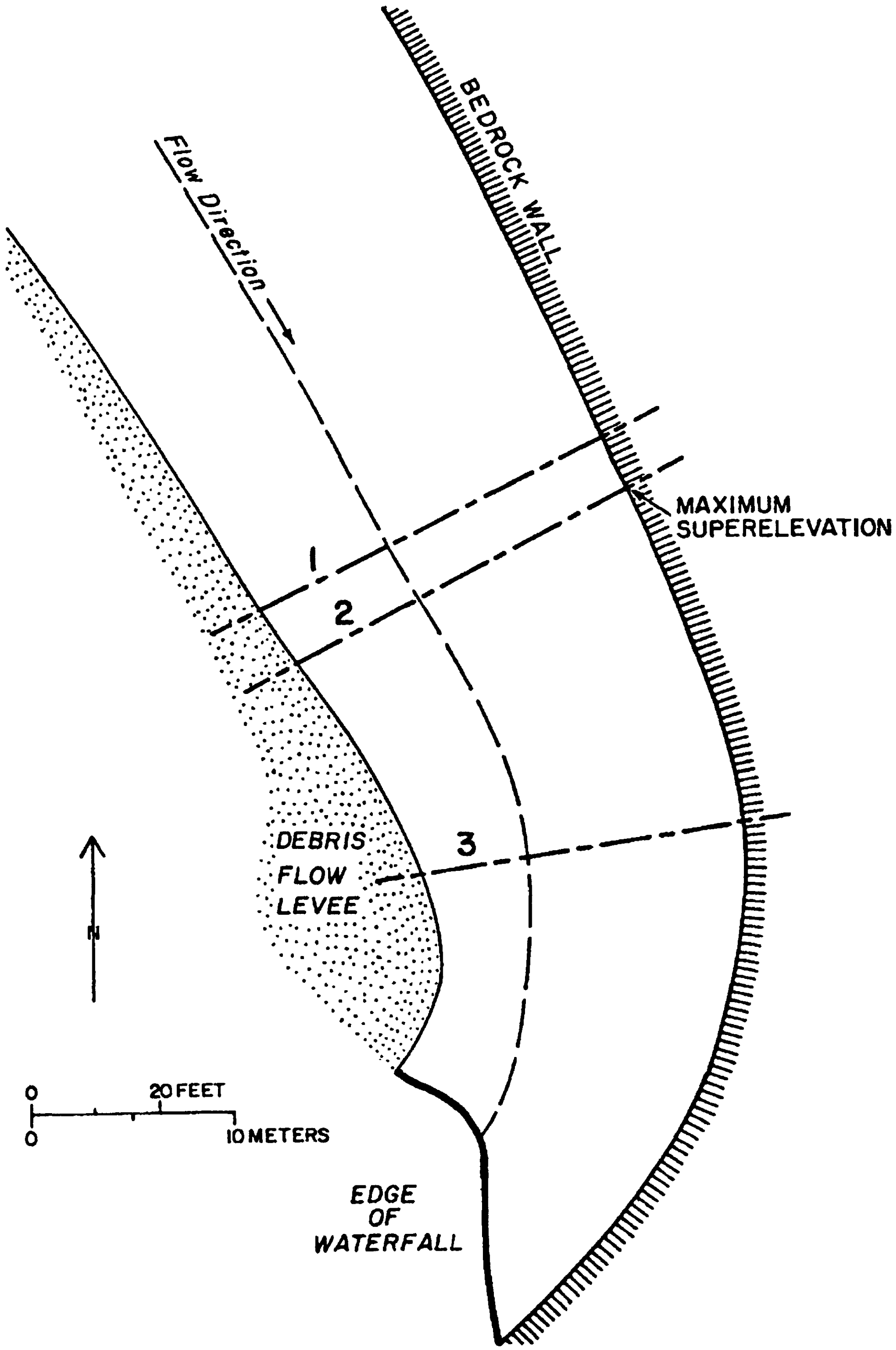
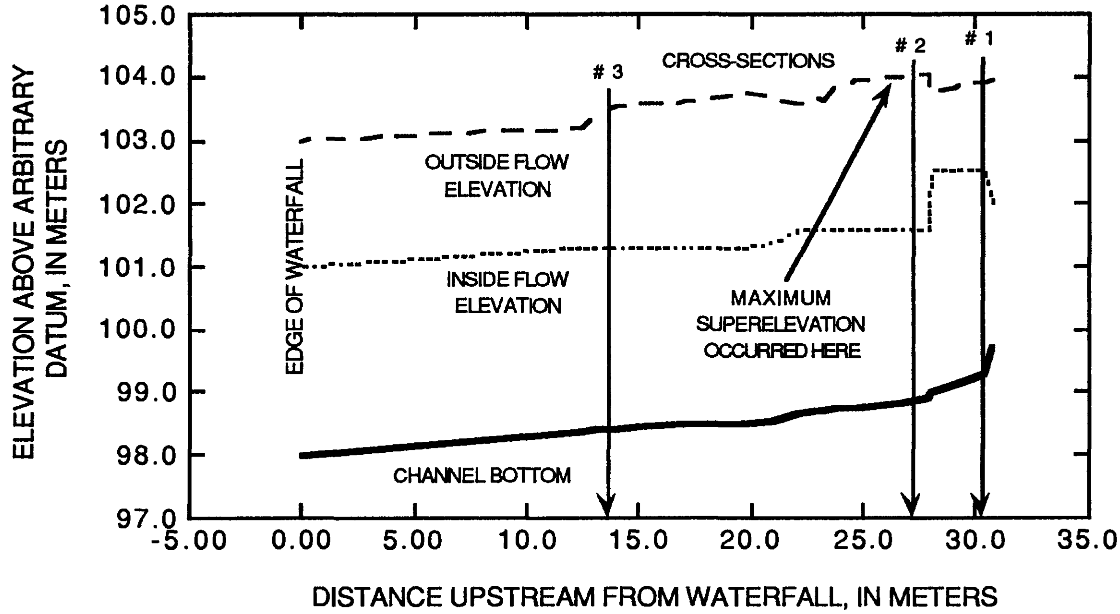


Figure 4. Methods used to indirectly estimate peak discharges in Marble and Grand Canyons. *A.* Plan view of channel bend at site A in "Crash Canyon" (river mile 62.6-R), a tributary of the Colorado River. This view illustrates a typical site containing flow superelevation evidence, which was used to indirectly estimate peak discharges of debris flows in Grand Canyon.



B. Longitudinal variation of the flow-surface profile of the 1990 debris flow at site A in "Crash Canyon" (river mile 62.6-R), a tributary of the Colorado River.

Figure 4. Continued.

techniques averaged 15 percent lower than actually-measured flow-surface velocities. If the plug-flow analogy is valid for debris flows in Grand Canyon, Pierson's work suggests that the velocities reported in this report may be underestimated.

In this study, debris-flow elevations on both sides of the channel were surveyed to fully encompass channel bends. The profiles of flow-surface elevations were compared to determine superelevation and (or) runup through the channel reach (fig. 4B). Indirect-discharge sites were subjectively rated as good, fair, or poor based on several site characteristics. If the channel contained continuous evidence of debris flow on both sides of the channel, was uniform, and was bedrock-controlled, it was rated as good. Designations of fair and poor were assigned as one-or more of these criteria were not met; the site-ratings are given in the peak discharge summary tables of this report. Bedrock-controlled cross sections were used for peak discharge estimations whenever possible. The points of maximum superelevation and runup were identified and superelevation and runup equations were used to estimate peak velocities at these points. At sites where velocity estimates could be determined by both superelevation and runup methods, both of the estimates were used to determine a range in velocity.

Peak discharges were estimated using equation (3). Cross sections were surveyed above, at, and below the site of maximum superelevation and (or) runup wherever possible. Normally, the area of the upstream cross section(s), where the flow-surface elevation was approximately equal on either side of the channel, were combined with the velocity calculated at the point of maximum superelevation or runup to calculate peak discharge. Upstream cross sections were preferred because they may better reflect the velocity of the debris flow immediately before encountering the channel bend, where it then expends energy in superelevation and (or) runup. However, each site was individually evaluated for accuracy, resulting in the selection of mean and averaged, final peak discharge values at some sites.

Webb and others (1989) found that cross-sectional areas at sites of maximum-superelevation were commonly 1.5 to 3.5 times greater than areas determined in cross sections up or downstream, assuming a linear cross-channel flow-surface. This can be explained by the fact that the viscous debris slurry does not maintain a linear flow surface as it superelevates around the bend. Photographs of superelevated debris flows taken in China (K. Scott, written commun., 1991) reveal that the surface of the flowing debris is curved. Therefore, cross-sectional areas determined at the point of superelevation may be much larger than the actual cross-sectional area occupied by the slurry. In two cases (a slight constriction occurring in the channel bend), we found that the cross-sectional area at the point of maximum superelevation was less than the area measured at cross sections either up or downstream from the bend. We concluded that the velocity estimated at the maximum superelevation reflected the effect of the constricted channel rather than the average flow velocity upstream or downstream. Therefore, we chose to report the peak discharge that occurred at that point in these exceptional cases.

All measured cross-sectional areas were evaluated at the 31 indirect-discharge estimate sites. The number of acceptable cross sections varied from one at 7 sites to 11 at one site. Commonly, only one cross section in the study site had definite flow-surface evidence and a stable channel bed; therefore, site selection was limited. In the case of one measured cross section, flow elevations were rarely equal on both sides of the channel and a linear flow-surface was assumed. Of the 24 indirect peak discharge estimates where multiple cross sections were surveyed, peak discharge estimates were calculated from the cross section with the minimal cross-channel elevation difference in 20 cases. At one study site with 11 cross sections, a mean discharge was determined; at two other sites, an averaged value derived from the upstream and downstream cross sections were chosen.

GEOMORPHICALLY-SIGNIFICANT TRIBUTARIES OF THE COLORADO RIVER

A total of 529 geomorphically significant tributaries of the Colorado River between Lees Ferry and Diamond Creek (river miles 0 to 225) were identified as having the potential to produce debris flows (appendix 2). These tributaries also produce relatively frequent streamflow floods that also deliver sand-and-finer sediment to the Colorado River. The total drainage area of tributaries of the Colorado River, excluding the Paria and Little Colorado Rivers and Kanab and Havasu Creeks, is 9,516 km^2. The average tributary has a drainage area of about 18.1 km^2; the median drainage area is 1.79 km^2 and the range is 0.02 to 934 km^2. The amount of drainage area contributing runoff, but without definite channels (E-areas) is about 408 km^2, or approximately 4 percent of the area of significant tributaries. The combined drainage area of geomorphically significant tributaries is 13 percent of the total contributing drainage area of Grand Canyon, which includes the Paria and Little Colorado Rivers and Kanab and Havasu Creeks.

The drainage area of geomorphically significant tributaries varies among the eleven study reaches (Table 5). Reach 10 has more than 3,500 km^2 of tributaries, or over an order-of-magnitude more than Reach 1, which has 268 km^2 of tributaries. Reaches 2, 10, and 11 have the largest tributaries, whereas Reaches 5 and 7 have the smallest (Table 5). The amount of contributing area of tributaries varies between the left and right sides of the river; reflecting the regional geology of the canyon. In reaches 1, 2, 6, 8, and 11, the area of drainages from one side is more than double the area from the other side. This asymmetry in contributing area of tributaries results from the slight regional dip (2 to 3 degrees) of Grand Canyon strata to the south; hence, the drainage divides of many south-side tributaries coincide with the south rim of Grand Canyon. This geologic control on drainage may explain many differences between the reaches in the frequency and magnitude of debris flows and their associated effects on the geomorphology of the Colorado River. Admittedly, the variability of drainage area between study reaches is greatly influenced by the fact that the reaches also vary significantly in length. This fact, however, also reflects the variability of geology along the river which ultimately controls the geomorphic character of the Colorado River channel throughout Grand Canyon.

Table 5. Summary of study-reach statistics for drainage areas tributary to the Colorado River in Grand Canyon
[Study-reach designations are taken directly from Schmidt and Graf (1990), based on bedrock geology and related morphology of the river channel. Number of tributaries, from appendix 2]

Study reach	River mile	Number of tributaries	Total area (km^2)	Mean area (km^2)	Mean area of left-side tributaries (km^2)	Mean area of right-side tributaries (km^2)
1	0.0-11.3	15	268	17.9	8.8	31.5
2	11.3-22.6	26	1,468	61.2	17.2	149.0
3	22.6-35.9	35	480	13.0	12.4	13.8
4	35.9-61.5	66	555	8.4	9.0	7.8
5	61.5-77.4	49	222	4.5	4.8	4.2
6	77.4-117.8	100	1,238	12.4	6.1	19.2
7	117.8-125.5	23	105	4.4	4.4	4.2
8	125.5-140.0	47	425	9.2	2.5	16.6
9	140.0-160.0	21	258	12.3	10.7	15.4
10	160.0-213.9	113	3,536	31.3	41.7	21.4
11	213.9-225.8	30	964	32.1	52.5	8.9

SOURCE AREAS AND INITIATION MECHANISMS FOR DEBRIS FLOWS IN GRAND CANYON

The occurrence of debris flows is related to the abundance and settings of source sediments in tributaries. Source sediments may either be weathered and jointed bedrock, colluvium, or sediment stored adjacent to channels (most commonly channel alluvium in the form of debris flow levees). The Paleozoic and Proterozoic strata exposed in Grand Canyon (fig. 3) provide a wide variety of source lithologies in a setting of high topographic relief. As the size and relief of Grand Canyon has increased through time, so has the variety of available debris-flow source sediments exposed by on-going erosion. In addition to weathered and fractured bedrock sources, abundant source sediments are available from Quaternary and Tertiary colluvium (Cooley and others, 1977, plate I; Huntoon and others, 1986). Observations of failure scarps, in both weathered bedrock and colluvium, suggests that source areas for debris flows may encompass most of the drainage area in many cases.

Ford and others (1974) list slab-failures and rock avalanches as commonly occurring throughout the Grand Canyon, although the exact frequency of these processes is poorly known. Furthermore, they reported that rockfalls generally occur in all seasons, at all times of day, and under a wide range of weather conditions. During our winter field excursions we have noticed the increased likelihood for rockfalls to occur during prolonged periods of rain. We witnessed such a period recently in January 1993, when several hundred small rockfalls occurred in Marble Canyon during a 4-day period. On the basis of our experiences, we have also noticed a likelihood of increased rockfalls in Grand Canyon in association with summer (monsoon) thunderstorm season. The elevational and temperature gradients of Grand Canyon range widely owing to the extreme topography of the region. The area is also subject to a high degree of annual and inter-annual climatic variability, especially during the warm-season (Graf and others, 1990; Hereford and Webb, 1992). These conditions are conducive to precipitation-related infiltration and frost action that affect large surface areas of bedrock. Generally speaking, prolonged winter precipitation and freezing temperatures favor rockfalls and the formation of talus and colluvium, while convective thunderstorms, driven by monsoonal circulation in summer, promote debris flows by creating short-duration, intense rainfall.

Regional and localized faults, folds, and joints probably play a large role in controlling conditions that promote mass wasting in the canyons of the Colorado River. Therefore, the degree of structural deformation associated with a given drainage basin can also influence the abundance of source sediments, drainage-area characteristics, and the location of future debris flows. In general, drainage basins that contain extensive faults should be expected to produce larger volumes of sediment available for debris-flow initiation, simply owing to the fracturing and weathering of exposed bedrock. 75-Mile Creek, which formed along strike of the east-trending 75-Mile Fault, provides a good example of the relation between faulted bedrock and debris-flow frequency. The asymmetry of this tributary, and its high frequency of debris flows, is related to preferential formation of drainages along the highly-fractured, footwall-side of the 75-Mile Fault. Three debris flows since 1959 have been initiated exclusively in colluvium accumulated in these footwall sub-basins.

Debris flows are commonly initiated by slope failures that occur during intense rainfall. The intensity of rainfall required to initiate debris flows in Grand Canyon is unknown, but sparse data indicate that a sustained intensity of more than 20 mm/hr and a total rainfall of 25 to 50 mm may be a minimum requirement (Webb and others, 1989; Melis and Webb, 1993).

We have identified three types of initiation mechanisms related to slope failures responsible for triggering Grand Canyon debris flows. These are 1) bedrock failures in weathered outcrops; 2) the fire-hose effect (Johnson and Rodine, 1984); and 3) failures in colluvial wedges during rainfall only. Bedrock failures typically occur in Hermit Shale, the Supai Group, and (or) the Muav Limestone. Failures may also occur in Redwall Limestone, but these are rare and form only small debris flows. Failures in bedrock occur along faces of weathered cliffs during intense precipitation, providing an excellent initiation mechanism for debris flows. Failures in colluvium caused by the fire-hose effect occur when floods pour over waterfalls and rapidly erode unconsolidated colluvial wedges mantling outcrops of Hermit Shale or Muav Limestone and Bright Angel Shale. This last mechanism is the most common type that initiates Grand Canyon debris flows. Talus-slip failures of saturated hillslope sediments in colluvium or talus-covered slopes, the third type of initiation mechanism, normally occurs during very intense and (or) prolonged rainfall. Colluvial-wedge failures generally initiate small debris flows.

Saturation of failure-prone talus may be intensified by concentrated sheetflow runoff from cliff faces. This situation is exemplified by talus at the base of prominent, cliff-forming strata, such as the Redwall Limestone. Precipitation intensities on a slope during a storm may be augmented with sheetflow running off the face of exposed bedrock. Accumulated sheetflow runoff is then concentrated at the intersecting line between the talus and bedrock. Under these conditions, saturation of materials may occur more quickly; the importance of this phenomenon has been discussed in relation to extreme floods in other arid environments (Schick, 1988). Because of these conditions, failures on talus slopes may occur during relatively moderate precipitation conditions, compared to those commonly reported at precipitation stations, when storm cells encounter high-relief, vertical walls commonly found in Grand Canyon. Talus-covered slopes in Grand Canyon that have limited vegetal cover, and are commonly adjacent to extensive bedrock exposures, further increase the likelihood of slope failures. Multiple source areas combined with extreme topographic relief can result in combinations of the three basic initiation mechanisms.

Ultimately, it is both the supply of source sediment, and occurrence of precipitation that controls the frequency and magnitude of debris flows (Bull, 1991). If production of colluvium is reduced, and the frequency and intensity of storms increases, debris flows will occur increasingly until source areas are scoured clean. Once this occurs, debris flow frequency will decline until sediment production resupplies favored source areas for debris flows. Geomorphic responses to climatic fluctuations have likely occurred in Grand Canyon.

Although the probability of occurrence of certain initiation mechanisms (*i.e.*, fire-hose effects) decrease as source sediments are removed, large volumes of sediment may remain on adjacent hillslopes. These source areas are still prone to classic soil-slip failures, but may not be subjected to rainfall intensities necessary to cause debris flows under prevailing climatic conditions. Hence, variability in the climate of northern Arizona, as well as changes in the locations of source sediments strongly affects debris-flow frequency and magnitude through time periods ranging from decades to millennia. Ultimately, both past and present climatic conditions related to debris flow probability are reflected in the geomorphic framework of the Colorado River.

DOCUMENTATION OF HISTORIC DEBRIS FLOWS

Debris fans at the mouths of 169 tributaries were analyzed for changes using 1,107 replicated photographs of the river corridor. The original views were taken between 1872 and 1980. These data, representing 32 percent of the geomorphically-significant tributaries of the Colorado River in Grand Canyon, provide one means for determining the frequency of historic debris flows. A total of 142 tributaries were recorded in replicate photographs spanning at least a century. The remaining 27 tributaries were recorded in photographs taken mostly in 1923. Sixteen small chutes in E-areas also were recorded in the photographs.

A time series of repeat photography was developed for several tributaries by collecting historical photographs taken at different times during the last century. For example, we have examined 161 historical photographs of Prospect Canyon (river mile 179.4-L) and Lava Falls Rapid (river mile 179.3-L) that allow detailed reconstruction of debris-flow magnitude and frequency. Other sites with considerable records of repeat photographic include Badger Canyon and Jackass Creek (river mile 7.9), Soap Creek (river mile 11.2-R), Palisades Creek (river mile 65.5-L), Monument Creek (river mile 93.5-L), Waltenburg Canyon (river mile 112.2-R), Kanab Creek (river mile 143.5-R), and Diamond Creek (river mile 225.8-L).

By analyzing the positions of boulders on debris fans and in rapids, we determined whether or not tributaries had debris flows during the span of time between replicate photographs. We identified 97 historic debris flows in historic photographs, indicating that 57 percent of the tributaries with repeat-photography records had debris flows during the last 122 years. Approximately 43 percent of the tributaries in Grand Canyon have a frequency of less than one debris flow per century. Twelve steep-angle chutes in E-areas that had debris flows during the last century indicate that these drainage areas are active producers of relatively-frequent, small debris flows.

MAGNITUDE AND FREQUENCY DATA FOR SPECIFIC TRIBUTARIES

Cathedral Wash (River Mile 2.8-R)

Cathedral Wash drains 17.27 km^2 in upper Marble Canyon (fig. 1). Using interpretations of replicate views from 1890 and 1991, Cathedral Wash has not had a debris flow during the last century. However, hyperconcentrated-flow deposits are preserved just upstream from the confluence. Wood preserved in the top of these deposits was radiocarbon dated as 106.2±1.2 percent modern activity of carbon (PMC), indicating a calendric date of either 1957 or 1989. No ^{137}Cs was detected in the sediment, which suggests a date before 1952. Using these constraints, and owing to the fact that we know of no hyperconcentrated or debris-flows that occurred in this tributary in 1989, we conclude that the most recent flooding in Cathedral Wash probably occurred in the early 1950s.

Badger Canyon (River Mile 7.9-R)

Badger Canyon and Jackass Creek (river miles 7.9-R and 7.9-L) are opposing drainages in eastern Marble Canyon that have drainage areas of 47.01 and 52.24 km^2, respectively (fig. 1). Badger Creek Rapid (river mile 7.9) is the first major rapid of the Colorado River downstream from Glen Canyon Dam in Marble Canyon. The rapid is formed by opposing, low-angle debris fans from the opposing tributaries (fig. 5). Historically, early river expeditions, beginning with the Brown-Stanton expedition of 1889-90, lined or portaged their boats around this rapid; consequently, most expeditions photographed the rapid from its margins. Also, because this area is easily accessible by road from both sides of the river, many people have photographed the rapid at various times from the rims (table 6). The tributaries that formed these debris fans head in Mesozoic rocks, which are the source area for debris flows; these areas include shales in the Chinle Formation.

On August 17, 1994, a debris flow followed by a larger streamflow flood occurred in Jackass Creek. Heavy rainfall between 5:30 and 8:00 PM, was the likely cause for the debris flow. The debris flow began in two tributaries of Jackass Creek in the steep terrain of the Echo Cliffs. The flow was initiated by failure in the Chinle Shale in one tributary, and in a colluvial wedge in the second. The debris flow enlarged the existing debris fan and altered flow through Badger Rapid, increasing its severity.

A total of 75 historical photographs of Badger Creek Rapid (table 6) were analyzed to determine if debris flows had occurred in either Badger Canyon or Jackass Creek during the last century. Before the 1994 event, no historic debris flows had occurred in Jackass Creek between 1890 and 1993 (river mile 7.9-L), although streamflow floods of substantial magnitude have apparently moved boulders 1-to-2 m in diameter down its channel during the last century. Most of the boulders on the left side of the rapid, presumably deposited by debris flows from Jackass Creek (fig. 5), have persisted over the last century. Some of these boulders have been rotated or moved by discharges in the Colorado River by streamflow floods in Jackass Creek.

A large debris flow occurred in Badger Canyon (river mile 7.9-R) during the last century. Comparison of views made by George Wharton James in 1897 and Raymond Cogswell in 1909 indicates that the left side of Badger Creek Rapid was aggraded around the turn of the century. Large rocks that form pourovers (water pouring over large boulders) in the center of the rapid at discharges between 142 and 850 m^3/s were deposited during this debris flow. Careful analysis of views made by Franklin A. Nims in 1889 and a repeat view made in 1990 also indicates that the apex of the debris fan at the mouth of Badger Canyon has aggraded. The deposition of large boulders at the top of the rapid changed the flow pattern of Badger Creek Rapid, and boulders on the lower right side of the rapid, shown in the foreground of James' view, have been removed. Sediment deposited by this debris flow contained no organic debris, and a ^{137}Cs activity of 0.008±0.007 pCi/g was measured. Although this is a detectable amount of ^{137}Cs, it probably represents atmospheric fallout and leaching transport through the sediment. No other debris flows have occurred in Badger Canyon since 1909.

Soap Creek (River Mile 11.2-R)

Soap Creek drains 90.26 km^2 on the north side of the river in eastern Marble Canyon (fig. 1). Soap Creek Rapid apparently formed the most serious navigational hazard on the river for early river runners based on historical accounts. All river runners before 1930 either chose to portage their boats around this rapid or unsuccessfully attempted to run it; this usually resulted in capsized boats (Webb, in press). By his own account, Soap Creek Rapid was the only rapid not run by George Flavell during his 1896 run of the river (Carmony and Brown, 1987). The Kolb brothers attempted to run the rapid in 1911, only to flip both of their boats (Kolb, 1914). The first successful run of Soap Creek Rapid was unintentional; the boatman was not aware that the rapid was Soap Creek Rapid (Eddy, 1929).

At some point in the mid-1930s, Soap Creek Rapid became less difficult to navigate. River runners encountered fewer of the violent hydraulic

Figure 5. Oblique aerial photograph of Badger Creek Rapid (river mile 7.9) and the mouth of Jackass Creek (river mile 7.9-L) on October 4, 1958 (P.T. Reilly, Sun City, Arizona, photograph L42-17). View is east and discharge in the Colorado River is about 162 m^3/s. A debris flow that occurred between 1897 and 1909 caused extensive deposition on the Badger Canyon debris fan (left center); rocks that appear in the top center of the rapid were deposited by that debris flow. The direction of river flow is left to right.

Table 6. List of historical photographs of Badger Creek Rapid (river mile 7.9), debris fans at the mouths of Jackass Creek and Badger Canyon (river miles 7.9-R and 7.9-L), and sand bars below the rapid

[For photographs taken before 1921, the discharge is estimated from known stage-discharge relations at Badger Creek Rapid. For photographs taken between 1921 and 1963, discharge is estimated from daily discharge records of the Colorado River at Lees Ferry. After 1963, discharge is estimated from known stage-discharge relations at Badger Creek Rapid. These estimates are perhaps accurate to ±1,000 ft^3/s. (AV), vertical aerial photography; (AL), photograph is an oblique aerial taken from the left side of the river; (AR), photograph is an oblique aerial taken from the right side of the river; (RL), photograph was shot from river-left; (RR), photograph was shot from river-right; (US), upstream view; DS, downstream view; (AC), view across the river; (UC), view looking up the tributary channel or away from the river; (R), view shows a rapid; (DF), view shows debris fan(s); (SB), view shows sand bar(s); (n.d.), no data; (n.m.), the photograph was analyzed, but not matched]

Year	Date	Photographer	Original number	Stake number	Side	Direction	Subject	Discharge (ft^3/s)
1889	Dec 28	Nims	277	1406a	RR	US	R,DF,SB	~5,000
	Dec 28	Nims	278	1403	RL	US	R,DF	~5,000
1897	Dec 1	James	P45271	2353	RR	US	R,DF	n.d.
	Dec 1	James	P45259	n.m.	RL	US	R,DF	n.d.
	Dec 1	James	P43996	n.m.	RR	US	R,DF	n.d.
	Dec 1	James	P44578	n.m.	RR	US	R,DF	n.d.
	Dec 1	James	P43990	n.m.	RL	AC	R,DF	n.d.
1909	Oct 28	Cogswell	616	2351	RR	US	R,DF,SB	n.d.
	Oct 28	Cogswell	617	n.m.	RR	US	R,DF	n.d.
1911	Nov 8	Kolb	NAU 568-1069	1401	RR	US	R,DF	n.d.
	Nov 8	Kolb	NAU 263-3423	1404	RL	US	R,DF	n.d.
1914	Dec	Tadje	n.d.	2354	RR	US	SB,DF	n.d.
1923	Jul 22	Freeman	16	1397	RR	DS	R,DF,SB	31,600
	Jul 22	LaRue	334	2057	RR	DS	R,DF,SB	31,600
1927	Jul 18	[1]Eddy	59	2757	RL	US	R,DF	25,100
	Dec 4	[1]Eddy	n.d.	1405	RL	AC	R,DF	9,730
1934	Jul 19	Fahrni	3-16	n.m.	RL	AC	R,DF	1,600
	Jul 19	Fahrni	3-17	n.m.	RL	AC	R,DF	1,600
1935	n.d.	SCS	3-284	n.m.	AV	AV	R,DF	n.d.
1938	Jul 14	Clover	2:13:02	2727	RL	AC	R,DF	23,800
1941	Jul 15	Heald	3:06:12	2726	RL	US	R,DF	25,900
1942	Jul 15	Wilson	4:06:12	2725	RL	US	R,DF	23,000
1947	Jul 12	Marston	477 COLOR 1013	2019	RL	US	SB,R	35,800
1952	Jun 19	Leding	NPS	705b	RL	DS	R,DF,SB	98,800
	Jun 19	Leding	NPS 2296	711	RL	DS	SB	98,800
	Jun 19	Leding	NPS 2298	712a	RL	AC	R,DF	98,800
	Jun 19	Leding	NPS 2299	712b	RL	AC	R,DF	98,800
	Jul 11	Belknap	Vol 43(80)	2016	RL	AC	DF	34,000
	Jul 12	Belknap	Vol 43(88)	2048	RL	DS	R,DF,SB	31,400
	Jul 12	Belknap	Vol 43(90)	2017	RL	DS	R,DF,SB	31,400
	Jul 12	Belknap	Vol 43(91)	2017	RL	DS	R,DF,SB	31,400
	Sep 21	Leding	NPS 2333	2059	RL	DS	R,DF,SB	7,050
1954	Jan 2	Reilly	R44-1	705b	RL	DS	R,DF,SB	4,440
1955	Mar 21	Reilly	L12-00	n.m.	AR	AC	R,DF,SB	10,400
	Sep 13	Marston	559 MECN 8.7	2012	RL	DS	R,DF,SB	3,140
1956	May 31	Atherton	Vol 43(103)	2064	RL	AC	R,DF,SB	55,400

Table 6. List of historical photographs of Badger Creek Rapid (river mile 7.9), debris fans at the mouths of Jackass Creek and Badger Canyon (river miles 7.9-R and 7.9-L), and sand bars below the rapid—Continued

Year	Date	Photographer	Original number	Stake number	Side	Direction	Subject	Discharge (ft^3/s)
1956	Jun 17	Marston	566 MECN 8.7	2013	RL	AC	R,DF,SB	40,600
	Jul	Nichols	n.d.	2060	RL	AC	R,DF	~14,000
1956	Jul	Nichols	n.d.	2058	RL	DS	SB	~14,000
1957	May 6	Reilly	L30-30	n.m.	AR	AC	R,DF,SB	17,000
	May 6	Reilly	L30-31	n.m.	AR	AC	R,DF,SB	17,000
	Oct 27	Butchart	5710 MECN 8.8	n.m.	AL	DS	R,DF,SB	12,900
1958	Oct 4	Reilly	L42-17	n.m.	AR	AC	R,DF,SB	5,700
1959	Jun 2	Marston	596 MECN 8.8	2015	RL	DS	R,DF,SB	19,300
	Aug 28	Marston	598 MECN 8.28.2.2	2014	RL	DS	R,DF,SB	7,010
	Aug 28	Marston	598 MECN 8.28.12	1787	RL	AC	R,DF	7,010
	Aug 28	Marston	598 MECN 8.28.3	2352	RL	AC	R,DF,SB	7,010
	Sep 26	Marston	599 MECN 8.11	1788	RL	AC	R,DF,SB	7,010
1962	Jun 24	Reilly	L56-02	2063	RL	DS	R,DF,SB	49,400
1963	Jun 17	Reilly	L66-15	2061a	RL	AC	R,DF,SB	2,520
	Jun 17	Reilly	R78-01	2061b	RL	AC	R,DF,SB	2,520
1964	Oct 31	Belknap	Koda 13	n.m.	AL	AC	R,DF,SB	n.d.
1965	May 14	USGS	n.d.	n.m.	AV	AV	R,DF,SB	26,700
1972	Aug 21	Turner	NPS	705b	RL	DS	R,DF,SB	n.d.
	Aug 22	Turner	NPS 2296	711	RL	DS	SB	n.d.
	Aug 22	Turner	NPS 2298	712	RL	AC	R,DF	n.d.
1973	Jun 16	USGS	n.d.	n.m.	AV	AV	R,DF,SB	3-14,000
	Jul 8	Weeden	1-5	2018a	RL	AC	SB	n.d.
	Jul 8	Weeden	1-4	2018b	RL	US	SB,DF	n.d.
	Jul 8	Weeden	1-7	1786a	RR	US	R,DF,SB	n.d.
	Jul 8	Weeden	1-8	1786b	RR	AC	SB	n.d.
1974	n.d.	Howard	785-4	2355a	RL	AC	SB	n.d.
	n.d.	Howard	785-5	2355b	RL	AC	SB	n.d.
	n.d.	Howard	785-6	2355c	RL	AC	SB	n.d.
	n.d.	Howard	785-9	2356	RL	AC	SB	n.d.
	n.d.	Howard	786-1	2357	RR	AC	SB	n.d.
1977	n.d.	[2]Blaustein	plate 10	2065	RL	DS	R,DF,SB	n.d.
1982	Oct 5	Turner	NPS 2298	712a	RL	AC	R,DF	n.d.
1983	Oct 17	Turner	NPS 2296	711	RL	DS	SB	n.d.
	Oct 17	Turner	NPS 2298	712a	RL	AC	R,DF	n.d.
1984	Aug 12	Turner	NPS 2296	711	RL	DS	SB	n.d.
	Oct 21	GCES	1-193	n.m.	AV	AV	R,DF,SB	n.d.

[1]See Eddy, 1929.

[2]See Blaustein, 1977.

standing-waves at the head of the rapid that had convinced early explorers to portage it. Soap Creek Rapid has been run regularly since that time (Webb, in press). Modern river runners do not consider the rapid to be a serious navigational hazard in Marble Canyon (Stevens, 1990).

Before changes that occurred to the rapid in the 1930s, the most significant navigational hazard in Soap Creek Rapid was a large standing wave formed by boulders at the head of the rapid (Kolb, 1914). The standing wave is visible in a 1935 aerial photograph of Soap Creek Rapid (table 7). The rocks forming this hazard are not visible in modern aerial photographs, even when the river discharge is low (less than 142 m^3/s) or in any historical photographs taken of the rapid after 1941 (table 7).

On the basis of our examination of photographs of Soap Creek Rapid taken throughout the last century, a debris flow occurred in Soap Creek between 1935 and 1941. We replicated 18 historical photographs of Soap Creek Rapid (table 7). The replicate pair that best shows the changes caused by this flood is based on an E.C. LaRue photograph taken in 1923 and replicated in 1988 (number 309, table 7). Our match shows that significant deposition of boulders on the upstream side of the debris fan has partly filled in the right side of the upper pool in the rapid. The large rock that created the navigational difficulty in the rapid may have been washed downstream or was buried under the debris. The change caused by this debris flow represents a classic example of how debris flows may actually decrease the navigational difficulty of some rapids. Whether the navigability of a rapid becomes more or less difficult depends on the specific arrangement of boulders in a rapid, the morphology of both the tributary and river channels at the point of confluence, and the extent of river-reworking that the rapid and debris fan have undergone.

House Rock Wash (River Mile 16.8-R)

House Rock Canyon (river mile 16.8-R) drains 770.52 km^2 in eastern Marble Canyon (fig. 1). House Rock Rapid (river mile 16.8), formed by the low-angle debris fan deposited at the mouth of House Rock Canyon, is one of the most severe in the first 70 river miles of the Colorado River in Grand Canyon (Stevens, 1990). Several replicates of historical photographs first taken in 1890 and 1923 show evidence of subsequent deposition on the debris fan by at least one large debris flow. This debris flow reportedly occurred in 1966 (Steiger, 1993), although it was not associated with the widespread tributary flooding that occurred in December 1966, which reportedly only affected tributaries downstream from river mile 65 (Cooley and others, 1977; John Cross II, written commun., 1994). River guides report the changes occurred sometime between 1966 and 1971 and claim the rapid became wider and easier to run after the large dam releases of 1983.

Several methods were used to constrain the date of this debris flow. Aerial photographs taken in 1935 and 1973 indicate the debris flow occurred between these dates. The aggraded debris fan appears in aerial photographs taken on an unknown date in the 1960s (Hamblin and Rigby, 1968). Several twigs collected from a preserved debris-flow levee about 1 km upstream from the Colorado River yielded a ^{14}C activity of 122.7±2.1 PMC, which indicates the debris flow occurred after the 1950s. On the basis of the relation of post-bomb ^{14}C, the plant that produced the dated organic matter died in either 1959 or 1982. The activity of ^{137}Cs in the debris-flow matrix was 0.123±0.009, indicating deposition after 1952. The results of both radiometric techniques are consistent with a date of 1966-1971 for the debris flow.

"18-Mile Wash" (River Mile 18.0-L)

This informally named tributary drains 5.06 km^2 on the south side of the Colorado River, of which 4.0 km^2 is above the rim of Marble Canyon (fig. 6). A large separation bar formerly present on the downstream side of the debris fan at 18-Mile Wash provided a popular camping beach for river runners in the 1960s, 1970s and early- to mid-1980s (fig. 7). Schmidt and Graf (1990) use this site as an example of changes in the elevation and volume of a sand bar in response to releases from Glen Canyon Dam between 1963 and 1986. As an unfortunate end to their studies, a debris flow in 18-Mile Wash completely buried the separation bar, constricted the Colorado River, and enlarged an existing riffle on or about August 24, 1987 (fig. 7).

Table 7. Historical photographs of Soap Creek Rapid (river mile 11.2), the debris fan at the mouth of Soap Creek (river mile 11.2-R), and sand bars below the rapid (river mile 11.3)

[For photographs taken before 1921, the discharge is estimated from known stage-discharge relations at Badger Creek Rapid. For photographs taken between 1921 and 1963, discharge is estimated from daily discharge records of the Colorado River at Lees Ferry. After 1963, discharge is estimated from known stage-discharge relations at Badger Creek Rapid. These estimates are perhaps accurate to ±1,000 ft3/s. (AV), vertical aerial photography; (AL), photograph is an oblique aerial taken from the left side of the river; (AR), photograph is an oblique aerial taken from the right side of the river; (RL), photograph was shot from river-left; (RR), photograph was shot from river-right; (US), upstream view; (DS), downstream view; (AC), view across the river; (UC), view looking up the tributary channel or away from the river; (R), view shows a rapid; (DF), view shows debris fan(s); (SB), view shows sand bar(s); (n.d.), no data; (n.m.), the photograph was analyzed, but not matched]

Year	Date	Photographer	Original number	Stake number	side	Direction	Subject	Discharge (ft^3/s)
1872	n.d.	Bell	102	1398	RR	DS	R,DF,SB	n.d.
	n.d.	Bell	276	2047	RR	DS	R,DF,SB	n.d.
1889	Jul 9	Nims	284	1556	RL	DS	R,DF,SB	~15,000
	Dec 30	Nims	283	1407	RL	DS	R,DF,SB	~5,000
1909	Oct 29	Cogswell	622	1555	RR	US	R,DF	n.d.
	Oct 29	Cogswell	624	n.m.	RR	US	R,DF	n.d.
	Oct 29	Cogswell	625	n.m.	RR	US	R,DF,SB	n.d.
1911	Nov 8	Kolb	568-887	2571	RR	US	R,DF	~5,000
	Nov 8	Kolb	568-1033	1411	RR	DS	R,DF,SB	~5,000
1921	May 9	LaRue	308	1247	RL	AC	R,DF,SB	n.d.
	May 9	LaRue	309	1248	RL	US	R,DF,SB	n.d.
1923	Aug 2	LaRue	339	1091	RR	AC	R,DF,SB	24,300
	Aug 3	LaRue	340	2200	RR	AC	R,DF	24,300
	Aug 3	LaRue	568-3253	1408	RR	DS	DF	24,300
	Aug 3	LaRue	568-3244	1409	RR	AC	R,DF	24,300
	Aug 3	LaRue	568-2977	1410	RR	US	R,DF	24,300
	Aug 3	LaRue	568-2984	n.m.	RR	AC	R,DF	24,300
	Aug 3	LaRue	568-2977	1410	RR	US	R,DF	24,300
	Aug 3	LaRue	568-2977	1410	RR	US	R,DF	24,300
	Aug 3	LaRue	568-5100	n.m.	RR	US	R,DF	24,300
1927	Dec 5	LaRue	J5-J10	n.m.	RR	DS	R,DF,SB	9,370
1934	Jul 19	Fahrni	3-26	n.m.	RR	US	R,DF	1,450
	Jul 19	Fahrni	3-27	n.m.	RR	US	R,DF	1,450
1935	n.d.	SCS	6307	n.m.	AV	AV	R,DF	n.d.
1941	Jul 15	Heald	3:2:9	2588	RR	US	R,DF	25,900
1942	Jul 15	Wilson	4:9:11	2589	RR	US	R	23,000
1957	May 4	Reilly	L30-28	n.m.	AV	AV	R,DF,SB	17,000
	May 4	Reilly	L30-29	n.m.	AR	AC	R,DF,SB	17,000
	Sep 30	Marston	579 MECN 11.8	n.m.	AR	AC	R,DF,SB	7,240
1958	Apr 20	Reilly	L37-5	n.m.	AL	US	R,DF,SB	31,400
	Apr 20	Reilly	584 MECN 11.6	n.m.	AL	US	R,DF,SB	31,400
	Jun 3	Marston	586 MECN 11.611.8.8	n.m.	RR	DS	R,DF,SB	100,000
	Jun 8	Marston	586 MECN	n.m.	RR	DS	R,DF,SB	88,600
1963	Jun 18	Reilly	L66-34	n.m.	RR	DS	R,DF,SB	2,500
1964	May 23	Reilly	L73-08	n.m.	RR	AC	R,DF,SB	1,020

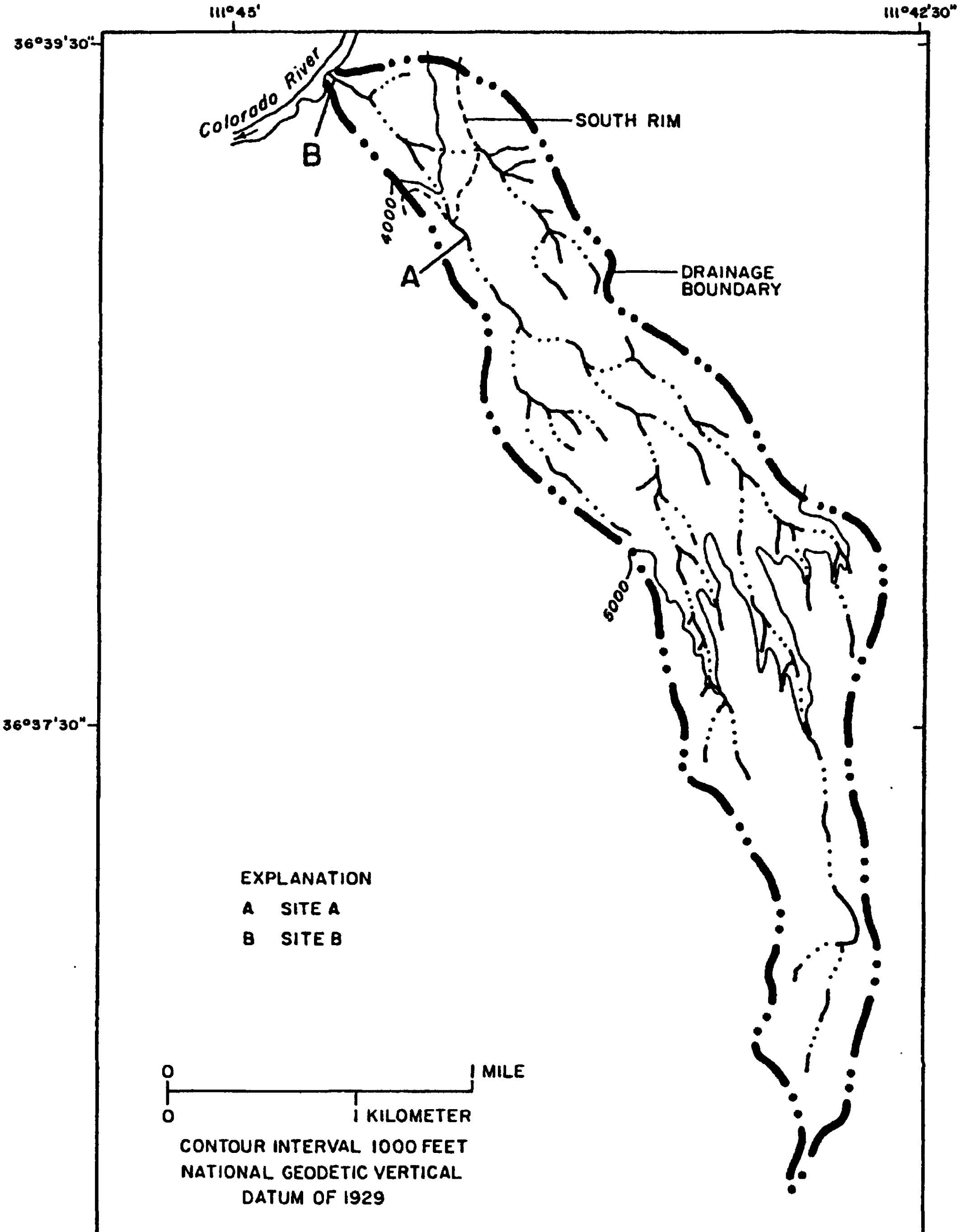


Figure 6. The drainage basin of "18-Mile Wash" (river mile 18.0-L), a tributary of the Colorado River in Marble Canyon.

Table 8. Indirect peak-discharge estimate for the streamflow flood of July 1987 in "18-Mile Wash" (river mile 18.0-L), site A

Site Description

Location: Site A, located above South Rim of Marble Canyon, about 100 m upstream from a Kaibab Limestone waterfall; evidence of peak discharge is a continuous line of driftwood.
Mean basin elevation: 1,521 m.
Drainage area: 4.04 km^2
Reach description: Reach is straight with falls of 1 to 3 m above and below the study section; depositional evidence indicates that the flood was streamflow with a bedload of gravel and coarse sand.

Slope-area Discharge Estimate

Cross section	Manning n-value	Area (m^2)	Conveyance	Velocity (m/s)	Froude number	Discharge (m^3/s)	Slope (m/m)
2	0.035	11.7	263	4.8	1.81	56	
4	0.040	17.3	405	3.2	1.06	55	0.05
5	0.035	15.4	396	3.6	1.25	55	

Discharge 2-4 = 54 m^3/s
Discharge 4-5 = 60 m^3/s
Discharge 2-5 = 56 m^3/s

Frequency

Source	Discharge, in cubic meters per second ± Percent Standard Error Q_{25}	Q_{50}	Q_{100}
[1]Thomas and Lindskov (1983) (Utah low plateaus)	41±65%	60±65%	84±66%
Roeske (1978) (Arizona NW plateaus)	9.3±83%	14±86%	21±91%
Roeske (1978) (Arizona NE plateaus)	6.3±80%	8.9±85%	11±91%

[1]Using Thomas and Lindskov (1983) estimates, which have lower standard errors, the approximate recurrence interval of the flood is estimated at 40 to 50 years.

The amount of precipitation that caused the debris flow is unknown because there are no precipitation stations near this watershed. The debris flow was initiated when streamflow originating above the South Rim of Marble Canyon fell about 100 m from the top of Kaibab Limestone cliffs onto slopes of Hermit Shale and Supai Group and mobilized colluvium and loose bedrock into a debris flow.

Discharge Estimate

Peak discharge for the streamflow flood that caused the debris flow in 18-Mile Wash was estimated in a channel reach 100 m upstream from the rim of Marble Canyon. The streamflow transported a bedload of well-sorted gravel with about 17 percent sand-and-finer sediment (fig. 8A). Continuous lines of driftwood and organic debris on both sides of the tributary channel were surveyed to define high-water marks used to estimate peak discharge. On the basis of the particle-size distribution of the alluvial bed deposits, and the roughness on the channel banks, we assigned a Manning *n*-value of 0.035 to one cross section and 0.040 to two others. A three-section slope-area analysis yielded a discharge of 56 m^3/s with a range between cross sections of 55 to 56 m^3/s (table 8). Froude numbers for the streamflow were greater than 1.0, which indicates that flow in the channel was supercritical as it approached the rim of Marble Canyon.

Figure 7. Replicate photographs' showing changes in the separation bar at "18-Mile Wash" (river mile 18.0-L) caused by the debris flow of August 1987. Photographs A and B were taken from approximately the same position. *A.* View of the separation bar at "18-Mile Wash" (J.C. Schmidt, U.S. Geological Survey, 1985) as it existed before the debris flow of 1987. Discharge in the Colorado River is about 1,475 m^3/s.

B. Replicate view of the aggraded debris fan at "18-Mile Wash" (Tom Wise, U.S. Geological Survey, February 1993) showing the effects of the debris flow of 1987. Discharge in the Colorado River is about 700 m^3/s.

Figure 7. Continued.

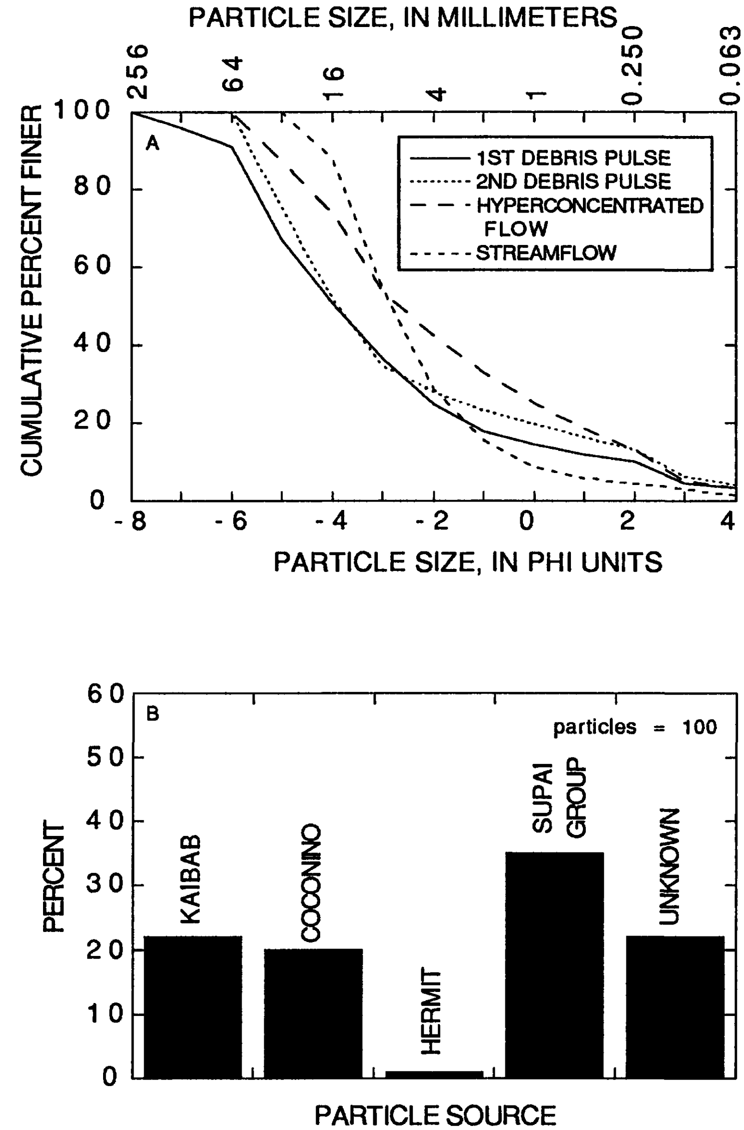
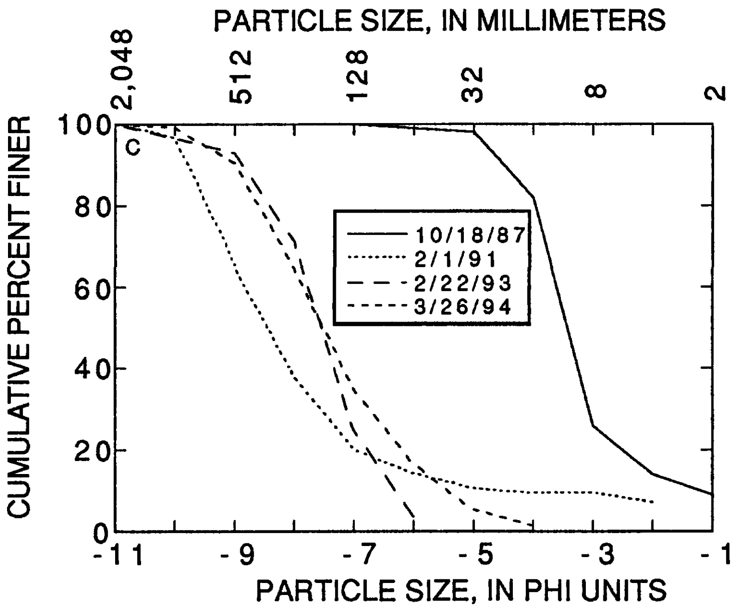


Figure 8. Particle-size and source distributions of various deposits associated with the debris flow of 1987 at "18-Mile Wash" (river mile 18.0-L). *A*, Particle-size distributions of a normal-streamflow deposit, hyperconcentrated-flow deposit, and deposits resulting from two debris-flow pulses that occurred during the 1987 debris flow. *B*, Source distribution of particles contained in the initial pulse of sediment deposited during the 1987 debris flow.



C, Time series of changes in the particle-size distribution of the distal edge of the 1987 debris fan exposed at a discharge of 140 m^3/s or less in the Colorado River.

Figure 8. Continued

We did not attempt to reach the steep terrain where the 1987 debris flow was initiated. However, observation from the rim indicated that the debris flow was mobilized in a colluvial deposit at the base of the waterfall. In the short (~200 m) reach upstream from where the channel plunged through a series of waterfalls in the Supai Group, debris flow levees were deposited on the right side of the channel. No other appropriate reaches for estimation of debris-flow peak discharge were observed from the rim or accessible from the river.

Sediment Characteristics

On the basis of the sediment deposits we analyzed at the debris-flow fan, the debris flow of August 1987 had at least two peaks. Sedimentological and stratigraphic evidence examined on the debris fan (fig. 6, site B) indicated that the 1987 flood consisted of an initial pulse of debris, followed by a smaller recessional debris-flow pulse that was separated from the first one by a short period of hyperconcentrated flow (fig. 8A). The main pulse of debris flow contained many large boulders, with the 10 largest ranging in weight from 1.3 to 6.7 Mg (appendix 8). The deposit associated with the initial debris-flow pulse contained about 20 percent sand-and-finer sediment and contained from 8 to 12 percent water by weight. Lithology of the coarse part of the main lobe of the debris flow was comprised of Supai Group rocks, Kaibab Limestone, and Coconino Sandstone (fig. 8B). This source distribution is consistent with our preliminary conclusion that the debris flow was initiated in deposits overlying the Hermit Shale and Supai Group.

Many point counts were made and sediment samples were collected from the debris fan at 18-Mile Wash to measure the variability of particle-size distribution. Of these, the particle-size distributions of the recessional debris-flow peak and the hyperconcentrated-flow deposit are noteworthy (fig. 8A). Although both contained mostly particles <64 mm, the debris flow contained

Table 9. Summary of mineralogies of clay-sized particles less-than 2 μm collected as subsamples from debris flow matrix sediments identified at selected sites where recent debris flows have occurred in Grand Canyon
[(0), indicates that the mineral was not detected; (1), indicates that trace quantities of the mineral were detected; (2), indicates that a small amount of the mineral was detected; (3), indicates that a moderate amount of the mineral was detected; (4), indicates that a large amount of the mineral was detected; and (5), indicates that the mineral was the dominant mineral detected. Muscovite and biotite were not differentiated]

		Interpreted Clay Monetarily Abundance							
Site	Year of debris flow	Montmor-illonite	Vermic-ulite	Chlorite	Micas	Kaolinite	Quartz	Feldspar	Calcite
"18-Mile Wash" Debris flow	1987	1	0	0	4	3	1	2	2
"18-Mile Wash" Hyper. flow	1987	2	0	0	3+	3	2	2	0
Mile 19.9-L	1987	0	0	0	4	2	0	2	0
Lava Canyon	1966	0	0	0	4	3	1	2	2
75-Mile Creek	1987	0	0	0	3	3+	1	2	2
75-Mile Creek	1987	0	0	0	4	2	1	0	0
75-Mile Creek	1987	0	0	0	4+	2	0	0	0
Monument Creek	1984	0	0	0	4	3	1	2	0
Crystal Creek	1966	0	0	0	4	3	1	2	1

significantly more particles with diameters between 16 and 64 mm than did the hyperconcentrated-flow deposit (fig. 8A). The dominant clay minerals in both the matrix sediments of the debris flow and the hyperconcentrated-flow deposits were undifferentiated micas and kaolinite; montmorillonite was detected in trace or small amounts in both the initial debris-flow pulse and the hyperconcentrated-flow deposit (table 9). The kaolinite likely originated in the Hermit Shale, and the montmorillonite probably was eroded from soils on top of the Marble Platform.

Effects on the Separation Bar

The 1987 debris flow buried the separation bar and the entire downstream side of the debris fan at the mouth of 18-Mile Wash. Exposures seen in rills incised through the debris-flow deposit indicate that little underlying sand was eroded by the flood before burial by the debris flow. The prograded fan decreased the width of the Colorado River by about 7 to 10 m and increased the gradient and total drop through the riffle around the debris fan. The newly aggraded debris fan is not completely inundated by river flows of less than about 1,270 m^3/s, which indicates that the separation bar will not be reestablished unless releases from Glen Canyon Dam (currently limited to a range of 142 to 510 m^3/s) are significantly increased in the future. By 1989, a veneer of sand had been deposited at the distal edge of the 1987 debris fan (fig. 7B).

The area of the 1987 debris fan inundated by river discharges of less than 850 m^3/s was significantly reworked between 1987 and 1991 by high fluctuating-flows ranging from less than 142 to about 850 m^3/s; these flows were associated solely with power plant operations at Glen Canyon Dam. Repetitive surveying of profile lines established along the medial axis of the new debris fan in January 1986 indicated no major differences in the topographic profile of the debris fan between October 1987 and January 1989 (Jack Schmidt, Utah State University, written commun., 1991). The particle-size distribution along the distal edge of the debris fan below the 142 m^3/s discharge level was periodically monitored (four times) between 1987 and 1994 (fig. 8C). These data show that coarsening of this part of the debris fan occurred under a high range of powerplant releases between 1987 and 1991. These releases included daily discharges up to 850 m^3/s; the coarsening of the deposit resulted from erosion of particles in the 1987 debris fan with diameters <256 mm. Repetitive particle-size measurement between 1992 and 1994 indicates that the distal edge of the debris fan contained finer sediment than it did in early 1991, just before the onset of interim flows ranging from 142 to 566 m^3/s. In contrast to the initial coarsening apparent on the fans distal edge as early as October 1987, particle-size data collected in 1993 and 1994 showed a slight reversal in the trend. Owing to the reduced competence of interim flows compared to normal powerplant operation, finer particles are apparently able to remain on the fans distal edge.

Frequency

Frequency of the 1987 debris flow at 18-Mile Wash was evaluated in three ways. First, regression relations of flood frequency have been developed for several regions surrounding Grand Canyon (Roeske, 1978; Thomas and Lindskov, 1983). These relations are between drainage-basin area and the quantile estimates of flood frequency, which usually are the 2-, 5-, 10-, 50-, and 100-year discharges. We considered three regions to be appropriate: the low plateaus of southern Utah (Thomas and Lindskov, 1983), the northwestern plateaus of Arizona, and the northeastern plateaus of Arizona (Roeske, 1978). Regional relations indicate that peak discharges between 6 and 84 m^3/s have recurrence intervals between 25 and 100 years (table 8). The substantial difference between regression relations of flood frequency in northern Arizona and southern Utah required a choice between the two sets of published regression equations. We rejected the relations of Roeske (1978) that indicated a recurrence interval of greater than 100 years for the flood. Even though Roeske's study sites are geographically closer to Grand Canyon, the standard errors associated with his method are higher than those provided by Thomas and Lindskov (1983); we therefore accepted a recurrence interval of approximately 50 years for the streamflow flood at 18-Mile Wash determined using their relations (table 8).

Comparison of aerial photographs taken in 1965 and 1984 reveal few changes in the debris fan at 18-Mile Wash. The only historic photograph of the debris fan was taken by Harmer Weeden in 1973. This view, which is similar to that of figure 8A taken in 1984, shows that the debris fan at 18-Mile Wash remained unchanged between 1973 and August 1987. Whereas the repeat and aerial photography does not address the occurrence of previous debris flows, it shows that the debris flow of 1987 was the only major sediment flood to occur between 1965 and 1994 (29 years).

At the apex of the debris fan, preserved remnants of two debris-flow deposits of unknown age overlie multiple deposits of silt and sand deposited by the Colorado River. On the basis of their positions, these older debris-flow deposits attained much higher flow elevations than did the 1987 deposit upon reaching the river, indicating that they were deposited by significantly larger floods. Analyses of the silt and sand and the overlying debris-flow deposit yielded no detection of ^{137}Cs activity, which indicates the silt and sand and the debris-flow sediments were deposited before about 1952. The analyses suggest that no large debris flows occurred in 18-Mile Wash between 1952 and 1987 (35 years).

Unnamed Tributary at River Mile 19.9-L

On August 13, 1987, an unnamed drainage at river mile 19.9-L had a debris flow during the same storm that affected "18-Mile Wash." The tributary

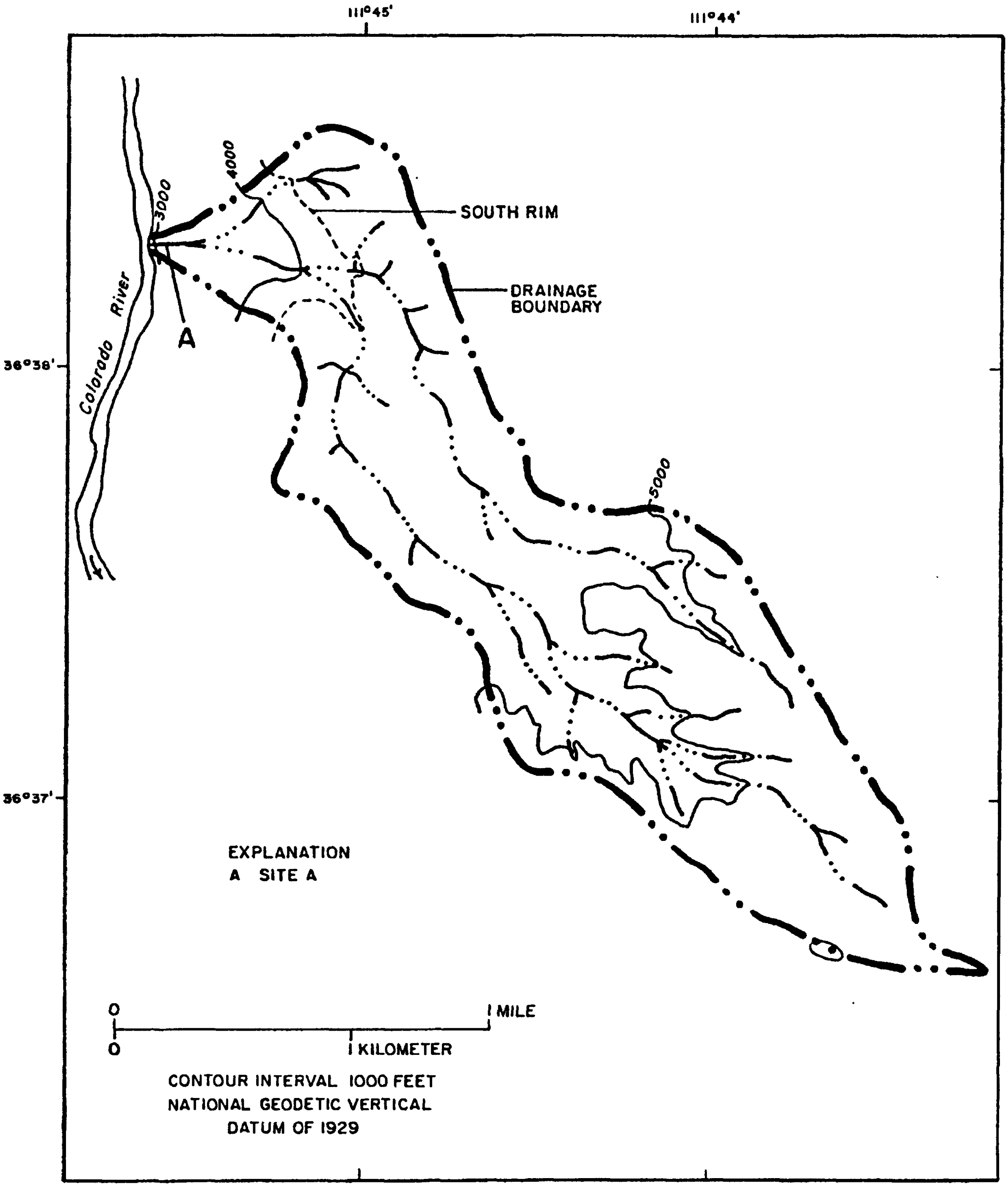


Figure 9. The drainage basin of an unnamed tributary of the Colorado River at river mile19.9-L in Marble Canyon.

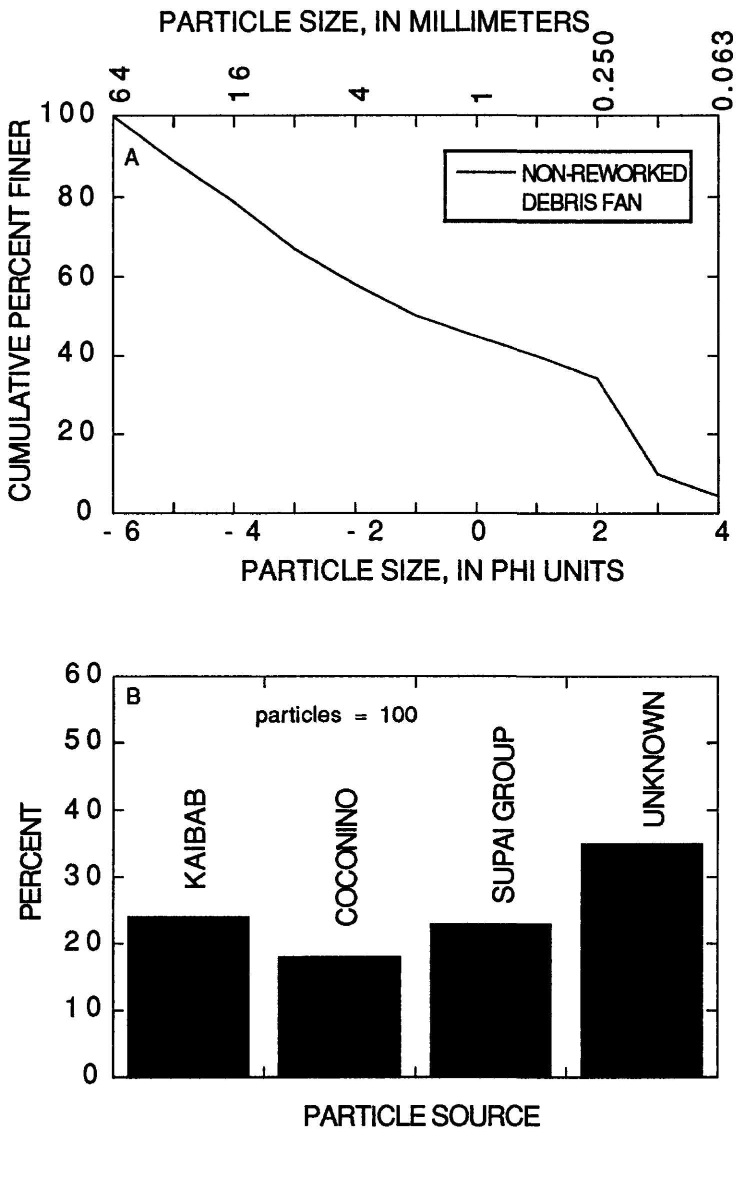


Figure 10. Particle-size and source distributions of various deposits associated with the debris flow of 1987 in an unnamed tributary of the Colorado River at river mile 19.9-L in Marble Canyon. *A*, Particle-size distribution of the undisturbed part of the 1987 debris fan. *B*, Source distribution of particles on the undisturbed, 1987 debris fan.

drains 3.78 km^2, most of which is above the rim of Marble Canyon on the south side of the river (fig. 9). Streamflow, which originated in the drainage basin above the South Rim, fell over a 120-m-high cliff of Kaibab Limestone and initiated a debris flow in the colluvium and rock of the Hermit Shale and Supai Group. This debris flow subsequently flowed through a channel incised into Supai Group rocks that dropped about 190 m before depositing on a steep, pre-existing debris fan. The debris flow eroded part of what is informally called "20-Mile Beach" and slightly enlarged an existing riffle in the Colorado River (fig. 9, site A).

Peak discharge could not be estimated for this debris flow because of a lack of suitable sites over the short distance that the debris flow travelled before reaching the river (fig. 9). New debris-flow levees were formed on the right side of the debris fan, whereas the left side of the debris fan was eroded. A particle-size distribution for the debris flow was determined by combining point-count and dry-sieve data derived from sediment sampled from the channel-right debris-flow levee at the debris fan (Site A, figs. 9 and 10A). The debris-flow fan deposit contained about 50 percent sand-and-finer sediment, on the basis of point-count data, and had a water content of 17 to 19 percent by weight. The coarser component of the sampled debris-flow deposit consisted mostly of sediments from Kaibab Limestone and Supai Group rocks, with lesser amounts of Coconino Sandstone (fig. 10B). About one-third of the clasts in the point-count sample could not be identified because they were finer than gravel. Undifferentiated micas and kaolinite are the most abundant clays contained in the debris-flows matrix; montmorillonite was not detected (table 9).

Unnamed Tributary at River Mile 30.5-R

An unnamed tributary at river mile 30.5-R had at least one debris flow on an unknown date during the last century. This tributary drains 0.95 km^2 of the north side of the river (fig. 1). Evidence of this debris flow is contained in recently-replicated views of historical photographs originally taken in 1890 and 1923. A small sample of wood collected from an undisturbed debris levee in the main channel about 0.2 km upstream from the confluence, yielded a ^{14}C activity of 103.4±1.3 percent of modern carbon. This corresponds to a calendric date of either 1956 or 1989, on the basis of the post-bomb ^{14}C relation. A comparison of aerial photographs taken in 1988 and 1990 indicates that one debris flow occurred in 1989 (appendix 1).

Nautiloid Canyon (River Mile 34.7-L)

Nautiloid Canyon drains 10.59 km^2 on the south side of the Colorado River (fig. 1). Much of the drainage area of this tributary is above the South Rim of Marble Canyon. A recent debris-flow lobe preserved near the mouth of Nautiloid Canyon overlies an older deposit of unknown age, as well as part of a separation bar. We analyzed the ^{137}Cs activity of both deposits and detected no ^{137}Cs in either. This result alone indicates that no debris flows occurred in Nautiloid Canyon since 1952. However, deposits seen on the debris fan in a comparison of aerial photographs taken between 1965 and 1984 indicate that a small debris flow probably occurred in Nautiloid Canyon between 1980 and 1984.

Unnamed Tributary at River Mile 42.9-L

A small debris flow occurred in this 1.33 km^2 drainage (fig. 1) during the summer of 1983. The local and regional precipitation data indicate the debris flow probably occurred in July or August. Owing to the inaccessibility of the tributary channel upstream from the confluence, we were unable to estimate a peak discharge for this debris flow. The debris flow deposited large boulders on the debris fan, which ranged in weight from 4 to 62 Mg (appendix 8), and created levees along the margins of the incised channel through the debris fan. Particle-size distributions for undisturbed deposits on the debris fan, boulder levees, and the reworked surface of the existing debris fan were determined by point counting (fig. 11A). The source distribution of the debris-flow levee sampled indicates the debris flow was comprised mostly of Supai Group rocks (fig. 11B). Comparison of the source distributions of the undisturbed debris-flow levee and the reworked debris-fan surface show a slight increase in Redwall Limestone boulders on the reworked surface (fig. 11B). These data reflect

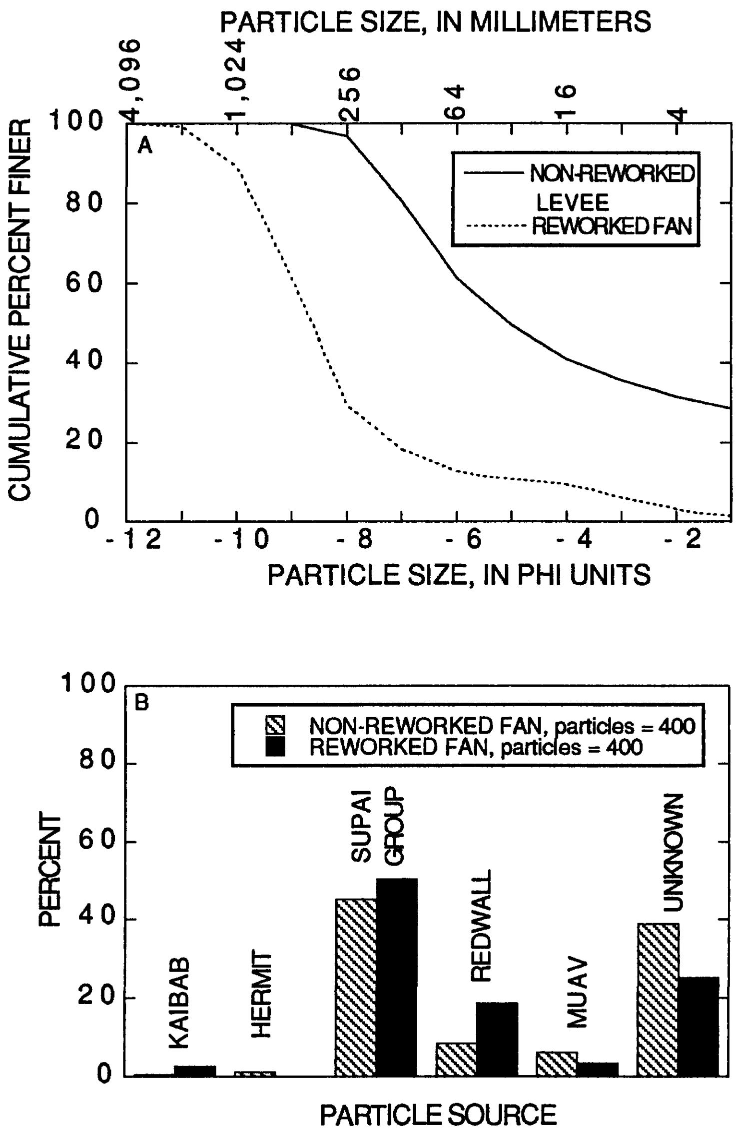


Figure 11. Particle-size and source distributions of various deposits associated with the 1983 debris flow in an unnamed tributary of the Colorado River at river mile 42.9-L in Marble Canyon. *A*, Particle-size distributions of an undisturbed 1983 debris-flow levee and the reworked surface of the pre-1983 debris fan. *B*, Source distributions of particles on the pre-1983 debris fan and the 1983 debris-flow levee.

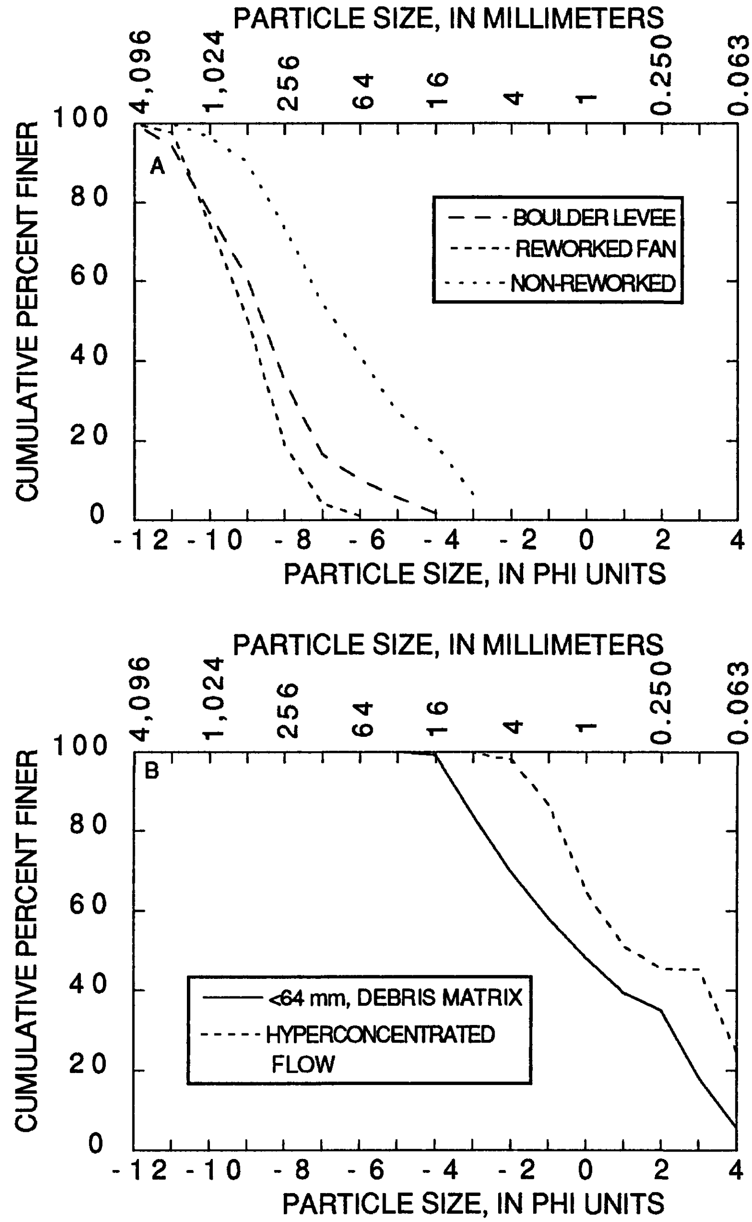
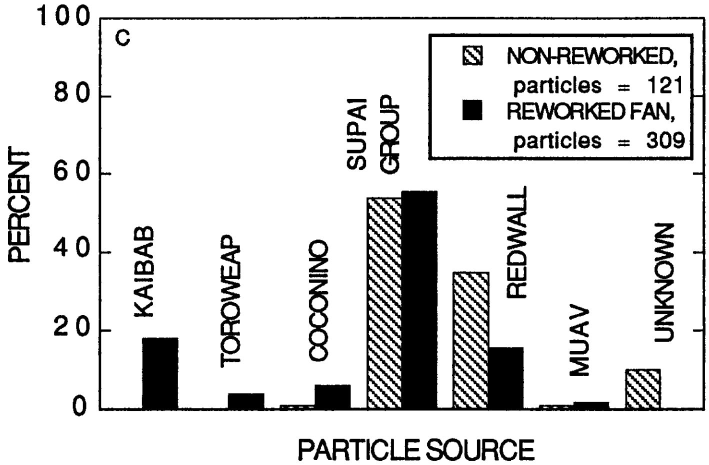
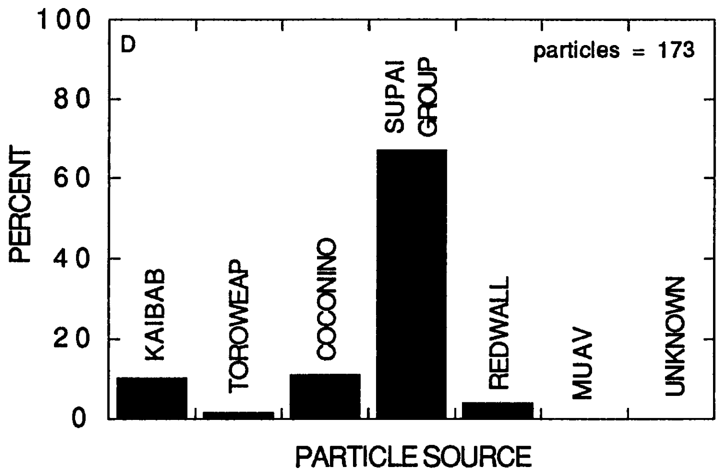


Figure 12. Particle-size and source distributions of various deposits associated with a 1983 debris flow in an unnamed tributary of the Colorado River at river mile 43.2-L in Marble Canyon. *A*, Particle-size distributions for a 1983 boulder levee, a 1983 debris-flow levee, and a pre-1983 reworked debris-fan surface. *B*, Particle-size distributions for a < 64 mm fraction of the 1983 debris-flow matrix and a 1983 hyperconcentrated-flow deposit.





C, Source distributions of particles on the 1983 debris-flow levee and the pre-1983, reworked debris fan surface. *D*, Source distribution of particles in the 1983 boulder-levee deposit.

Figure 12. Continued

the significance of the Supai Group in the formation and evolution of debris fans and rapids in Reach 4 (river miles 36 to 61). Part of the existing separation bar was buried by debris-flow sediment transported by this relatively small debris flow.

The frequency of debris flow in this unnamed tributary was determined from examination of aerial photographs of the debris fan taken between 1965 and 1992. These photographs indicate that the debris flow must have occurred between 1980 and 1984. The activity of ^{137}Cs in sediment on the debris fan is 0.046±0.007 pCi/g, which is consistent with post-bomb deposition. Our information does not refute the 1983 date provided by river guides (G. Bolton and D. Silva, oral commun., 1991). Replicate photographs near the mouth of this tributary, taken originally in 1890 and matched in 1991, indicate that the 1983 debris flow was probably the only one to occur in this tributary during the last century.

Tatahoysa Wash (River Mile 43.2-L)

During the summer of 1983, a small debris flow occurred in Tatahoysa Wash, which drains 50.77 km^2 on the south side of Marble Canyon (fig. 1). We assume that the debris flow occurred on the same date as the one at river mile 42.9-L, because we have no evidence to indicate otherwise (G. Bolton and D. Silva, oral commun., 1993). The debris flow also deposited prominent boulder levees along the margins of the debris fans incised alluvial channel; it also destroyed several catclaw trees growing on the debris fan. We were unable to estimate a peak discharge for the debris flow owing to the inaccessibility of the tributary channel upstream from the confluence.

Particle-size distributions for the boulder levee, preserved remnants of the debris-flow deposit, and the reworked debris fan were determined from point counts, whereas particle-size data for a hyperconcentrated-flow deposit associated with the 1983 flood were obtained through dry-sieve analysis (fig. 12A and 12B). The undisturbed debris-flow fan deposit has a significantly finer particle-size distribution than the reworked fan surface (fig. 12A). However, the 1983 boulder levee has a particle-size distribution that is similar to the reworked fan surface. Figure 12C shows a comparison of source distributions for the pre-1983, reworked debris-fan surface, and the undisturbed debris-flow fan deposit. Although the debris flow buried part of a separation bar on the debris fan, it apparently had little effect on the hydraulics of the Colorado River, or the existing rapid that was formed by a large Redwall Limestone boulder deposited in the middle of the river channel. The source distribution of the boulder levee indicates that the coarsest clasts in the debris flow were mostly from the Supai Group (fig. 12D).

The year of this debris flow was determined from personal accounts obtained from professional river guides (G. Bolton and D. Silva, oral commun., 1993). However, the frequency for debris flow in Tatahoysa Wash was also determined using ^{137}Cs analysis and matches made of historical photographs showing the debris fan in 1890 and again in 1983 and 1992. The activity of ^{137}Cs in debris-flow sediment was 0.042±0.006 pCi/g, which is consistent with post-bomb deposition. Two replicates of an 1890 photograph of the debris fan, matched in 1983 and 1991, indicate that the 1983 debris flow was probably the only one in Tatahoysa Wash to reach the Colorado River during the last century. Multiple sets of aerial photographs taken of the debris fan between 1965 and 1992 also support the account claiming that the debris flow occurred between 1980 and 1984. We were able to determine that the debris flow in fact had occurred by 1983, using a 1983 replicate of an 1923 photograph. The replicate that showed substantial change in the debris fan had occurred by October 1983 and had not been reworked by the high dam releases of the previous June.

Unnamed Tributary at River Mile 62.5-R

A debris flow occurred in an unnamed tributary at river mile 62.5-R on or about September 24, 1990, during locally intense thunderstorms. Although the debris flow was relatively small, it resulted in significant geomorphic changes to the existing debris fan, a small riffle, and a separation bar. This unnamed tributary drains 0.67 km^2 of the north side of the river on the southeastern flank of Chuar Butte (fig. 13). The source sediments in the drainage consist of continuous, massive colluvial wedge sediment deposits perched along the base of Redwall Limestone cliffs. Fresh-looking erosional rills cut into these colluvial deposits indicate that the 1990 debris flow was initiated mainly by fire-hose effects.

This tributary consists of several small, steep gullies incised into colluvial hillslopes overlying Muav Limestone. These channels join the larger, main tributary channel at the base of the colluvium and continue down to the river through Bright Angel Shale and Tapeats Sandstone. No major geologic structures exist in the tributary, but the East Kaibab Monocline, which trends southward immediately west of Chuar Butte (Huntoon and others, 1986), dominates the regional structure.

Sediment Yield Estimate

An estimate of the volume of sediment recently scoured from the colluvial wedges was made in March 1991. A minimum of 300 to 600 m^3 of sediment was mobilized from the colluvial wedges during the debris flow. No evidence of bedrock failure was found in the cliffs along Chuar Butte, although the overall volume of colluvium indicates that rockfalls probably occur frequently in these cliffs.

Sediment Characteristics

Sediment data were collected from debris-flow fan sediment deposited by the 1990 debris flow. Point-count data were collected from the surface of a debris-flow levee on the right margin of an alluvial channel incised into the debris fan. Results from that analysis indicate that the debris flow contained about 41 percent sand-and-finer sediment, on the basis of the <16 mm diameter fraction of the sample. This is slightly higher than the percent of sand-and-finer sediment indicated by the point-count data (~33 percent sand-and-finer sediment; fig. 14A); the total volume of debris deposited in the Colorado River could not be determined. The point-count data indicates that the 1990 debris flow was comprised of mostly Supai Group rocks with lesser amounts of Redwall Limestone (fig. 14B). Reconstitution of the levee sample indicated that the debris flow contained about 19 percent water by weight.

Boulder Transport

The exact number of large boulders transported into the Colorado River by the 1990 debris flow at river mile 62.5-R is unknown, but enough large particles reached the river channel to form a new rapid. At least two dozen large boulders were transported to the edge of the river exposed at 142 m^3/s. Many boulders were also deposited at the apex of the existing debris fan and near the downstream, distal edge of the debris fan. Several of these boulders were apparently transported by the initial pulse of the debris flow, perhaps as a lobate, bouldery snout. The boulders consisted mostly of semi-angular to sub-rounded particles of Redwall Limestone with well-abraded surfaces. The largest of these was estimated to weigh about 300 Mg (appendix 8).

Effects on the Colorado River

Before the 1990 debris flow, a mid-channel debris bar comprised of gravel and cobbles was present immediately upstream from the debris fan at river mile 62.5-R. This debris bar is visible during periods of low river discharge (less than about 200 m^3/s) and is visible in aerial photographs as early as 1965. However, it does not appear in aerial photographs taken in 1935 or in an 1890 oblique photograph (appendix 4). During the 1990 debris flow, sediment deposited by the debris flow physically connected the debris bar with the debris fan. After the 1990 debris flow, a significantly-enlarged eddy upstream from the debris fan forms during low river discharges (100 to 200 m^3/s). This new eddy greatly enhances deposition of fine sediment and the newly formed habitat has attracted Humpback Chub (*Gila cypha*), an endangered species (Mike Yard and Allen Hayden, Glen Canyon Environmental Studies, oral commun., 1994).

Decreased flow velocities in this area now favor deposition and storage of river-transported sand. Additional changes caused by the debris flow include transport of several large boulders to the river along with an unknown amount of finer sediment. The largest boulder (~300 Mg) has a b-axis diameter of approximately 5 m. At discharges between 200 and 850 m^3/s, this boulder, along with the other new ones deposited by the debris flow,

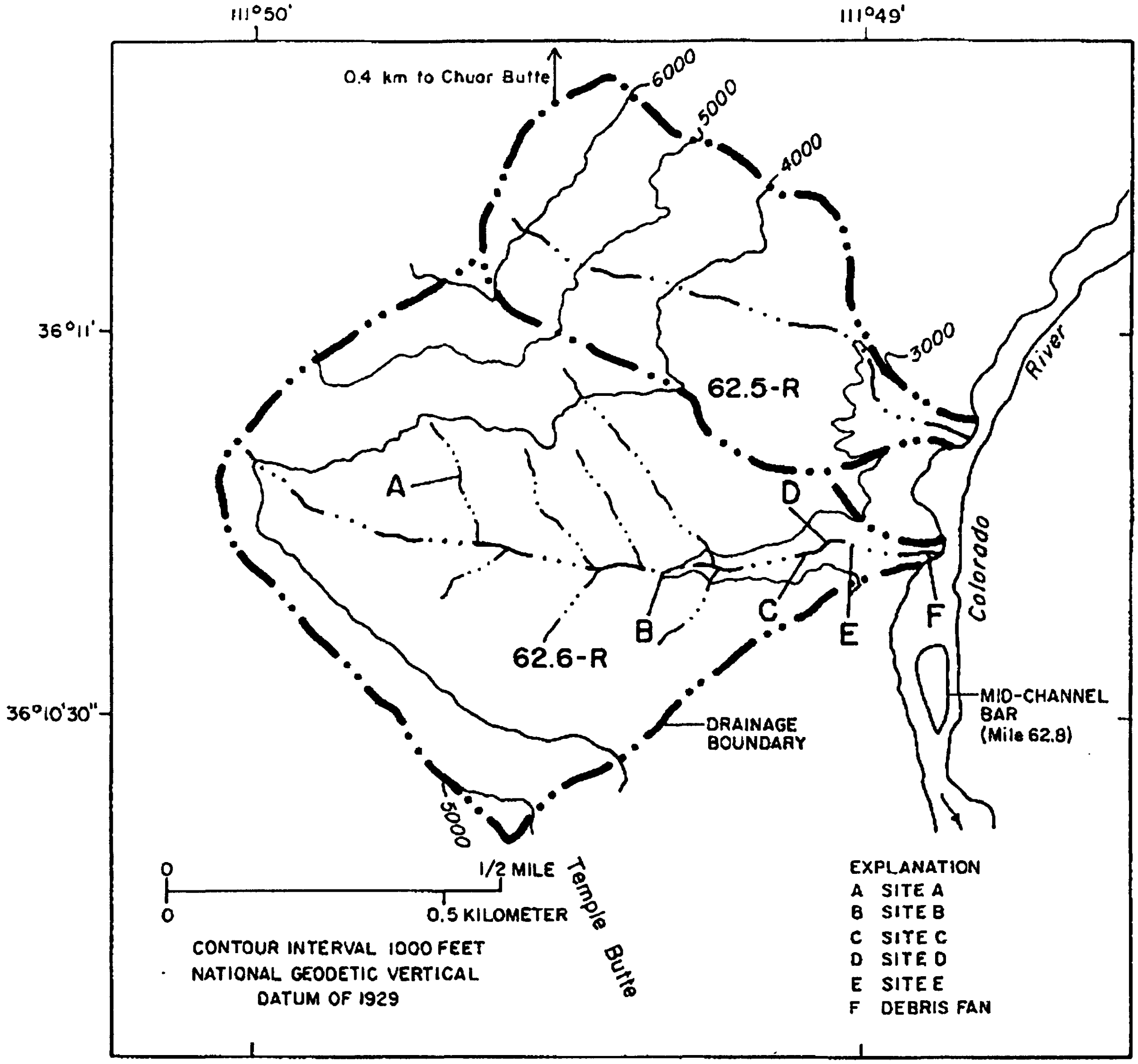


Figure 13. The drainage basins of an unnamed tributary of the Colorado River at river mile 62.5-R and "Crash Canyon" (river mile 62.6-R) in Grand Canyon.

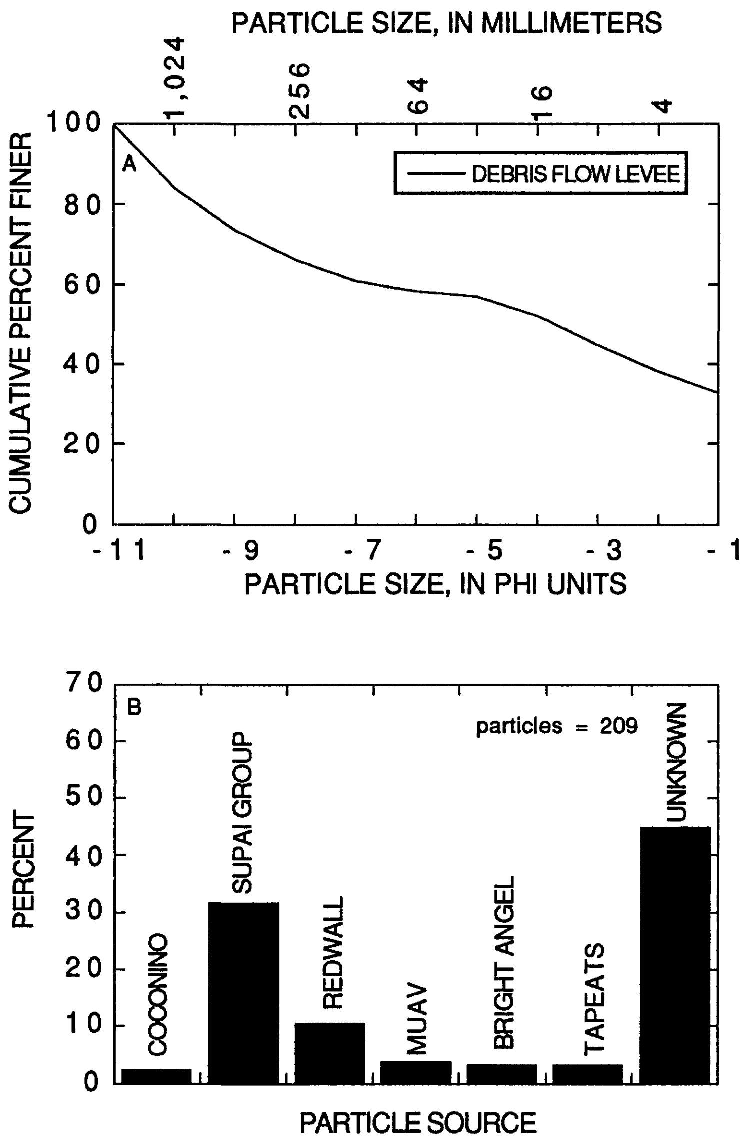


Figure 14. Particle-size and source distributions of a debris-flow levee deposited by the 1990 debris flow in an unnamed tributary at river mile 62.5-R. *A*, Particle-size distribution of the 1990 debris-flow levee. *B*, Source distribution of the 1990 debris-flow levee.

form a significant new navigational hazard in the river. At river discharges below 142 m^3/s, these boulders block navigation of the channel on the right side of the debris bar (formerly the island). The former riffle, which consisted mainly of turbulent, shallow flow over a gravel bar, was transformed by the 1990 debris flow into a significant rapid. Positions of new boulders in the new rapid have remained unchanged by high fluctuating-flows following the debris flow between September 1990 and July 1991 (less than 142 to 850 m^3/s), interim flows (ranging from 226 to 566 m^3/s), and two floods (approximately 850 to 950 m^3/s) from the Little Colorado River during January and February 1993.

Depth of the existing debris fans incised, alluvial channel was increased by about 2 to 3 m by erosion from the flood, whereas the left margin of the debris fan was aggraded by deposition of a new boulder levee. Most of the existing separation bar on the downstream side of the debris fan was covered with a thin coat of reddish mud 10 to 30 mm thick. We interpreted this sediment deposit to be the fine matrix-mud of the debris flow that became fractionated during the dewatering of the bouldery debris-flow levees deposited on the debris fan.

Frequency

The frequency of debris flows at this drainage was determined mainly from repeat photography. An 1890 photograph with a view upstream from the right bank just downstream from the river mile 62.5-R debris fan was replicated during January 1990, just before the debris flow, and again in February 1991 following the debris flow. Between 1890 and 1990, the only obvious change to the river channel at river mile 62.5 is the appearance of the mid-channel debris bar. The debris bar must have formed between 1935 and 1965 using aerial photographs. The lack of significant changes in the first replicate of an 1890 photograph, taken in January 1990, indicates no alterations in the debris fan or rapid in the intervening century. The rapid formed at mile 62.5 by the debris flow of 1990 apparently is the only rapid at this site to form during the last century. The activity of ^{137}Cs in the sediment deposited in 1990 was 0.233±0.017 pCi/g, which is consistent with the date of the debris flow.

"Crash Canyon" (River Mile 62.6-R)

A small, channelized debris flow occurred in this tributary, informally referred to as Crash Canyon, on or about September 24, 1990. The drainage divide of this basin is bounded by Chuar Butte to the north and Temple Butte to the south (fig. 13); it drains 1.79 km^2 on the north side of the river. The headwaters of the tributary are along the faces of Chuar and Temple Buttes, which are formed by the south-trending East Kaibab Monocline. Sediment sources here are similar but more extensive than those described in the unnamed tributary at river mile 62.5-R. Crash Canyon has a more dendritic drainage pattern than the unnamed tributary at mile 62.5-R and includes eight small sub-basins.

Source-Area Sediments

The source sediment for the 1990 debris flow was derived primarily from colluvial deposits in the north-half of the drainage basin along the base of Chuar Butte. Sediment was also contributed by channels on the south side of the basin along the base of Temple Butte, but to a lesser extent. Precipitation runoff accumulated mostly on top of Chuar Butte, flowed over cliffs of Redwall Limestone and apparently initiated the debris flow by the fire-hose effect in colluvial deposits below. Part of the debris flow may have been initiated in the highest parts of a north-side tributary owing to a bedrock failure in Redwall Limestone. It is likely that a combination of these two factors were responsible for triggering the debris flow.

An 8-kg sediment sample was collected from colluvium deposited near the head of the tributary in the vicinity of flow initiation points (fig. 13, site A). The <64 mm fraction of the sample was dry sieved to obtain a particle-size distribution of the source sediment (fig. 15); this sample contained about 24 percent sand-and-finer sediment. In general, the other major source areas for debris flows in the tributary (colluvium) contain sediments similar to the 1990 debris-fan deposit. Small failures in weathered exposures of bedrock and

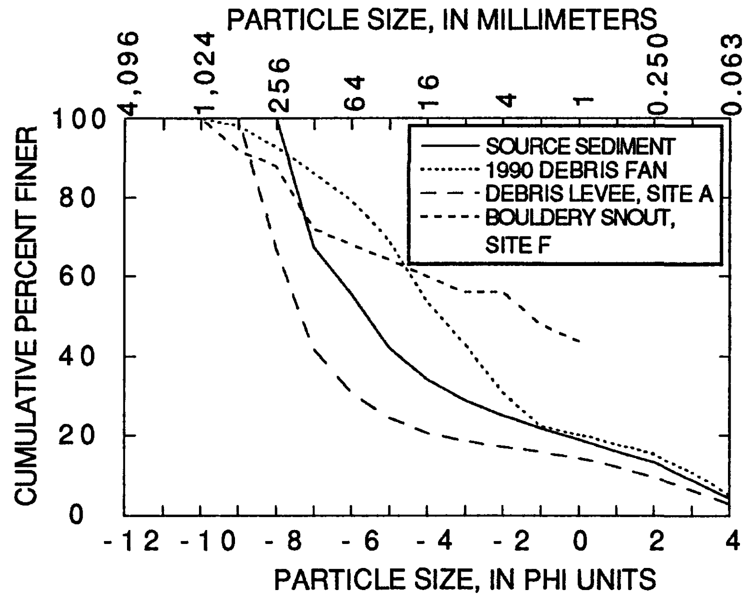


Figure 15. Particle-size distributions of source sediments, the 1990 debris-fan deposit, a 1990 debris-flow levee at site A, and the 1990 snout deposit at site F in "Crash Canyon" (river mile 62.6-R).

erosional scars in colluvium were identified at other locations throughout the drainage and revealed similar compositions for those source areas. The exact timing of contributions of sediment from various parts of the drainage during the 1990 debris flow is unknown.

Discharge Estimates and Sediment Characteristics

Site A

At site A (figs. 4 and 13), an 80-kg sediment sample was collected from a preserved debris-flow levee in the main tributary channel of "Crash Canyon." Point counts were also made on the surface of the debris-flow deposit where the sample was collected. On the basis of the distribution of <64 mm particles obtained from this subsample, the debris flow contained about 18 percent sand-and-finer sediment, which is identical to the fine-sediment content of source area colluvium (fig. 15). The source distribution of the site A debris-flow levee deposit indicates that the larger particles in the debris flow were mostly Redwall Limestone. Reconstitution of the debris-flow levee sample collected at site A indicates that the debris flow contained 18 percent water by weight.

Evidence of the early stages of the debris flow were abundant at this site. Site A is in a sharp bend in a small sub-basin tributary to the main tributary channel (fig. 13); the tributary channel here drops abruptly through Muav Limestone. Mudlines and debris-flow levees in the bend were highly superelevated (fig. 4B). The bedrock channel is relatively uniform and showed no evidence of scour from the debris flow; we estimated a peak discharge of 90 m^3/s (table 10).

A large failure in weathered bedrock at the base of a Redwall Limestone cliff, just upstream from site A, was probably associated with the initiation of the debris flow. Large boulders fell from weathered exposures along the cliff onto unconsolidated colluvium mantling Muav Limestone ledges below. However, it is doubtful that this bedrock failure is the sole cause of the debris flow's initiation because fresh erosional rills formed in hillslopes from fire-hose effects were widespread near site A and throughout the drainage. Downstream from site A, the debris flow passed over a 15-m waterfall in Bright Angel Shale and entered the main drainage channel of the

Table 10. Indirect peak-discharge estimate for the September 1990 debris flow at "Crash Canyon" (river mile 62.6-R), site A

[Thalweg distance, was measured for individual cross sections relative to the cross section at which ΔH_s max occurred. Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Type of estimate procedure used: superelevation in a right-hand bend
Outside high-water mark: continuous mudline
Inside high-water mark: well-preserved, recent debris flow levee
Visually estimated percentage of channel controlled by bedrock: 100 percent

Superelevation data

Radius of curvature (R_c) = 12 m
Maximum elevation difference (ΔH_S) = 2.4 m
Mean Velocity (V_S) = 3.8 m/s
Channel top width (W) = 20 m
Channel slope (S) = 0.048

Cross-section Data

Cross-section location	Thalweg distance, in meters	Area, in square meters	Hydraulic radius, in meters	Hydraulic depth, in meters	Flow-elevation difference, in meters	Top width, in meters
Downstream #1	15	23	0.8	0.9	0.7	24
Downstream #2	8	38	1.5	1.9	2.2	20
Downstream #3	5	25	1.0	1.2	2.4	20
Superelevation	0	42	1.8	2.1	2.4	20
Upstream #1	4	34	1.3	1.7	1.2	12
Upstream #2	30	30	1.1	2.5	1.3	12

Q_s = [1]90 m^3/s
Site rating for estimating discharge: Good

[1]Final discharge estimate based on minimum flow-elevation difference, L to R.

tributary. Well preserved debris-flow levees deposited along the channel just below the waterfall indicate that the debris flow had mobilized no more than 100-m downstream from the rockfall.

Mud preserved on channel walls immediately downstream from site A had a highly-viscous texture, somewhat like the consistency of dried plaster. On the basis of their appearance, the mudcoat deposits at site A are interpreted to represent the matrix of a highly-viscous debris flow. Twigs were extracted from this mud and radiocarbon dated to check the association of organic debris with a transporting debris flow of known age. A ^{14}C activity of 118.4±1.4 percent of modern carbon is consistent with a post-1950s deposition. Using the post-bomb ^{14}C relation, a calendric date for the debris flow of 1990 is indicated by the twigs (appendix 7).

Site B

Site B (fig. 13) consists of a bedrock-controlled channel bend in Bright Angel Shale; this reach has reasonably uniform cross-sectional geometry. A prominent mudline preserved on the outside of the channel bend indicates superelevated debris flow, whereas inside flow elevations are preserved as a continuous scour line along the top of a low, pre-existing, debris-flow terrace. Evidence of runup was also found in this left-hand bend. Flow elevations and channel cross sections were surveyed at this site with a total-station, and peak discharges were estimated using both the runup and superelevation equations. The resultant discharges (table 11) estimated indicate that the debris flow increased in peak discharge from 90 m^3/s at site A to between 140 and 170 m^3/s at site B.

The main tributary channel upstream from the site A showed no evidence of a recent debris flow, although evidence of streamflow flooding from the head of the drainage was indicated by well-sorted sediment deposits in the channels bed. Additional sediment and water was added to the main channel by other tributaries before the flow entered site B. Mud preserved on the bedrock walls between sites A and B had a texture indicative of a less-viscous sediment mixture than indicated by similar mud coats observed immediately downstream from site A; these latter mud coats had a dripping appearance, which probably indicates the water content of the debris flow had increased by the time it traveled downstream from site B.

Site C

Site C is in a right-hand bend of the main tributary channel where it flows through Tapeats Sandstone (fig. 13). Evidence of superelevation consists of a continuous mudline preserved on the outside of the curve and a continuous scour line on the terrace along the inside of the channel. The channel geometry of the bend is irregular, but the bedrock channel was not significantly eroded by the debris flow. The peak discharge at site C was estimated to be 290 m³/s (table 12), indicating that the magnitude of the debris flow increased significantly between sites B and C. The increase probably resulted from scour of bed material and the contribution of sediment-transporting streamflow that originated in the sub-basins entering the main tributary channel between the two sites.

Site D

Site D (fig. 13) consists of a left-hand bend in a bedrock channel flowing through Tapeats Sandstone. This channel reach showed no indication of scour by the debris flow. Evidence of

Table 11. Indirect peak-discharge estimate for the September 1990 debris flow at "Crash Canyon" (river mile 62.6-R), site B

[Thalweg distance, was measured for individual cross sections relative to the cross section at which ΔH_s max occurred. Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Type of estimate procedure used: superelevation in a left-hand bend also containing a runup
Outside high-water mark: continuous mudline
Inside high-water mark: continuous scourline with damaged plant remains
Visually estimated percentage of channel controlled by bedrock: 40 percent

Superelevation and runup data

Radius of curvature (R_c) = 19 m
Elevation difference (ΔH_S) = 2.4 m
Mean velocity (V_S) = 5.1 m/s
Mean velocity (V_r) = 4.0 m/s
Channel top width (W) = 17 m
Elevation difference (ΔH_r) = 0.80
Channel slope (S) = 0.11

Cross-section data

Cross-section location	Thalweg distance, in meters	Area, in square meters	Hydraulic radius, in meters	Hydraulic depth, in meters	Flow-elevation difference, in meters	Top width, in meters
Downstream	18	34	0.2	2.2	0.6	15
Superelevation	0	146	0.4	8.6	2.4	17
Upstream	54	71	0.3	5.1	1.2	14

Q_s = [1]170 m³/s and Q_r = [1]140 m³/s
Site rating for estimating discharge = Good

[1]Final discharge estimates based on minimum flow-elevation difference, L to R

Table 12. Indirect peak-discharge estimate for the September 1990 debris flow at "Crash Canyon" (river mile 62.6-R), site C

[Thalweg distance, was measured for individual cross sections relative to the cross section at which ΔH_s max occurred. Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Type of estimate procedure used: superelevation in a right-hand bend
Outside high-water mark: continuous mudline
Inside high-water mark: continuous scourline with damaged plant remains
Visually estimated percentage of channel controlled by bedrock: 50 percent

Superelevation data

Radius of curvature (R_c) = 12 m
Elevation difference (ΔH_s) = 3.6 m
Mean velocity (V_s) = 4.6 m/s
Channel top width (W) = 20 m
Channel slope (S) = 0.096

Cross-section data

Cross-section location	Thalweg distance, in meters	Area, in square meters	Hydraulic radius, in meters	Hydraulic depth, in meters	Flow-elevation difference, in meters	Top width, in meters
Downstream	3	79	3.0	4.0	3.1	20
Upstream #1	6	97	3.1	4.6	1.9	21
Upstream #2	11	81	2.8	4.0	2.3	20
Upstream #3	17	63	2.3	2.8	0.3	22
Upstream #4	26	67	1.9	3.1	1.6	22

Q_s = [1]290 m^3/s

Site rating for estimating discharge: Fair

[1]Final discharge estimate based on minimum flow-elevation difference, L to R.

Table 13. Indirect peak-discharge estimate for the September 1990 debris flow at "Crash Canyon" (river mile 62.6-R), site D

[Thalweg distance, was measured for individual cross sections relative to the cross section at which ΔH_s max occurred. Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Type of estimate procedure used: superelevation in a left-hand bend
Outside high-water mark: continuous mudline
Inside high-water mark: continuous scourline with damaged plant remains
Visually estimated percentage of channel controlled by bedrock: 90 percent

Superelevation data

Radius of curvature (R_c) = 15 m
Elevation difference (ΔH_s) = 3.7 m
Mean velocity (V_s) = 6.5 m/s
Channel top width (W) = 13 m
Channel slope (S) = 0.097

Cross-section data

Cross-section location	Thalweg distance, in meters	Area, in square meters	Hydraulic radius, in meters	Hydraulic depth, in meters	Flow-elevation difference, in meters	Top width, in meters
Downstream #1	48	44	1.6	2.7	0.2	16
Downstream #2	37	62	2.0	3.2	0.6	20
Superelevation	0	54	0.9	4.0	3.7	14
Upstream	7	48	0.9	3.4	0.2	14

Q_s = [1]290 m^3/s

Site rating for estimating discharge: Good

[1]Final discharge estimate based on minimum flow-elevation difference, L to R, and minimal cross-sectional area.

Table 14. Indirect peak-discharge estimate for the September 1990 debris flow at "Crash Canyon" (river mile 62.6-R), site E

[Thalweg distance, was measured for individual cross sections relative to the cross section at which ΔH_s max occurred. Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Type of estimate procedure used: superelevation in a right-hand bend
Outside high-water mark: continuous mudline
Inside high-water mark: continuous scourline with damaged plant remains
Visually estimated percentage of channel controlled by bedrock: 90 percent

Superelevation data

Radius of curvature (R_C) = 20 m
Elevation difference (ΔH_S) = 3.2 m
Mean velocity (V_S) = 5.3 m/s

Channel top width (W) = 22 m
Channel slope (S) = 0.078

Cross-section data

Cross-section location	Thalweg distance, in meters	Area, in square meters	Hydraulic radius, in meters	Hydraulic depth, in meters	Flow-elevation difference, in meters	Top width, in meters
Downstream #1	21	85	1.4	5.6	1.7	15
Downstream #2	14	100	2.5	5.1	2.6	20
Superelevation	0	81	2.7	3.8	3.2	22
Upstream #1	13	76	2.2	3.7	1.3	21
Upstream #2	25	49	1.4	3.7	0.2	13

Q_S = [1]260 m^3/s

Site rating for estimating discharge: Good

[1]Final discharge estimate based on minimum flow-elevation difference, L to R

superelevation was preserved by a mudline on the outside of the curve and a scour line on the inside of the channel. The peak discharge of the debris flow was 290 m^3/s (table 13), which is equivalent to the discharge estimated upstream at site C.

Site E

Site E (fig. 13) is in a sharp, right-hand bend flowing through Tapeats Sandstone; this reach also showed no indication of scour during the debris flow. A continuous mudline preserved beneath a bedrock overhang on the outside of the bend provided evidence of flow superelevation. Flow evidence on the inside of the bend consists of a continuous scour line in terrace deposits. The peak discharge of the debris flow was 260 m^3/s (table 14).

Summary

Peak discharge of the 1990 debris flow in Crash Canyon generally increased as it flowed toward the Colorado River (fig. 16). Accurate reconstruction of this debris flow was complicated by the existence of numerous tributary channels in the drainage, multiple source areas, and combination of initiation mechanisms, including rockfall and fire-hose effects. Five sites between the primary initiation site and the river showed evidence of superelevated flow in bends. The peak discharge of the debris flow increased between sites A and C, a distance of about 0.6 km (fig. 16). Between sites C and E, the discharge remained about the same or decreased slightly. Changes in the peak discharge of the debris flow probably resulted from additions of water and sediment from other tributaries and (or) scouring of sediments stored along the channel in terraces.

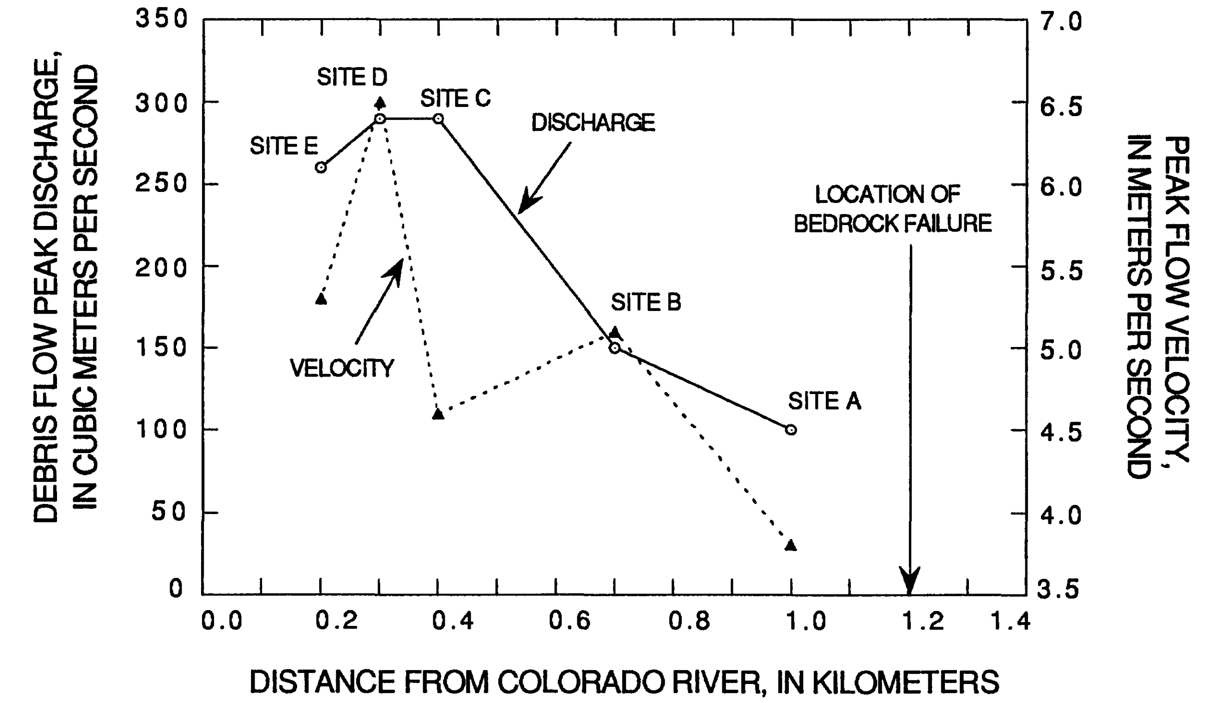


Figure 16. Longitudinal changes in peak velocity and discharge between sites A and E in "Crash Canyon" (river mile 62.6-R) during the debris flow of September 1990.

Deposition and Characteristics of the 1990 Debris Fan

The 1990 debris-flow fan deposit was sampled from a 1 m^2 by 1.7-m deep test pit, excavated into the center of the sediment deposit. Deposits exposed in the sides of the test pit showed no sedimentary structures. Well-sorted beach sand was found at a depth of 1.6 m with a 50-mm zone of mixing between beach sand and debris-flow deposits. This sand represented the surface of the pre-existing separation bar and appeared to be only slightly eroded by the debris flow. A 389-kg sample of the 1990 debris-fan deposit was collected from the test pit; this sample contained all particles including several cobbles and 23 boulders. The entire sample was returned to the laboratory and analyzed for particle-size and source distributions. The deposit contained 19 percent sand-and-finer sediment, and 33 percent boulders (fig. 17A). The clay fraction of the debris-flow deposit had a ^{137}Cs activity of 0.3±0.1 pCi/g, which is consistent with its post-1952 origin. Reconstitution of the <16 mm fraction of the test-pit sample indicated that the debris flow contained 17 to 19 percent water by weight. Most of the boulders and cobbles in the 1990 debris fan deposit were derived from Redwall Limestone (fig. 17B), as was the colluvium in which the debris flow was initiated near site A.

Part of the debris fan at the edge of the Colorado River (fig. 13, site F) was point counted to determine a particle-size distribution (fig. 15). This part of the deposit is diagnostic of the snout of a typical debris flow (Rodine and Johnson, 1976). The largest boulders transported to the river by the debris flow were measured to determine their size, source, and weight; the largest ranged in weight from 1 to 57 Mg (appendix 8). On the basis of the shape and appearance of this coarse deposit when first examined six weeks after the debris flow, we concluded that it represents a single, initial debris-flow surge. The presence of a single, lobate, intact bouldery snout might indicate that the entire volume of the debris flow was deposited on the existing sand bar and that little sediment was deposited in the river channel or had been substantially reworked by river flows. The deposit of the 1990 debris flow had a plan area of 700 m^2, an average thickness of 1.7 m, and a total volume of 1,200 m^3. Following the initial debris-flow pulse, the surface of the fan deposit was partly overtopped by recessional streamflow flooding from the tributary, but little reworking of the debris-flow deposit occurred; this indicates that the recessional flow was probably of a short duration.

The percentage of sand-and-finer sediment contained in the test-pit sample was used to estimate a total sand-and-finer sediment volume of 280 m^3 in the debris-flow deposit. Most of the new debris-flow deposit is contained in an area of the existing debris fan inundated by river flows ranging from 100 to 1,000 m^3/s. The 1990 debris-fan deposit shows little sign of reworking because daily peak discharges on the Colorado River have been limited to between 142 and 850 m^3/s since August 1991. All debris fan reworking has occurred along the distal edge of the debris fan.

Effects on the Separation Sand Bar

The 1990 channelized debris flow debouched from Crash Canyon on the downstream side of the existing debris fan. It scoured the channel previously incised into the debris fan and later deposited a small debris lobe on the existing separation bar. The debris fan and separation bar were affected in several ways. Approximately one-third of the separation bar was buried by debris-flow sediments. The existing channel through the debris fan was scoured by the debris flow following deposition of a large boulder berm at the apex of the fan that was probably a result of the initial debris-flow pulse. In addition, most of the pre-1990 debris fan was covered by a veneer of reddish-orange mud that we interpreted as being the dewatered matrix sediment that drained out of the left-channel margin, boulder levee; the effects of this deposition were minor compared to the initial debris-flow pulse. On the basis of an oblique photograph taken of the mouth of Crash Canyon in 1937 (appendix 6) and aerial photographs that show the separation bar and debris fan there between 1935 and 1990, the 1990 debris flow was the first in at least a century to impact the existing separation bar.

Sediment Characteristics

Particle-size and source data from the 1990 debris flow, the reworked debris fan, and the mid-channel debris bar just downstream (river mile 62.8) were compared to show the lithological fractionation caused by reworking. The origin of the mid-channel debris bar (fig. 13) is presumed to be the result of inputs of coarse sediment from both Crash Canyon and upstream tributary debris flows, including the Little Colorado River (river mile 61.1-L). Source data from the mid-channel bar and the pre-1990, reworked debris-fan surface reveal several relations between source sediments for debris flows and geomorphic features of the Colorado River.

Redwall Limestone dominates the surface of the pre-1990, reworked debris fan at Crash Canyon. However, the mid-channel debris bar contains a larger percentage of Coconino Sandstone and Supai Group particles derived from higher-elevation strata in the Paleozoic section (fig. 17C). Not only are these higher-elevation strata subjected to greater abrasion during transport to the river by debris flows and rockfalls, but they are more-poorly indurated than lower-elevation Redwall and Muav Limestone clasts. Throughout Grand Canyon, Redwall Limestone tends to produce many large boulders that are better able to withstand abrasion than most other rock types. Therefore, the reworked debris-fan surface at Crash Canyon is dominated by Redwall Limestone because many of these boulders exceed the competence of river discharges. Lithologies that are less resistant to abrasion during transport to the river (*i.e.*, clasts derived from the Supai Group) produce smaller clasts that can be transported away from the debris fan and deposited as cobbles on the downstream debris bar.

Grading of debris-fan deposits commonly occurred during the pre-dam era. Reworking has been limited since 1963 owing to regulated releases from Glen Canyon Dam. Similar relations between reworked debris fans and debris bars are typical along the Colorado River in Grand Canyon. Particle-size distributions of recent deposits on debris fans, reworked debris fans, and mid-channel bars mainly reflect sorting that occurred almost annually during pre-dam floods (fig. 17A). Because of the absence of occasional large river floods, debris fans are now aggraded by finer sediments,

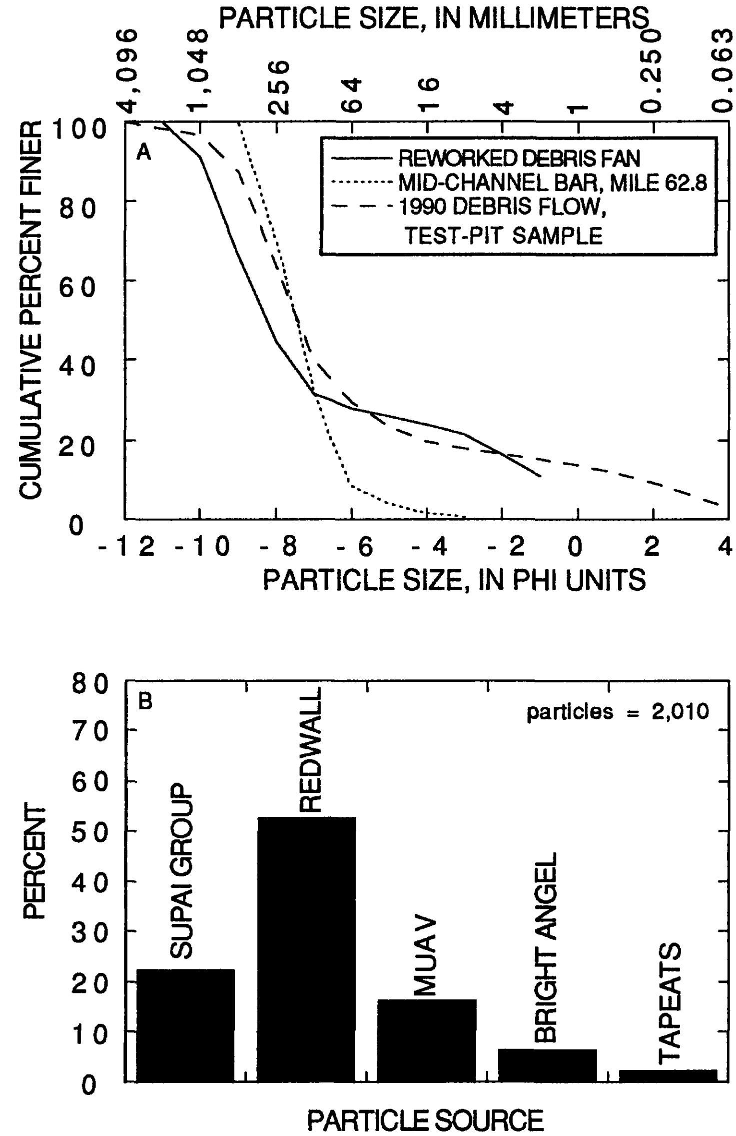
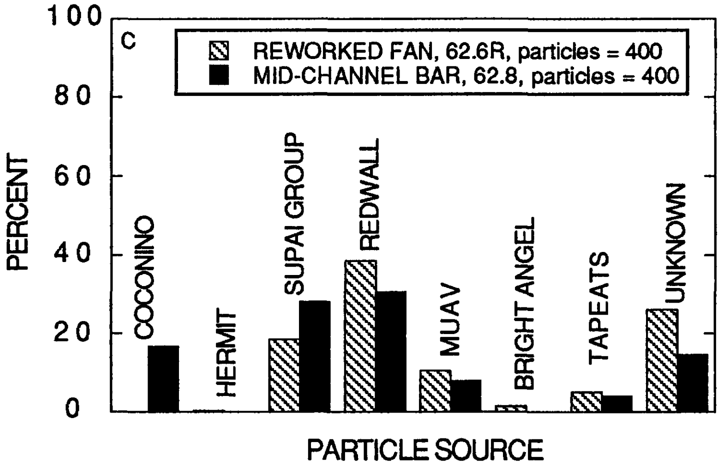


Figure 17. Particle-size and source distributions of various deposits associated with the debris flow of 1990 in "Crash Canyon" (river mile 62.6-R). *A*, Particle-size distributions for the pre-1990 debris fan surface at "Crash Canyon" (river mile 62.6-R), the mid-channel debris bar downstream (river mile 62.8), and the 1990 debris fan at "Crash Canyon." *B*, Sources of 2,010 cobbles and boulders excavated from the test pit in the 1990 debris fan at "Crash Canyon" (river mile 62.6-R).



C, Source distributions of particles on the pre-1990 debris fan at "Crash Canyon" (river mile 62.6-R) and the mid-channel debris bar downstream (river mile 62.8).

Figure17. Continued.

whereas mid-channel debris bars remain relatively stable. Recently-collected debris-fan data presented throughout this report demonstrates how quasi-equilibrium conditions (Langbein and Leopold, 1964) between the Colorado River and its tributaries have been perturbed downstream from Glen Canyon Dam.

Frequency

Historical photographs were used to document the frequency of debris flows in Crash Canyon that have reached the Colorado River. An 1890 photograph taken from above the Crash Canyon debris fan looking downstream shows the mouth of the tributary and a small part of the existing, pre-1990 debris fan; this view, replicated in 1991, records small changes to the debris fan that resulted from deposition of the 1990 debris-flow fan deposit. We concluded that no larger debris flows from Crash Canyon reached the Colorado River between 1890 and 1990. A second photograph, taken in 1937, shows the pre-1990 debris fan from the head of the mid-channel debris bar (fig. 13, river mile 62.8). A replicate view made in 1991 shows deposition of the 1990 debris fan and boulder levee deposited on the existing debris fan, as well as partial burial of the separation bar; no other large-scale changes in the morphology of the debris fan between 1937 and 1990. This lack of major changes is also documented in aerial photographs that show the debris fan in 1935 and at various intervals between 1965 and June 1990. Large pieces of plane wreckage deposited in the main channel of the tributary in the 1950s remained stable until removed from the tributary channel by the 1990 debris flow (Kenton Grua, oral commun., 1994). Apparently, the debris flow of 1990 was the first debris flow in Crash Canyon to affect the river corridor in over 100 years. The net effects of the 1990 debris flow on the debris fan appear minor in relation to its overall geometry and size, because the debris flow was of low magnitude and most of the debris-flow sediment was channelized.

Unnamed Tributary at River Mile 63.3-R

A small, channelized debris flow occurred in an unnamed tributary at river mile 63.3-R during the same storm on or about September 24, 1990 that spawned debris flows at river miles 62.5-R and Crash Canyon. The unnamed tributary at mile 63.3 drains 0.66 km^2 on the north side of the river (fig. 18). The volume of the 1990 debris flow was probably small owing to the relatively small volume of new deposits on the debris fan, but several large boulders were transported into the Colorado River and enlarged an existing riffle. The debris flow was initiated mainly by fire-hose effects that occurred in a colluvial wedge deposit at the head of the tributary. This small, steep tributary has a well-defined main channel; depositional evidence along this channel allowed estimation of peak discharge for the 1990 and one ancient debris flow.

Estimate of Sediment Yield

A minimum of 200 m^3 of sediment was mobilized from hillslopes in the drainage during this debris flow. Examination of the dra inage also indicated that some unknown volume of sediment was entrained from the channel during the debris flow. Debris-flow levees on the left side of the main tributary channel at a runup site indicate that debris flows of much greater magnitude than the 1990 flow have occurred in the basin.

Discharge Estimates

Site B

At site B (fig. 18), we estimated the peak discharge for the 1990 debris flow and one ancient debris flow that we were able to radiocarbon date. Superelevated mudlines from both of these debris flows were found beneath overhanging ledges of Bright Angel Shale at a left-hand bend upstream from the Colorado River (fig. 18). Flow elevations were indicated by preserved continuous mud and scourlines for the 1990 debris flow and a discontinuous mudline for the ancient flow. The peak discharges were 350 m^3/s for the 1990 debris flow (table 15) and 790 m^3/s for the ancient debris flow (table 16).

Site A

Site A also contained evidence of both the 1990 and the ancient debris flows. Runup mudlines from both of these flows are preserved beneath overhanging ledges of Bright Angel Shale 0.25 km upstream from the Colorado River (fig. 18). The channel upstream from the runup site is straight and directs flow against a vertical wall; the channel then curves 90 degrees to the right, towards a 20-m high waterfall directly above the debris fan. Flow elevations were indicated by continuous mud and scourlines for the 1990 debris flow and discontinuous debris levees deposited by the ancient debris flow. Peak discharge was 390 m^3/s for the 1990 debris flow (table 17) and 1,100 m^3/s for the ancient debris flow (table 18).

Sediment Characteristics

A particle-size distribution for the 1990 debris flow was estimated from debris-flow levee deposits on the debris fan. A 40-kg sediment sample was collected from a debris-flow levee and dry sieved; point counts were also made along the vertical erosional face of the debris-flow levee, as well as along the top surface of the deposit. The 1990 debris flow contained 18 to 20 percent sand-and-finer sediment. Reconstitution of the <16 mm fraction of the sample yielded a water content of 10 to 12 percent by weight.

No undisturbed debris-flow deposits, other than from the 1990 debris flow, were found at either of the two sites in the tributary, but samples of hyperconcentrated and streamflow sediments were identified and collected. These sediment samples, along with sediment from the debris-flow levee, were dry sieved to obtain particle-size distributions (fig. 19A). The particle-size distribution of the hyperconcentrated-flow deposit contains a higher percent of fine sediment than both the streamflow and debris-flow deposits. The streamflow deposit is mostly comprised of gravel and coarse sand, probably explaining its lack of cohesiveness, whereas the debris-flow deposit is coarser, more-poorly sorted, and cohesive with matrix-supported clasts. The hyperconcentrated-flow deposit had some characteristics of each of the other samples. Analysis of ^{137}Cs in the <0.63 mm fraction of the debris flow yielded a ^{137}Cs activity of 0.2±0.1 pCi/g, which is consistent with a post-1952 deposition.

Boulders were deposited on the debris fan in levees on both sides of the channel from the apex of the debris fan to the Colorado River. Point counts

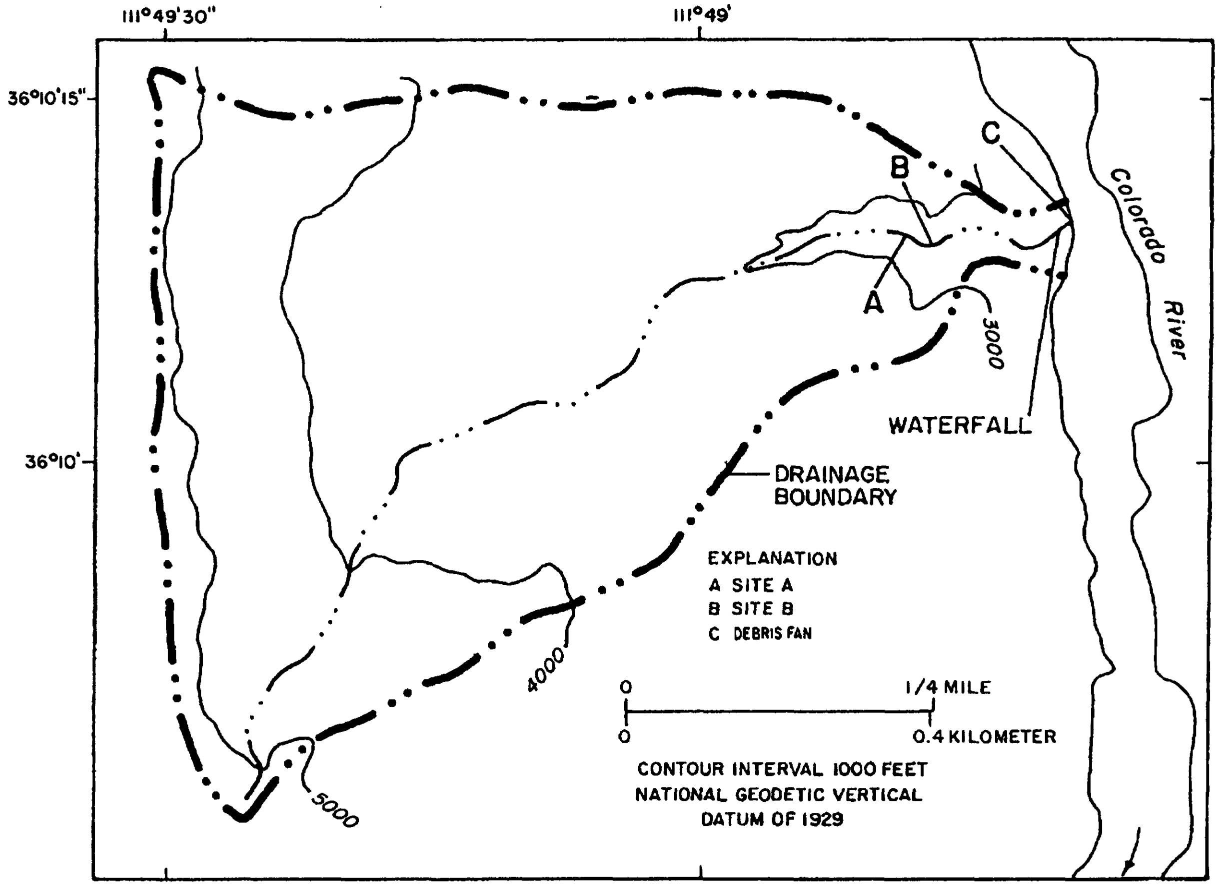


Figure 18. The drainage basin of an unnamed tributary of the Colorado River at river mile 63.3-R in Grand Canyon.

Table 15. Indirect peak-discharge estimate for the September 1990 debris flow in an unnamed tributary at river mile 63.3-R, site B

[Thalweg distance, was measured for individual cross sections relative to the cross section at which ΔH_s max occurred. Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Type of estimate procedure used: superelevation in a left-hand bend
Outside high-water mark: continuous mudline
Inside high-water mark: continuous scourline with damaged plant remains
Visually estimated percentage of channel controlled by bedrock: 90 percent

Superelevation data

Radius of curvature (R_c) = 8 m
Elevation difference (ΔH_s) = 3.8 m
Mean velocity (V_s) = 3.8 m/s

Channel top width (W) = 21 m
Channel slope (S) = 0.098

Cross-section data

Cross-section location	Thalweg distance, in meters	Area, in square meters	Hydraulic radius, in meters	Hydraulic depth, in meters	Flow-elevation difference, in meters	Top width, in meters
Downstream	5	92	0.4	7.7	4.0	12

$Q_S = 350\ m^3/s$

Site rating for estimating discharge: Good

Table 16. Indirect peak-discharge estimate for an ancient debris flow in unnamed tributary at river mile 63.3-R, site B

[Thalweg distance, was measured for individual cross sections relative to the cross section at which ΔH_s max occurred. Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Type of estimate procedure used: superelevation in a left-hand bend
Outside high-water mark: continuous mudline
Inside high-water mark: discontinuous debris flow deposits
Visually estimated percentage of channel controlled by bedrock: 90 percent

Superelevation data

Radius of curvature (R_c) = 15 m
Elevation difference (ΔH_s) = 4.9 m
Mean velocity (V_s) = 5.9 m/s

Channel top width (W) = 21 m
Channel slope (S) = 0.098

Cross-section data

Cross-section location	Thalweg distance, in meters	Area, in square meters	Hydraulic radius, in meters	Hydraulic depth, in meters	Flow-elevation difference, in meters	Top width, in meters
Downstream	5	140	0.5	11.2	5.2	13
Upstream	18	135	0.9	6.9	3.6	20

Q_S = [1]790 m^3/s

Site rating for estimating discharge: Fair

[1]Final discharge estimate based on minimum flow-elevation difference, LL to R.

were made to determine a source distribution of the cobbles and boulders at the debris fan (fig. 19B). These data indicate that source areas for debris flow in the drainage are dominated by Redwall Limestone, with lesser amounts of Supai Group rocks and Muav Limestone.

Effects on the Debris Fan and River Channel

The 1990 debris flow scoured the channel through the debris fan by about 2 m and deposited new boulders on the debris fan near its distal edges at the river. Many large mesquite trees at the apex of the debris fan were damaged or destroyed by the debris flow. The degree to which debris-fan deposits were reworked and fine sediments were removed from between boulders indicates that a significant streamflow flood in the tributary followed the debris flow. Several large boulders were transported into the Colorado River during the debris flow, resulting in increased severity of the existing riffle, especially at lower discharges (less than about 142 m^3/s). Many of the largest boulders could not be measured owing to submergence in the river. Changes to the hydraulics of the former riffle are readily apparent in videotape footage and aerial photographs taken between 1990 and 1992 (available for viewing at the Glen Canyon Environmental Studies office, Flagstaff, Arizona).

Frequency

Aerial photographs of the debris fan between 1965 and June 1990 indicate that the 1990 debris flow was the first in at least 24 years. On the basis of older debris-flow deposits preserved in the tributary channel, at least one larger debris flow was identified. A sample of shredded twigs was collected from a matrix-mud coat preserved under an overhang in the tributary channel. This radiocarbon age was 5,410±175 yrs BP, which calibrates to a calendric date of BC 4458 to 4006 (appendix 7). No detectable ^{137}Cs was measured in the sediment surrounding the twigs. Therefore, we conclude that the 5,400-year-old debris flow was the largest in this tributary during the last 6,000 years.

Lava Canyon (River Mile 65.5-R)

Lava Canyon drains 54.71 km^2 on the north side of the Colorado River, some of which is above the North Rim (fig. 1). The debris fan at the mouth of Lava Creek, in concert with the opposing debris fan of Palisades Creek (river mile 65.5-L), forms Lava Canyon Rapid (river mile 65.5). In December 1966, runoff resulting from prolonged, intense rainfall on the North Rim caused multiple slope failures in Hermit Shale and Esplanade Sandstone of the Supai Group (Cooley and others, 1977; Webb and others, 1989). The resulting debris flow travelled 10.5 km to the Colorado River.

Using evidence of superelevation, Webb and others (1989) estimated a peak discharge of 110 m^3/s for the debris flow at a point 0.2 km upstream from the Colorado River. They also estimated the reconstituted-water content of the debris flow at about 23 percent by weight; the sand-and-finer sediment content ranged from 30 to 35 percent (Webb and others, 1989). Undifferentiated micas and kaolinite dominate the clay mineralogy of the debris-flow matrix; no montmorillonite was present (table 9). According to Webb and others (1989), the largest boulder moved during the 1966 debris flow weighed approximately 8.2 Mg.

Webb and others (1989) concluded that debris flows occur every 20 to 30 years in Lava Canyon based on radiocarbon dates of organic material collected from debris-flow levee deposits. Large debris flows that overtopped stream-channel terraces in Lava Canyon and reached the Colorado River occurred between 600 and 1,500 yrs BP. In addition to the 1966 debris flow, two other debris flows reached the Colorado River between 1970 and 1990. One of these debris flows was initiated in Precambrian Dox Sandstone, whereas the larger of these two debris flows was initiated in Hermit Shale and Esplanade Sandstone.

Hereford (1993) described and mapped the stratigraphy on channel-left just upstream from the confluence of Lava Canyon, which was not described by Webb and others (1989). He found two debris flows preserved in the stratigraphy that were radiocarbon dated at 100 to 300 years before the debris flow of 1966.

Table 17. Indirect peak-discharge estimate for the September 1990 debris flow in an unnamed tributary at river mile 63.3-R, site A

[Thalweg distance, was measured for individual cross sections relative to the cross section at which ΔH_S max occurred. Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Type of estimate procedure used: runup beneath an overhang
Channel left high-water mark: well-preserved mudline
Channel right high-water mark: well-preserved scourline
Runup evidence: mudline
Visually estimated percentage of channel controlled by bedrock: 75 percent

Runup data

Elevation difference = 3.4 m
Mean velocity (V_r) = 8.2 m/s
Channel slope (S) = 0.17

Cross-section data

Cross-section location	Thalweg distance, in meters	Area, in square meters	Hydraulic radius, in meters	Hydraulic depth, in meters	Flow-elevation difference, in meters	Top width, in meters
Upstream	50	48	0.4	1.6	0.2	31

$Q_r = 390\ m^3/s$
Site rating for estimating discharge: Poor

Table 18. Indirect peak-discharge estimate for an ancient debris flow in an unnamed tributary at river mile 63.3-R, site A

[Thalweg distance, was measured for individual cross sections relative to the cross section at which ΔH_S max occurred. Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Type of estimate procedure used: runup beneath an overhang
Channel left high-water mark: well preserved, but discontinuous debris flow levee
Channel right high-water mark: discontinuous, preserved debris flow levee
Runup evidence: mudline
Visually estimated percentage of channel controlled by bedrock: 75 percent

Runup data

Elevation Difference (ΔH_r) = 5.4 m
Mean velocity (V_r) = 10.3 m/s
Channel Slope (S) = 0.17

Cross-section data

Cross-section location	Thalweg distance, in meters	Area, in square meters	Hydraulic radius, in meters	Hydraulic depth, in meters	Flow-elevation difference, in meters	Top width, in meters
Upstream	50	104	0.4	2.4	0.1	44

$Q_r = 1{,}100\ m^3/s$
Site rating for estimating discharge: Poor

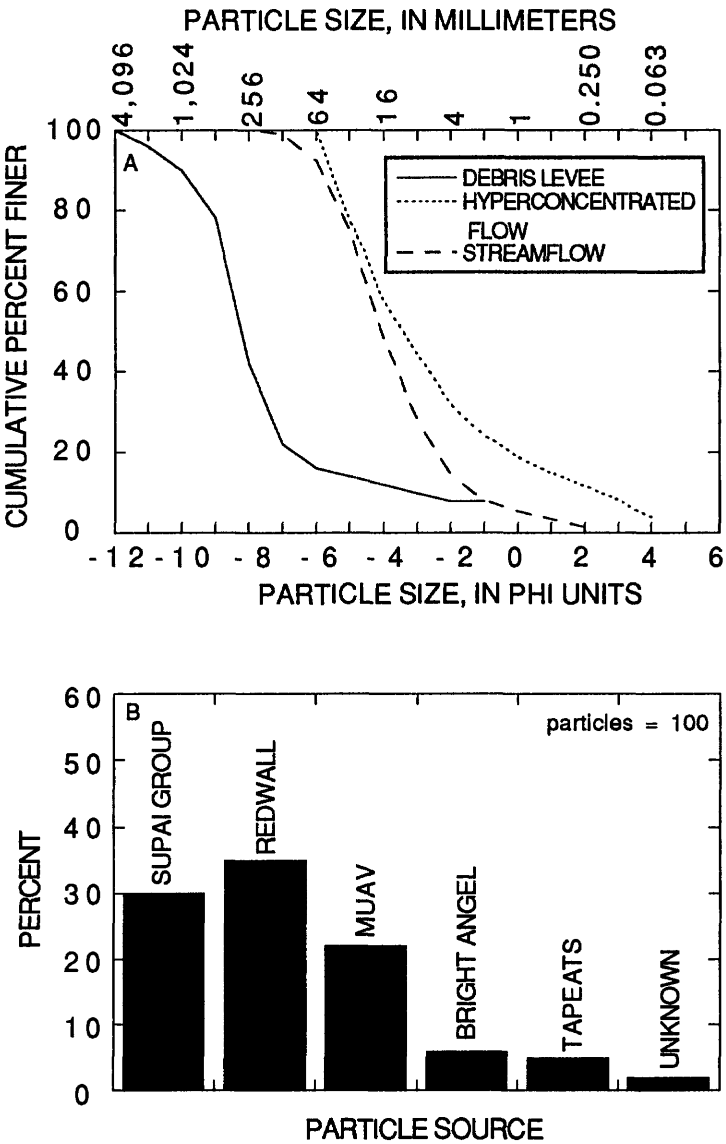


Figure 19. Particle-size and source distributions of various sediment deposits associated with the 1990 debris flow in an unnamed tributary at river mile 63.3-R. *A*, Particle-size distributions of a streamflow deposit, a hyperconcentrated-flow deposit, and an undisturbed debris-flow levee deposited during the debris flow of September 1990. *B*, Source distribution of an undisturbed debris-flow levee deposited during the debris flow of 1990.

Palisades Creek (River Mile 65.5-L)

Palisades Creek (river mile 65.5-L) drains 4.06 km^2 on the south side of the Colorado River (fig. 1). Its headwaters are in a line of cliffs known as the Palisades of the Desert; the drainage divide is at the top of these cliffs. Abundant colluvium overlying the lower units of the Paleozoic section in the Palisades Creek drainage provides ample source sediment for debris flows, which have occurred frequently in this tributary. In September 1990, a debris flow occurred in Palisades Creek, probably at the same time as the other debris flows described between river miles 61 and 64. Because the channel of Palisades Creek is not bedrock-controlled in its lower reaches, no discharge estimates were possible for this small, channelized debris flow.

Frequency

The surficial geology of the debris fan at the mouth of Palisades Creek was described by Hereford (1993) and Hereford and others (1993). Hereford (1993) mapped debris-flow deposits and showed that three to four large debris flows occurred during the past 2,000 years. These fan-forming debris flows appear to have a recurrence interval of about one per 600 years. Not all debris flows in Palisades Creek are preserved in the stratigraphy of its large debris fan. Many large debris fans in Grand Canyon are formed by a similar combination of infrequent, large debris flows and smaller, frequent debris flows. Channelized debris flows, like many of the historic debris flows described in this report, mainly deliver large boulders to the river corridor and cut channels through debris-fan deposits.

Several small debris flows, which remained channelized through the debris fan, have occurred in the last century in Palisades Creek. Historical photography (table 19) indicates that the debris fan at the mouth of Palisades Creek formerly did not protrude far into the Colorado River at Lava Canyon Rapid (river mile 65.5) before 1965, because no changes are observable in the photographs taken between 1935 and 1965. However, a large channelized debris flow occurred between 1965 and 1973 that significantly aggraded the debris fan at the mouth of Palisades Creek.

Effects on the Colorado River

Aggradation associated with the 1965 to 1973 era debris flow significantly changed the left side of Lava Canyon Rapid. As a consequence, the configuration of the reattachment bar downstream on the left side of the Colorado River has also changed. The reattachment bar appeared streamlined with a narrow configuration before 1973, whereas the reattachment bar that formed after 1973 is more arcuate. In addition, several other floods, including one channelized debris flow that occurred between 1973 and 1984, one in 1987, and another in 1990, also aggraded this debris fan (appendix 1).

Palisades Creek yields frequent, small debris flows by failure of colluvial wedges. These post-1963 debris flows have significantly aggraded a small part of the debris fan at the Colorado River and have constricted Lava Canyon Rapid. The consequences of the increased constriction are changes in the hydraulics of the Colorado River and the configuration of the recirculation zone downstream, which has altered the shape of the reattachment bar. Larger, fan-forming debris flows, which have occurred infrequently over the past 2,000 years, have certainly affected the navigability of the river and the stability of sand bars downstream and are likely to occur again during the proposed lifetime of Glen Canyon Dam.

Espejo Creek (River Mile 66.8-L)

Espejo Creek drains 1.73 km^2 on the south side of Grand Canyon just upstream from Comanche Point. The drainage heads along the South Rim (fig. 20). A small channelized debris flow occurred in Espejo Creek during the summer of 1984, on the basis of aerial photographs taken in 1980 and October 1984. The exact date of the debris flow was also bracketed by accounts of river guides who agreed that the flood occurred during July or August of 1984 (Kenton Grua, Gary Bolton, and Dennis Silva, oral commun., 1993). No peak discharge or debris-flow volume estimates were possible owing to subsequent reworking of deposits by streamflow flooding in the drainage basin and reworking by the Colorado River.

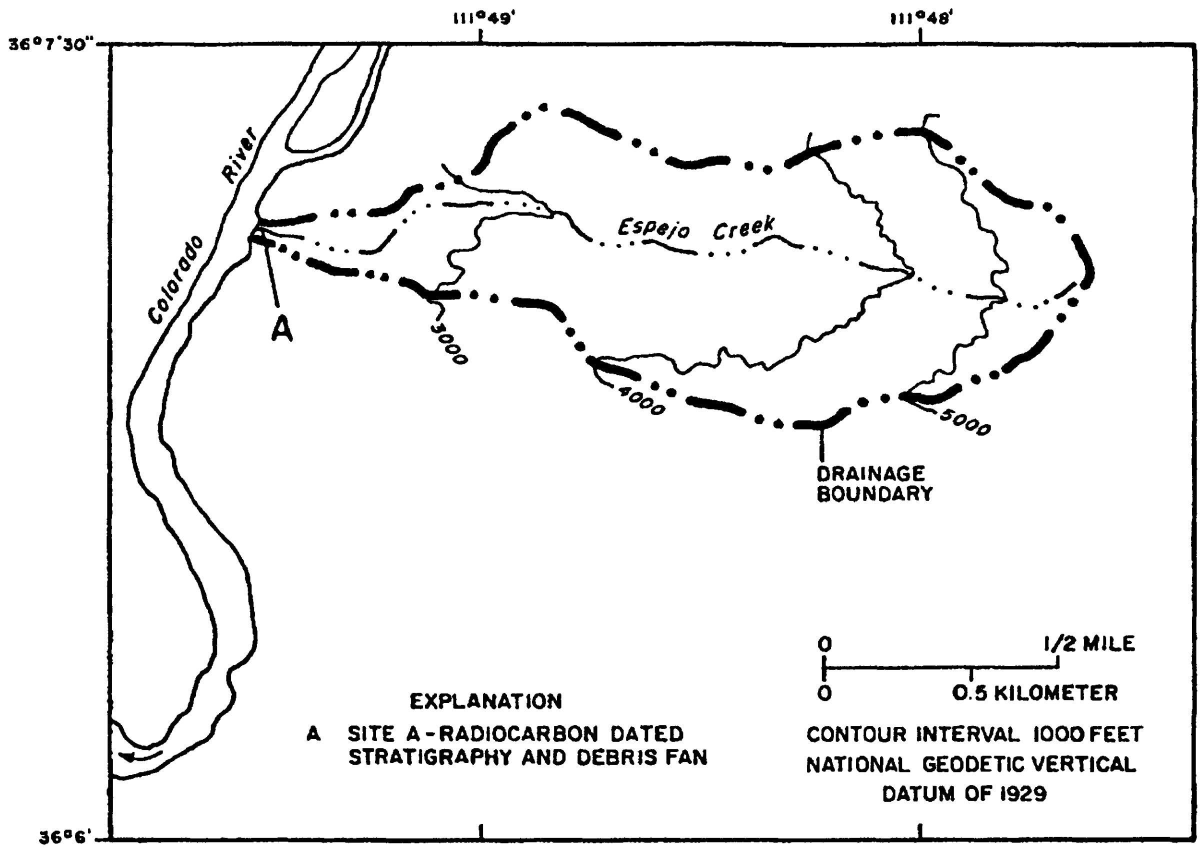


Figure 20. The drainage basin of Espejo Creek (river mile 66.8-L), a tributary of the Colorado River in Grand Canyon.

Table 19. Historical photographs of Lava Canyon Rapid (river mile 65.5) and the debris fans at the mouths of Palisades Creek and Lava Canyon (river miles 65.5-L and 65.5-R)

[For photographs taken before 1921, the discharge is estimated from known stage-discharge relations at Lava Canyon Rapid. For photographs taken between 1921 and 1963, discharge is estimated from daily discharge records of the Colorado River at Lees Ferry. After 1963, discharge is estimated from known stage-discharge relations at Lava Canyon Rapid. These estimates are perhaps accurate to ±1,000 ft3/s. (AV), vertical aerial photography; (AL), photograph is an oblique aerial taken from the left side of the river; (AR), photograph is an oblique aerial taken from the right side of the river; (RL), photograph was shot from river-left; (RR), photograph was shot from river-right; (US), upstream view; (DS), downstream view; (AC), view across the river; (UC), view looking up the tributary channel or away from the river; (R), view shows a rapid; (DF), view shows debris fan(s); (SB), view shows sand bar(s); (n.d.), no data; (n.m.), the photograph was analyzed, but not matched]

Year	Date	Photographer	Original number	Stake number	Side	Direction	Subject	Discharge (ft^3/s)
1890	Jan 21	Stanton	380	1431c	RR	US	R,DF	4,000
	Jan 21	Stanton	381	1431a	RR	UC	DF	n.d.
	Jan 21	Stanton	382	1431b	RR	DS	DF,SB	4,000
	Jan 22	Stanton	383	1434b	RL	US	DF,SB	4,000
	Jan 22	Stanton	384	1434a	RL	AC	R,DF,SB	4,000
	Jan 22	Stanton	385	1434c	RL	DS	R,DF,SB	4,000
1911	Nov 14	Kolb	1016	n.m.	RL	DS	R,DF,SB	n.d.
1923	Aug 14	LaRue	406	1092	RL	US	R,DF,SB	23,500
	Aug 14	LaRue	407	1707a	RL	DS	R,DF,SB	23,500
	Aug 14	LaRue	409	1707b	RL	AC	R,DF,SB	23,500
1935	n.d.	SCS	153	n.m.	AV	AV	R,DF,SB	~5,000
1937	Oct	Campbell	n.d.	2358	RL	US	R,DF,SB	n.d.
1941	Jul 19	Heald	3:06:09	2733	RL	US	DF,SB	n.d.
1942	Jul 19	Wilson	4:07:11	2734	RL	AC	DF,SB	n.d.
1959	Jun 25	Reilly	L44-26	2026	RR	DS	R,SB	6,130
1965	May 14	WRD	124	n.m.	AV	AV	R,DF,SB	n.d.
	Jun 5	Reilly	L67-19	n.m.	AR	AC	R,DF,SB	n.d.
1966	Nov 17	Visbak	76	n.m.	RL	DS	R,DF,SB	~10,000
1966	Apr	Hildreth	19	n.m.	RL	DS	R,DF,SB	~8,000
1973	Jun 16	WRD	168	n.m.	AV	AV	R,DF,SB	n.d.
	n.d.	Weeden	I-90	2344	RR	AC	R,DF	n.d.
	n.d.	Weeden	I-91	2345	RR	DS	R,DF,SB	n.d.
1984	Oct 22	GCES	3-81	n.m.	AV	AV	R,DF,SB	5,000

Frequency

We documented prehistoric debris flows in Espejo Creek using radiocarbon dating of organic materials entrained in mud coatings preserved under overhanging channel walls and deposits on the debris fan (fig. 20, site A). On the basis of the interleaved strata of debris-flow and river-sand deposits along the creek channel 100-m upstream from the Colorado River, at least three debris flows occurred in Espejo Creek after about AD 1600. Charcoal collected from two deposits of river sand directly below and above the lowest channelized debris-flow deposit was radiocarbon dated at 2,410±125 yrs BP and 1,565±110 yrs BP, respectively. These dates were calibrated to calendric age ranges of BC 770 to 390 and AD 360 to 636 (appendix 7). Two additional debris-flow deposits above these units did not contain datable material, but must have been deposited since about AD 1650 using stratigraphic position. The highest of the deposits is buried by 0.30 m of river-deposited sand, which has a poorly-developed soil and supports a community of mature mesquite trees. A ^{137}Cs activity of 0.018±0.010 pCi/g was measured in the uppermost unit, which suggests post-1952 deposition; six lower units had no detectable ^{137}Cs.

Further up the channel of Espejo Creek, twigs were extracted from mud coats preserved under overhanging walls. These mudlines were interpreted as recent debris flows that predated the 1984 debris flow but postdated the debris-flow stratigraphy examined near the confluence; this interpretation was based on the height of the flow evidence above fresher-looking flood debris and on the bright, unweathered orange color of the preserved debris-flow matrix mud. The two samples of twigs at one site about 0.5 km upstream from the confluence yielded radiocarbon dates of 315±110 and 340±60 yrs BP, which calibrate to calendric dates of AD 1440 to 1660 and AD 1450 to 1642, respectively. Twigs sampled from a similar-looking mudline 0.8 km upstream from the river yielded a radiocarbon date of 305±60 yrs BP, which corresponds to a calendric date of AD 1488 to 1652. We conclude that these two isolated mud coats were probably deposited by the same debris flow, and the average of the three radiocarbon dates was calibrated to a calendric date range of AD 1490 to 1642 (appendix 7).

We estimate that the frequency of debris flows in Espejo Creek has been about one every 300 to 500 years. The overall size of the prehistoric debris fan at Espejo Creek indicates that debris flows may have been larger and more frequent during the earlier evolutionary stages of debris fan development at the mouth of this tributary.

Tanner Canyon (River Mile 68.5-L)

On August 22, 1993, a small, channelized debris flow was triggered by a brief, albeit intense, thunderstorm that occurred over Tanner Canyon (river mile 68.5-L). Tanner Canyon drains 19.25 km^2 of the south side of Grand Canyon just west of Comanche Point (fig. 21A). An eyewitness reported approximately 75 mm of rainfall accumulated in empty buckets during the storm in slightly less than one hour (Suzanne Rhodes, O.A.R.S. Inc., oral commun., 1993). Precipitation records from Desert View ranger station, near the head of Tanner Canyon on the South Rim, indicate that 28 mm of rain fell on August 21 and again on the 22nd. Within a few minutes after the rainfall subsided, eyewitnesses reported a loud, crashing sound coming from near the mouth of Tanner Canyon as the initial pulse of debris debouched from the tributary and entered the river. Following the initial pulse of debris, a muddy, recessional flow followed that reportedly lasted 2 to 3 hours.

Discharge Estimates

Like most Grand Canyon debris flows, the 1993 event in Tanner Canyon consisted of both streamflow and debris flow, each generated from different areas of the watershed. Streamflow was generated from most of the drainage, whereas the debris flow was generated mostly in one sub-basin that drains much of the lower-elevation, eastern part

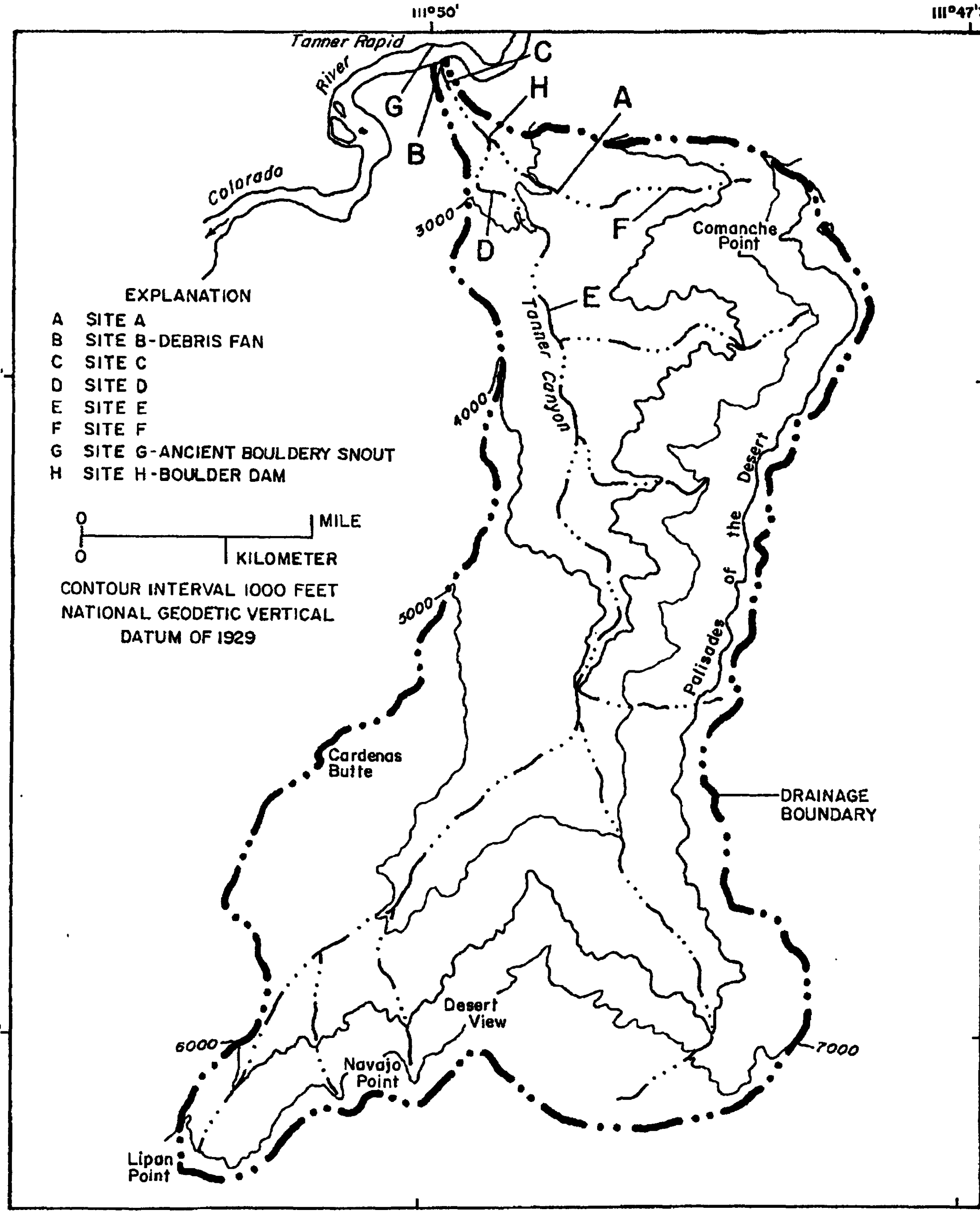
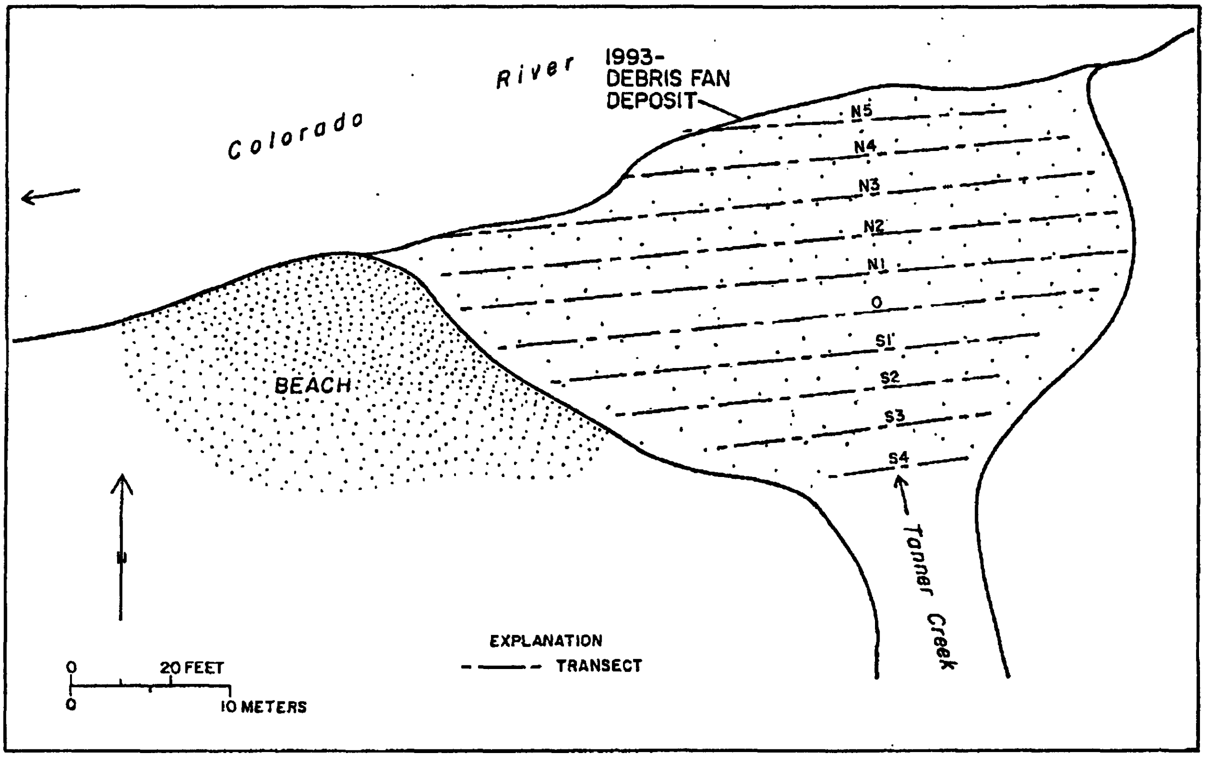


Figure 21. The study sites of the 1993 debris flow in Tanner Canyon (river mile 68.5-L), a tributary of the Colorado River in Grand Canyon. *A*, The drainage basin of Tanner Canyon showing the locations of study sites.



B, The locations of particle-size transects on the 1993 deposit on the debris fan of Tanner Canyon.

Figure 21. Continued.

of the Tanner Canyon drainage basin adjacent to Comanche Point (fig. 21A, site F).

Discharge for the streamflow generated upstream from the debris-flow producing tributary was estimated at sites C, D, and E (fig. 21A). Site C is about 0.2 km upstream from the confluence of Tanner Canyon and the Colorado River, whereas sites D and E (fig. 21A) are 1.2 and 2.3 km upstream from the confluence, respectively. Straight, bedrock-controlled reaches with continuous high-water marks, including lines of damaged vegetation and deposits of organic debris, were chosen at these sites; two or more cross sections were surveyed to describe each reach. Manning-*n* values of 0.055 to 0.075 for channel roughness were selected for the estimates based on a visual estimate.

Peak discharges of 8 to 11 m^3/s were estimated at sites D and E, respectively (table 20). Discharge increased downstream; a peak discharge of 37 m^3/s was estimated for streamflow at site C (table 20). The streamflow transported mostly gravel and coarse sand, which was sampled along the margins of the channel of Tanner Canyon near site H (fig. 21A).

The debris flow was initiated by fire-hose effects along the base of Comanche Point where the rainfall intensity was apparently greatest. We identified several areas that had been scoured of unconsolidated colluvium on slopes below cliffs of Tapeats Sandstone at site F (fig. 21A). At site A (fig. 21A), in a canyon tributary to the main channel of Tanner Canyon 1.5 km from the Colorado River, evidence of both runup and superelevation were identified. The peak discharge for the debris flow was estimated to be 200 m^3/s (table 21) from superelevation evidence. Sediment deposits in the main channel of Tanner Canyon are evidence that the snout of the debris flow temporarily dammed the main channel of Tanner Canyon at site H after debouching from the tributary. As streamflow originating in Tanner Canyon upstream from site C ponded behind the boulder dam, sand was deposited on the left side of the channel. After an unknown period of time, the boulder dam was breached; part of the deposit was remobilized along the right side of Tanner Canyon. This secondary pulse of debris deposited large boulders immediately downstream from site H (fig. 21A). This break-out type flood may explain the relatively large streamflow discharge estimated at site C, which is downstream from site H and upstream from the debris fan (fig. 21A, site B).

1993 Debris Fan Volume

The 1993 debris flow deposited at least 7,500 m^3 of poorly-sorted sediment in and near the Colorado River, including many large boulders that ranged in weight from 5 to 22 Mg (appendix 8). The newly aggraded debris fan constricted the river at Tanner Rapid (river mile 68.5) by about 30 m, which significantly increased the severity and gradient of the rapid.

Table 20. Indirect peak-discharge estimates for the August 22, 1993, streamflow flood in Tanner Canyon (68.5-L), sites C through E

[Evidence of peak discharge is a continuous line of scoured and abraded vegetation. Depositional evidence indicates that the recessional flow following the debris flow was streamflow with a sediment load of gravel and coarse sand. Based on eyewitness accounts, recessional flooding lasted from 2 to 3 hours]

Site descriptions

Locations: site C, located in the main channel of Tanner Canyon, 0.2 km upstream of the Colorado River confluence; site D, located in the main channel of Tanner Canyon, 1.2 km upstream of the Colorado River; and site E, located in the main channel of Tanner Canyon, 2.2 km upstream of the Colorado River
Drainage area: 19.36 km^2
Reach description: All reaches have straight bedrock-controlled channels with minor fill of graveL to cobble bedload which showed evidence of minimal scour (~0.2 m).

Slope-area discharge estimates for Tanner Canyon - August 22, 1993

Cross-section	Manning n-value	Area (m^2)	Conveyance	Velocity (m/s)	Froude number	Discharge (m^3/s)	Slope (m/m)
				Site C			
1	0.060	34	692	1.1	0.25	37	0.05
				Site D			
1	0.065	16	188	0.6	0.21	10	
2	0.065	14	139	0.6	0.28	8	0.05
3	0.065	21	264	0.4	0.15	8	
				Site E			
1	0.065	12	150	0.9	0.31	11	
2	0.065	17	304	0.6	0.17	10	0.20
3	0.065	14	249	0.7	0.19	10	

Site C, Q = 37 m^3/s
Site D, Q = 8 to 10 m^3/s
Site E, Q = 10 to 11 m^3/s
Site ratings for estimating discharge: C = fair, D = good, E = good.

Table 21. Indirect peak-discharge estimate for the August 22, 1993, debris flow in Tanner Canyon (river mile 68.5-L), site A

[Thalweg distance, was measured for individual cross sections relative to the cross section at which ΔH_s max occurred. Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Type of estimate procedure used: superelevation in a right-hand bend
Outside high-water mark: continuous mudline
Inside high-water mark: continuous mudline
Visually estimated percentage of channel controlled by bedrock: 100 percent

Superelevation data

Radius of curvature (R_c) = 16 m
Maximum elevation difference (ΔH_s) = 3.1 m
Mean velocity (V_s) = 4.5 m/s
Channel width (W) = 24 m
Channel slope (S) = 0.103

Cross-section data

Cross-section location	Thalweg distance, in meters	Area, in square meters	Hydraulic radius, in meters	Hydraulic depth, in meters	Flow-elevation difference, in meters	Top width, in meters
Superelevation	0	110	3.5	4.5	3.2	24
Downstream #1	15	60	2.5	3.0	0.5	20
Downstream #2	30	55	2.3	2.3	1.0	21
Downstream #3	41	78	3.2	5.1	4.4	16
Downstream #4	55	52	2.4	3.3	1.1	15

Q_s = [1]200 m^3/s
Site rating for estimating discharge: Fair

[1]Final discharge estimate based on minimum flow-elevation difference, L to R.

Sediment Characteristics

Particle-size and source distributions of sediment deposited by streamflow, hyperconcentrated flow, and the debris flow, as well as the reworked zone on the newly aggraded debris fan, are shown in figures 22A and 22B. Figure 22A shows that the streamflow flood that followed the debris flow significantly reworked part of the new debris-flow deposits, removing 800 m^3 of sediment. Dam releases between August and December 1993 reworked the distal toe of the debris fan along the vertical cut-bank. These data indicate that reworking by recessional streamflow was slightly more effective in coarsening the particle-size distribution of the new debris fan than river reworking. Figure 22B shows how tributary reworking also altered the source distribution of particles on the affected parts of the debris fan. Mostly sand-and-finer sediment (*i.e.*, the debris flows matrix) was removed from the reworked deposit. Rock types that provided finer sediment for the debris flows matrix, but that were preferentially winnowed away during the streamflow flood, included Cardenas Lava and Muav and Kaibab Limestones. The amount of Redwall Limestone remained about the same and the percentage of Supai Group rocks increased slightly, which illustrates that these lithologies provided some of the coarsest sediment in the debris flow.

On the basis of the particle-size distribution of the undisturbed surface of the 1993 debris fan, the debris flow contained 25 to 35 percent sand-and-finer sediment. Out of the 0.5 m^3 pit excavated in the debris fan, 524 clasts >64 mm in b-axis diameter were removed, identified by source, and measured (fig. 22G). Total volume of sand-and-finer sediment in the 1993 debris fan is between 1,900 and 2,600 m^3. Large boulders deposited on the debris fan (appendix 8), which are as much as 2.2 m in diameter, are likely to remain on the debris fan indefinitely, owing to the lack of river-reworking by the Colorado River under present regulated releases from Glen Canyon Dam (226 to 566 m^3/s).

Point counts were used to estimate particle-size and source distributions for the boulder berm that dammed the main channel of Tanner Canyon when it deposited at site H (fig. 21A). The coarseness of the boulder berm reflects the size distribution of the snout of the initial debris-flow surge (fig. 22C). The berm consists mostly of Supai Group rocks, with lesser but nearly-equal amounts of Redwall and Muav Limestone clasts (fig. 22D). The absence of Tapeats Sandstone boulders in the boulder-berm deposit supports the observation that the debris flow was initiated in colluvium in the lower elevations of Tanner Canyon; these deposits are dominated by Supai Group and Redwall Limestone and are devoid of Tapeats Sandstone and Kaibab Limestone.

A large number of particles (n = 2,128) were measured in the tributary-reworked and undisturbed 1993 debris-fan surface in December 1993. Point counts were made along a series of parallel transects spaced at 5-m intervals extending from the edge of the river to the apex of the fan and parallel to the river (fig. 21B). These measurements were designed to characterize the debris-fan deposit after partial reworking by recessional flow in Tanner Canyon and interim flows (142 to 556 m^3/s) in the Colorado River between August and December 1993 (figs. 22E and 22F). The variability in particle size exhibited by these data (fig. 22E) reflects the fact that the transects covered different amounts of tributary-reworked versus undisturbed deposits instead of poor reproducibility in the sampling methodology. The particle-size distribution on the new debris fan is dominated by sand-and-finer sediment. The source of the larger clasts indicates a dominance of Redwall Limestone, with a lesser amounts of Supai Group rocks (fig. 22F), in the debris flow, illustrating the source material of a colluvial wedge.

Frequency

Ample evidence exists in Tanner Canyon to indicate that large debris flows have occurred in the past. Repeat photography spanning the period of 1890 to 1991 showing Tanner Rapid and the juncture of Tanner Canyon and the Colorado River show no change in the debris fan or rapid. Aerial photography taken between 1965 and 1992 also show no evidence of debris flows in Tanner Canyon. Therefore, we conclude that the 1993 debris flow is the first one since at least 1890.

Large boulders that could only have come from Tanner Canyon are present on the right side of Tanner Rapid, indicating that a prehistoric debris flow occurred with sufficient size to cross (and temporarily dam) the river. The particle-size and source distributions of the boulder deposits (fig. 21A, site G) show a considerably larger percentage of boulders (fig. 21A, site B). These boulders have withstood Colorado River floods that exceeded 6,000 m^3/s during the last century. The twenty largest boulders measured at site G greatly exceed the size of any boulder transported by the 1993 debris flow (appendix 8).

We interpret the ancient boulder deposit (site G) as reflecting the coarsest remnant of one or more large, fan-forming debris flows that probably occurred during the mid- to late Holocene. The largest boulders are mostly Supai Group rocks and Redwall Limestone with smaller amounts of Tapeats Sandstone. These clasts may have been transported in the debris flow that created Tanner Rapid. However, the two largest boulders are from the Kaibab Limestone; both have b-axis diameters exceeding 6 m. The difference in source distribution of boulders on the right side of Tanner Rapid and those transported in the 1993 debris flow may reflect the fact that large, ancient debris flows were initiated at higher elevations, and in higher strata, than smaller events such as the 1993 debris flow.

Effects on the Colorado River

The primary impact of the 1993 debris flow in Tanner Canyon was an increase in the constriction of Tanner Rapid. Deposition of poorly-sorted sediment reduced the width of the river by at least 30 m near the head of the rapid. The increased constriction increased flow velocities in the center of the channel, deflected flow toward a number of large boulders in the center and right side of the channel, and raised the elevation of the pool upstream from the rapid by 1.0 to 1.5 m. Because of these changes, we expect increased fine-sediment accumulation in the upper pool. Future debris flows from Tanner Canyon could potentially cause large hydraulic and geomorphic changes to the Colorado River, especially under present flow regulation from Glen Canyon Dam.

Cardenas Creek (River Mile 70.9-L)

A debris flow occurred in Cardenas Creek (fig. 23) on August 22, 1993. Cardenas Creek drains 3.87 km^2 on the south side of the Colorado River. Because the channel is unconfined near the juncture with the Colorado River, most of the sediment transported by the flood was deposited near the apex of the existing debris fan and did not enter the river. As a result, the debris flow of 1993 in Cardenas Creek had virtually no effect on the hydraulics of the Colorado River.

One discharge estimate for the debris flow was made at site A (fig. 23) using superelevated-flow evidence in a left-hand bend. The channel bend is bedrock-controlled in Dox Sandstone. The peak discharge for the debris flow was 200 m^3/s (table 22). The debris flow was followed by a smaller streamflow of unknown discharge and duration. Because recessional flow was minimal, well preserved debris-flow levees were deposited along the margins of the channel in the vicinity of site A.

The 1993 debris flow deposited a minimum of 3,000 to 4,000 m^3 of sediment on top of the existing debris fan. Particle-size distributions for a debris-flow levee on the left margin of the tributary at site A and the new deposit at site B (figs. 23 and 24A) indicate that the debris flow carried poorly-sorted, relatively fine-grained sediment, of which 13 and 41 percent is sand and finer, respectively. Source distributions indicate that about 35 percent of the particles in the levee deposits (site A) were from the Dox Sandstone, but equal amounts of Dox Sandstone and Redwall Limestone particles were deposited on the debris fan (fig. 24B). The <2 mm sediments at both locations were probably derived from the Dox Sandstone, owing to the similar reddish color of the rock and deposits. Many large boulders that ranged in weight from 0.8 to 9.1 Mg were transported from the drainage to the debris fan (appendix 8).

Replication of historic photographs taken in 1890 reveal no changes that would indicate that debris flows have occurred in the drainage during the last century. In addition, aerial photographs taken between 1965 and 1994 show no change on the debris fan or in the riffle opposite the creeks mouth. Therefore, we conclude that the 1993 debris flow was the only one to occur during the last century in Cardenas Creek.

Unnamed Tributary at River Mile 71.2-R

A debris flow that occurred in an unnamed tributary at river mile 71.2-R during summer of 1984 formed a new mid-channel debris bar and riffle in the Colorado River. The exact date of the debris flow is unknown, but daily precipitation records at Desert View ranger station on the South Rim indicate that the debris flow may have occurred during the latter half of July or the third week of August. The most likely date for the debris flow is August 18th, because the Desert View record indicates that 20 mm of rainfall occurred in one-half hour; 55 mm of rainfall occurred during the month before this date.

This tributary drains 1.11 km^2 on the north side of the river; it heads on the southeast face of Apollo Temple (fig. 25). The lower part of the tributary occurs primarily in exposures of Dox Sandstone. Source sediments are abundant in the drainage, including hillslopes of colluvium at the base of prominent cliffs formed by Tapeats Sandstone and Cardenas Lava in the vicinity of site F (fig. 25).

Most of the unconsolidated sediment in the tributary is comprised of Tapeats Sandstone and clasts from the Cardenas Lavas. Particles in the source material range in size from silt to boulders and mantle the underlying Dox Sandstone, which is generally poorly-indurated and subject to failure. Localized thunderstorms in the upper sections of the drainage triggered failures in colluvium that mobilized into the 1984 debris flow.

Discharge Estimate

Evidence of superelevated flow is preserved at site A (fig. 25) as lines of Tapeats Sandstone cobbles and boulders deposited along the channel. The peak discharge, determined from the superelevation evidence, was 600 m^3/s (table 23).

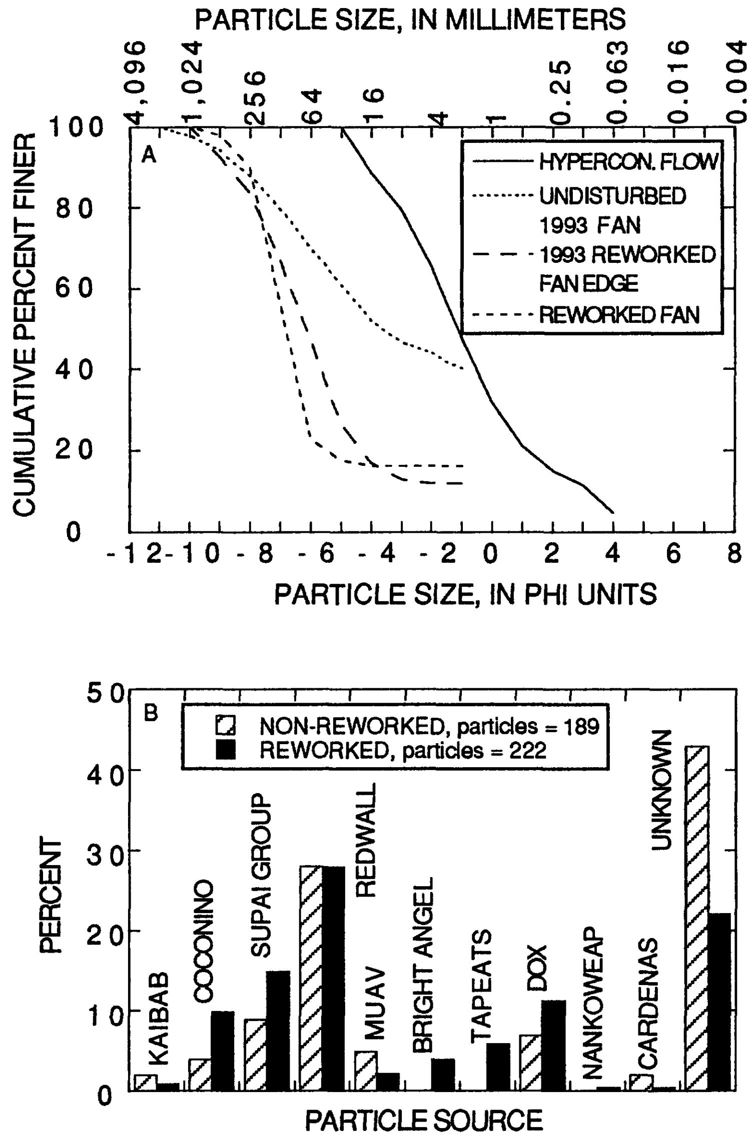
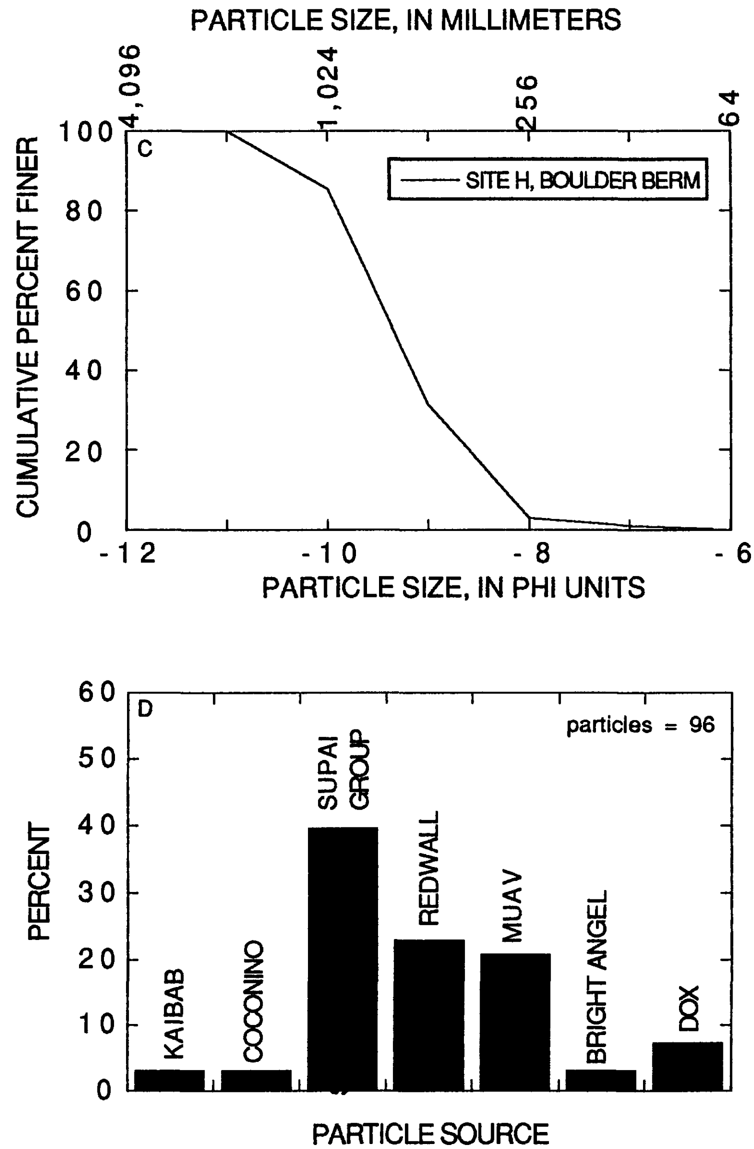
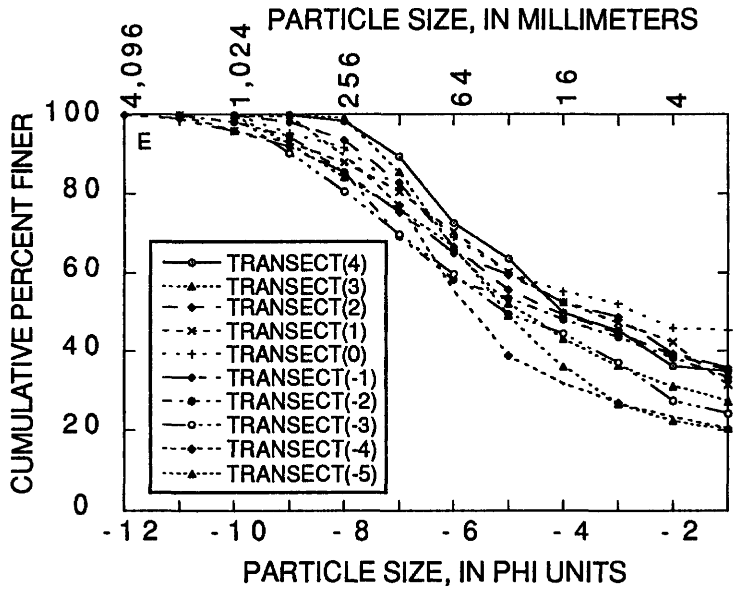


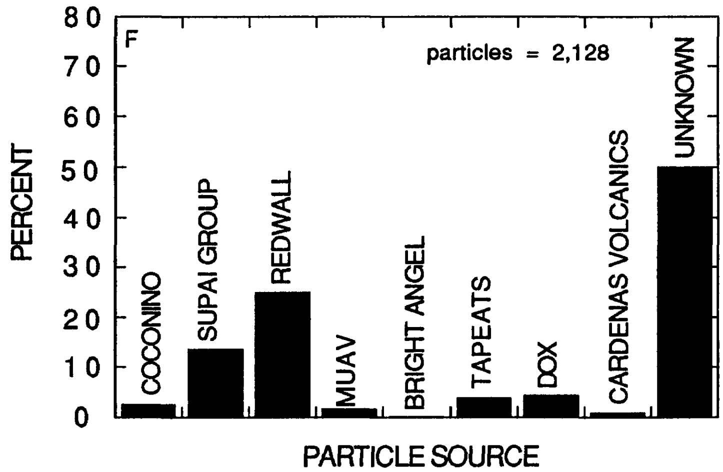
Figure 22. Particle-size and source distributions of various deposits associated with the debris flow of 1993 in Tanner Canyon (river mile 68.5-L). *A*, Particle-size distributions of the undisturbed, 1993 debris-fan surface; the pre-1993 debris fan; the partially reworked, distal edge of the 1993 debris-fan; and the 1993 hyperconcentrated-flow deposit. *B*, Source distributions of particles on the undisturbed surface of the 1993 debris fan and the pre-1993 reworked debris fan.



C, Particle-size distribution for the 1993 boulder-berm deposit at site H. *D,* Source distribution of the 1993 boulder-berm deposit at site H.

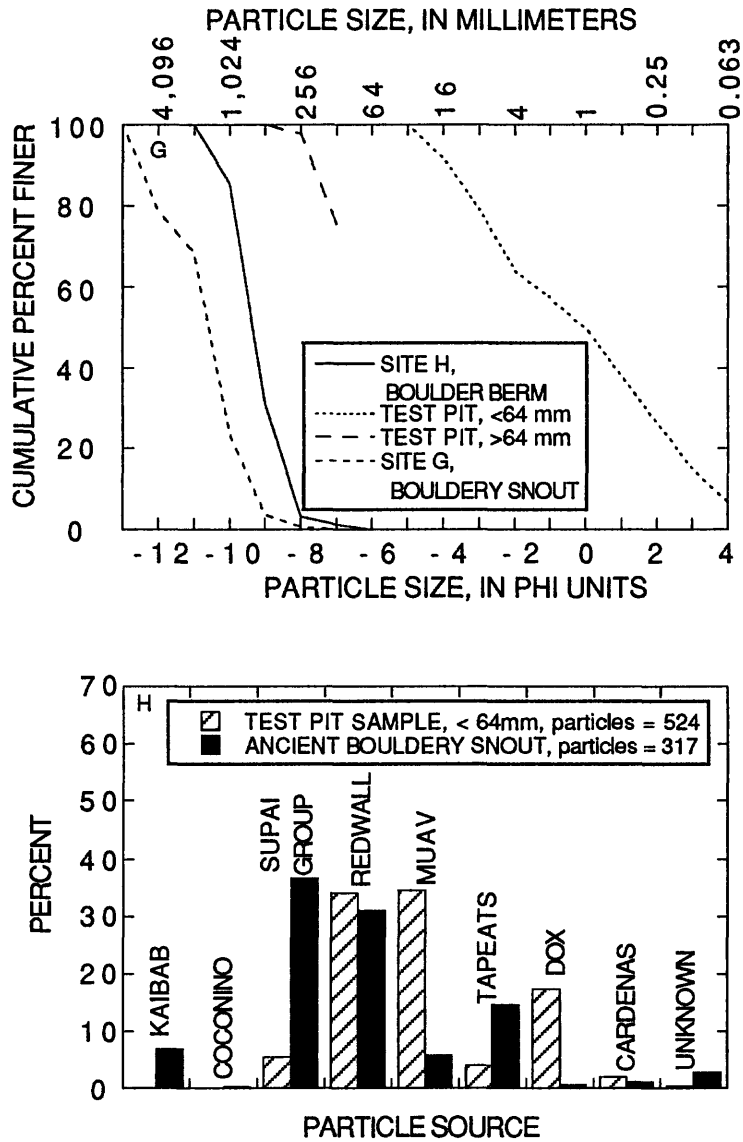
Figure 22. Continued.





E, Particle-size distributions for a series of parallel transects (fig. 21b) across the surface of the 1993 debris-flow deposit. *F*, Source distribution of particles sampled from the surface of the 1993 debris-flow deposit.

Figure 22. Continued.



G, Particle-size distributions of the 1993 boulder-berm at site H, the > 64mm fraction and the < 64 mm fraction of the test-pit sample collected from the 1993 debris-fan deposit, and the river-reworked boulder deposit located at site G. *H,* Comparison of source distributions of > 64 mm particles sampled from the test pit excavated into the 1993 debris fan and the pre-existing reworked boulder deposit at site G.

Figure 22. Continued.

Sediment Characteristics

A 40-kg sample, collected from a debris-flow levee at site A, was analyzed to determine the particle-size and source distributions of the debris flow. The <64 mm fraction of the sample contained 57 percent sand-and-finer sediment (fig. 26A). Additional point-count data were collected from both the reworked and undisturbed parts of the 1984 debris-fan deposit at site H (fig. 26A). Comparison of these data shows significant coarsening of the debris-fan sediments owing to Colorado River flows of 141 to 1,200 m^3/s that occurred between 1984 and 1994. Debris-fan reworking mainly occurred between 1984 and 1986 owing to abnormally-high releases from Glen Canyon Dam. Source data for both the reworked and undisturbed debris-fan samples show that the debris flow contained mostly particles from the Dox Sandstone with lesser amounts of Cardenas Lava (fig. 26B). On the basis of reconstitution of the <16 mm fraction of the sample, the water content of the debris flow was approximately 17 percent by weight.

Overbank flow from the debris flow deposited a veneer of sand and silt overlying an aeolian dune field on a hillslope situated between the tributary channel and the Colorado River. Deep erosional rills were formed in these aeolian sand deposits in the vicinity of site J. Archeological sites of various ages were exposed as a result of the formation of these rills (Hereford and others, 1993). These archaeological sites were buried by aeolian and fluvial sediments that were easily eroded by the overbank component of the 1984 event. Strata preserved in the tributary channel upstream from the superelevation bend reveal alternating episodes of debris-flow deposits and aeolian sand in thin deposits (from 0.1- to 0.5-m thick).

Effects on the Colorado River

The existing debris fan at the mouth of the unnamed tributary at river mile 71.2-R was significantly aggraded by the 1984 debris flow. The area of the 1984 deposition, measured from low-elevation aerial photographs taken in October 1984, was 4,800 m^2. The thickness of the debris fan deposit was estimated to be 1.5 m, yielding a minimum volume of 7,200 m^3. The newly aggraded debris fan was reworked by dam releases less than 1,200 m^3/s. The volume of sediment eroded from the debris fan was not estimated. Runoff in the unnamed tributary has also reworked the 1984 deposit. With a sand-and-finer sediment content of 57 percent, the total volume of sand-and-finer particles added to the debris fan was about 4,100 m^3.

Boulder Transport

Many large boulders were deposited in the Colorado River at river mile 71.2 during the 1984 debris flow. The largest 25 boulders deposited on the 1984 fan surface at site H were measured and their lithologies and dimensions were recorded (appendix 8); these boulders typically ranged in weight from 0.1 to 0.2 Mg with one boulder weighing 29 Mg. Most of these boulders are Tapeats Sandstone with a few boulders of Dox Sandstone, Nankoweap Sandstone, and Cardenas Lava. The average b-axis diameter of these boulders is 0.45 m. The snout of the debris flow deposited several large boulders in the center of the river channel, which were reworked into a new, persistent debris bar in the Colorado River (fig. 25). The size and rock type of the 8 largest boulders in the debris bar were estimated from the shore. All of the boulders are Tapeats Sandstone with an average b-axis diameter of about 1 m.

Frequency

From analysis of aerial photographs, the 1984 debris flow in the unnamed tributary at mile 71.2 appears to be the first since 1965. Several debris flows are recorded in the stratigraphy of the channel walls 0.4 km upstream from the Colorado River. These deposits record a series of thin, dark brown debris-flow deposits that are inter-layered with aeolian and fluvial sands; however, these strata could not be dated. The approximate age of these debris-flow deposits has been inferred by their stratigraphic association with archeological sites of known age. Hereford and others (1993) referred to the interfingered sand and debris-flow deposits as "striped" alluvium. These deposits were apparently deposited over a poorly-known period of time before the Pueblo III period of occupation beginning about AD 1100.

Table 22. Indirect peak-discharge estimate for the August 22, 1993 debris flow in Cardenas Creek (river mile 70.9-L), site A

[Thalweg distance, was measured for individual cross sections relative to the cross section at which ΔH_s max occurred. Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Type of estimate procedure used: superelevation in a left-hand bend
Outside high-water mark: continuous scourline
Inside high-water mark: continuous mudline
Visually estimated percentage of channel controlled by bedrock: 80 percent

Superelevation data

Radius of curvature (R_c) = 58 m
Maximum elevation difference (ΔH_s) = 2.2 m
Mean velocity (V_s) = 9.4 m/s
Channel width (W) = 13 m
Channel slope (S) = 0.08

Cross-section

Cross-section location	Thalweg distance, in meters	Area, in square meters	Hydraulic radius, in meters	Hydraulic depth, in meters	Flow-elevation difference, in meters	Top width, in meters
Upstream	75	31	1.1	1.2	0.1	25
Superelevation	0	21	1.4	1.6	2.7	13
Downstream	40	30	1.5	1.7	0.0	15

Q_s = [1]200 m^3/s
Site rating for estimating discharge: Good

[1]The final peak-discharge estimate was based on the minimum cross-sectional area

Unnamed Tributary at River Mile 72.1-R

An unnamed tributary at river mile 72.1-R had a debris flow during August 1984, probably on the same date as the debris flow at river mile 71.2-R. The unnamed tributary at river mile 72.1-R drains 1.16 km^2 on the north side of the Colorado River (fig. 25); the tributary has its headwaters on the south side of Apollo Temple. The debris flow of 1984 caused significant aggradation of an existing debris fan and partial burial of a separation bar. Before 1984, this large sand bar was commonly used by commercial and private river runners as a campsite. Changes caused by the debris flow, along with erosion caused by the high dam releases between 1983 and 1986 (up to about 2,700 m^3/s), have dramatically decreased the size of this sand bar.

The 1984 debris flow was initiated by scour in the steep talus slopes mantling the Cardenas Lava at the base the Tapeats Sandstone in the vicinity of site I. This scour resulted from fire-hose effects of runoff originating above the Tapeats Sandstone cliffs. The mobilized debris flow then traveled about 1.3 km to the Colorado River. Enroute, the discharge of this debris flow substantially increased with the addition of water and sediment from hillslopes and small tributary channels and with the entrainment of channel-stored sediments. In addition, the failure of a vertical wall of Dox Sandstone at site G (fig. 25) contributed a considerable volume of coarse, angular boulders to the debris flow near the top of the debris fan (site E, fig. 25).

Discharge Estimates

Site B

At site B (fig. 25), peak discharge was estimated just downstream from the source area(s) of the debris flow (site I). Site B contains evidence of superelevated flow along the margins of the Dox Sandstone channel. Flow elevations consist of a semicontinuous mudline on the outside of the channel and a semicontinuous debris levee on the

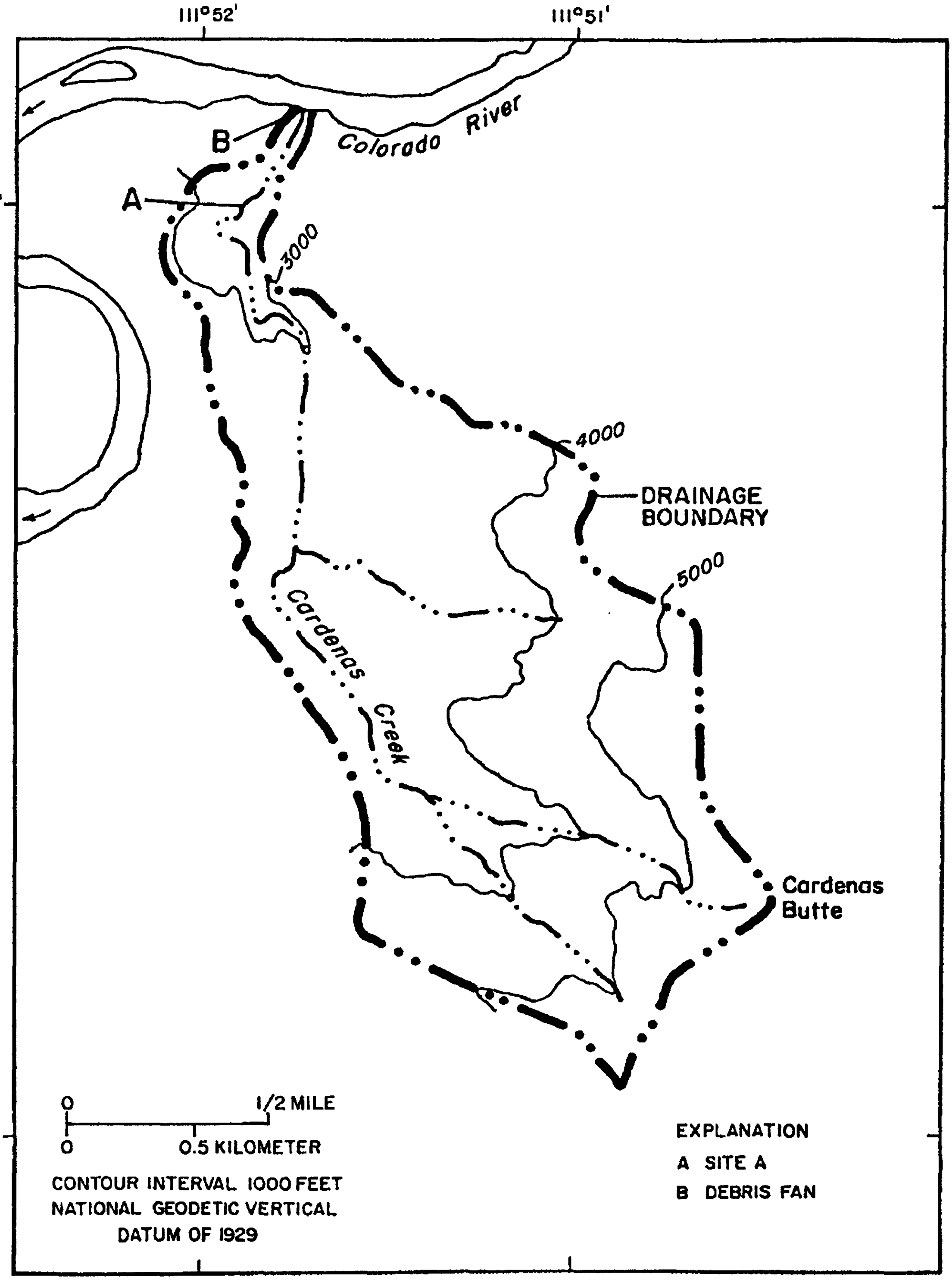


Figure 23. The drainage basin of Cardenas Creek (river mile 70.9-L), a tributary of the Colorado River in Grand Canyon.

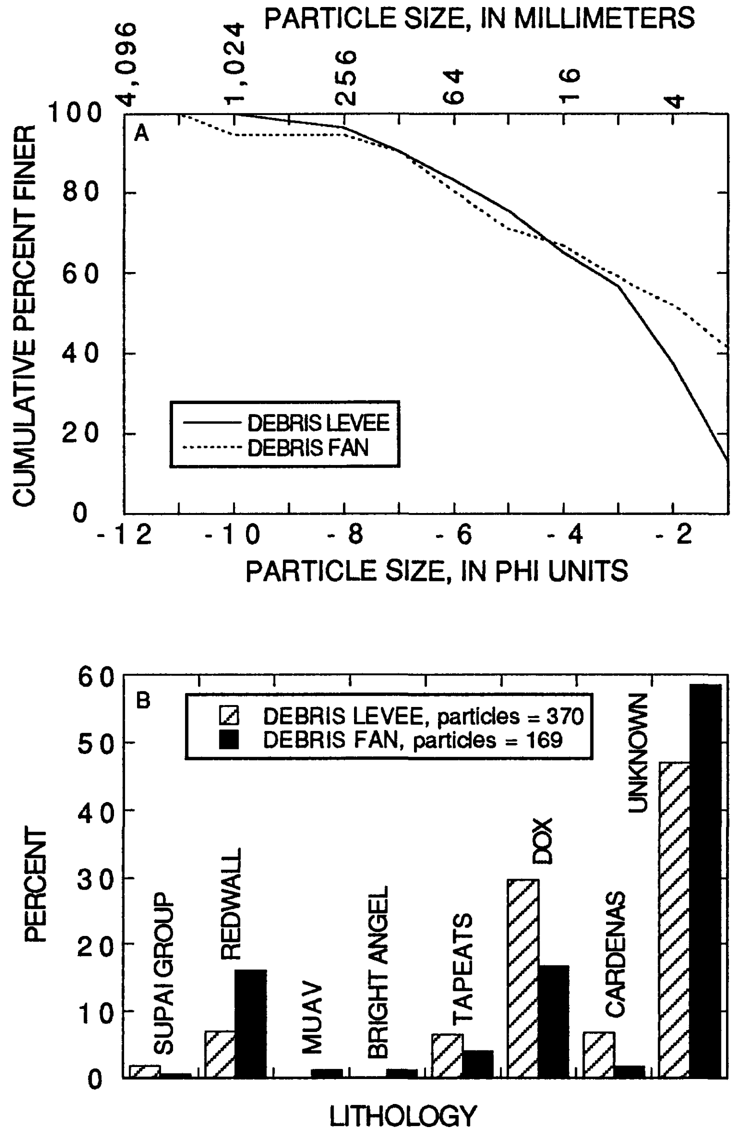


Figure 24. Particle-size and source distributions of various sediment deposits associated with the debris flow of 1993 in Cardenas Creek (river mile 70.9-L). *A*, Particle-size distributions of the 1993 debris-flow deposit at site B and an undisturbed 1993 debris-flow levee at site A. *B*, Source distributions of particles on the undisturbed 1993 debris-flow levee at site A and the 1993 deposit in the debris fan at site B.

Table 23. Indirect peak-discharge estimate for the August 1984 debris flow in an unnamed tributary at river mile 71.2-R, site A

[Thalweg distance, was measured for individual cross sections relative to the cross section at which ΔH_s max occurred. Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Type of estimate procedure used: superelevation in a right-hand bend
Outside high-water mark: continuous line of boulders and scour zone with damaged plants
Inside high-water mark: line of boulders
Visually estimated percentage of channel controlled by bedrock: 80 percent

Superelevation data

Radius of curvature (R_c) = 36 m
Elevation difference (ΔH_s) = 2.3 m
Mean velocity (V_s) = 3.9 m/s
Channel top width (W) = 53 m
Channel slope (S) = 0.11

Cross-section data

Cross-section location	Thalweg distance, in meters	Area, in square meters	Hydraulic radius, in meters	Hydraulic depth, in meters	Flow-elevation difference, in meters	Top width, in meters
Downstream #1	21	152	1.1	3.7	2.1	41
Downstream #2	10	194	0.7	3.7	1.5	52
Downstream #3	6	208	1.3	4.0	0.6	52
Superelevation	0	111	0.7	2.1	2.3	52
Upstream #1	10	194	1.2	3.7	1.2	52
Upstream #2	17	77	0.3	1.9	4.6	41
Upstream #3	24	100	0.4	2.5	0.6	40
Upstream #4	29	104	0.4	2.6	1.6	40
Upstream #5	32	76	0.5	1.9	1.0	39
Upstream #6	38	93	0.4	2.3	1.1	41
Upstream #7	44	90	0.4	1.7	2.2	54

Q_s = [1]600 m^3/s
Site rating for estimating discharge: Good

[1]Final peak-discharge estimate is based on the average of cross sections DS#3 and US#3.

inside of the channel. We estimated a peak discharge of 24 m^3/s for the debris flow in this reach, which we interpreted as the early stage of the flood (table 24).

Site C

Site C is a right-hand channel bend controlled by Dox Sandstone (fig. 25, site C). The debris flow was channelized in bedrock comprised of Dox Sandstone as it continued downstream toward the Colorado River. Evidence of the debris flow consists of preserved, semicontinuous debris deposits on the inside of the bend and a continuous scour line with some discontinuous mudlines on the outside of the bend. Continuous lines of Tapeats Sandstone cobbles and boulders also delineate the flow boundaries at this site. Evidence of superelevated flow and runup are apparent in the deposits and mudlines. Peak discharge for the debris flow was estimated to be 190 m^3/s using superelevation evidence and 170 m^3/s using runup evidence (table 25). At this site, about 0.5 km downstream from site B, peak discharge had increased by nearly an order-of-magnitude because of additional sediment and water contributed by

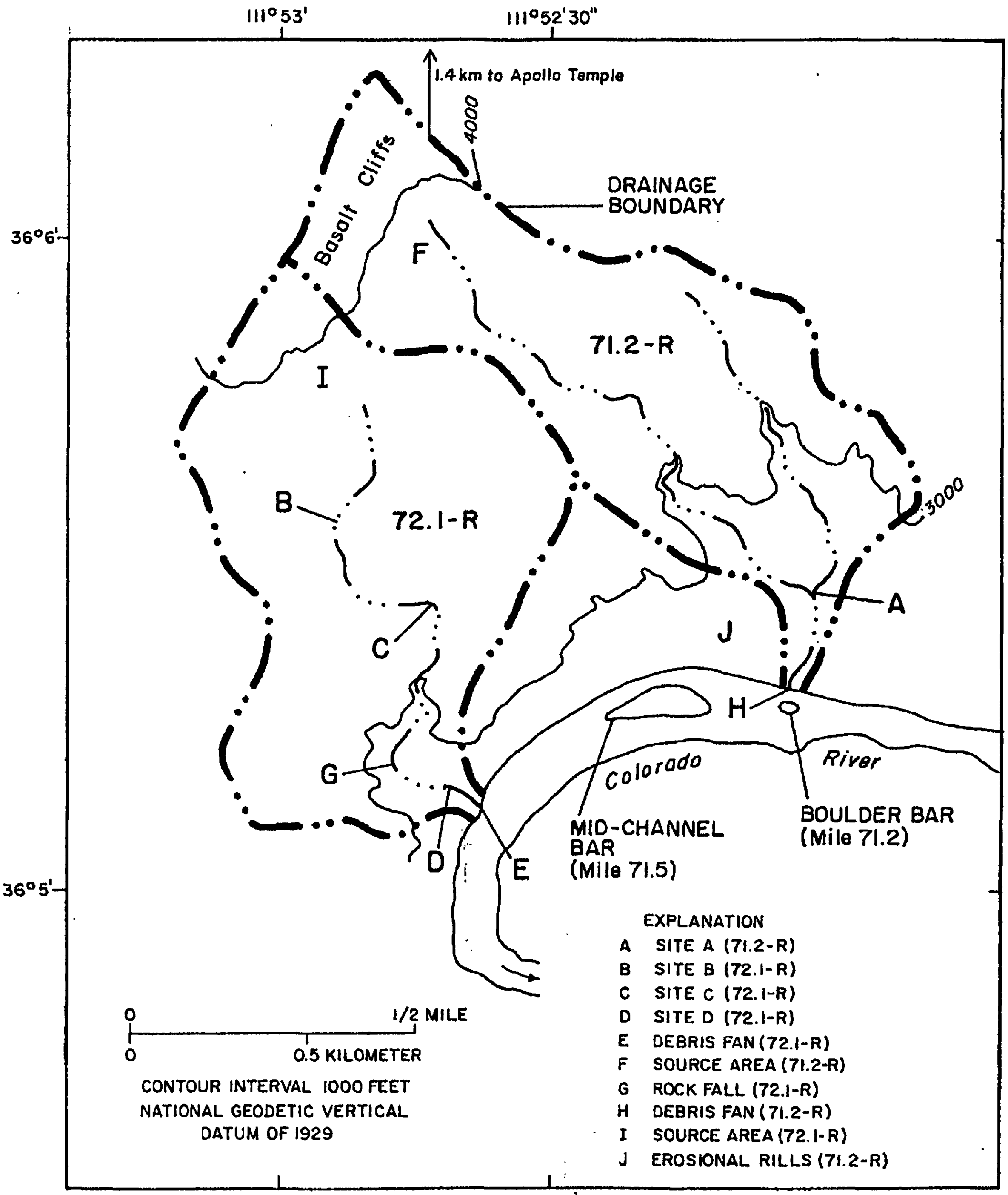


Figure 25. The drainage basins of unnamed tributaries of the Colorado River at river miles 71.2-R and 72.1-R in Grand Canyon.

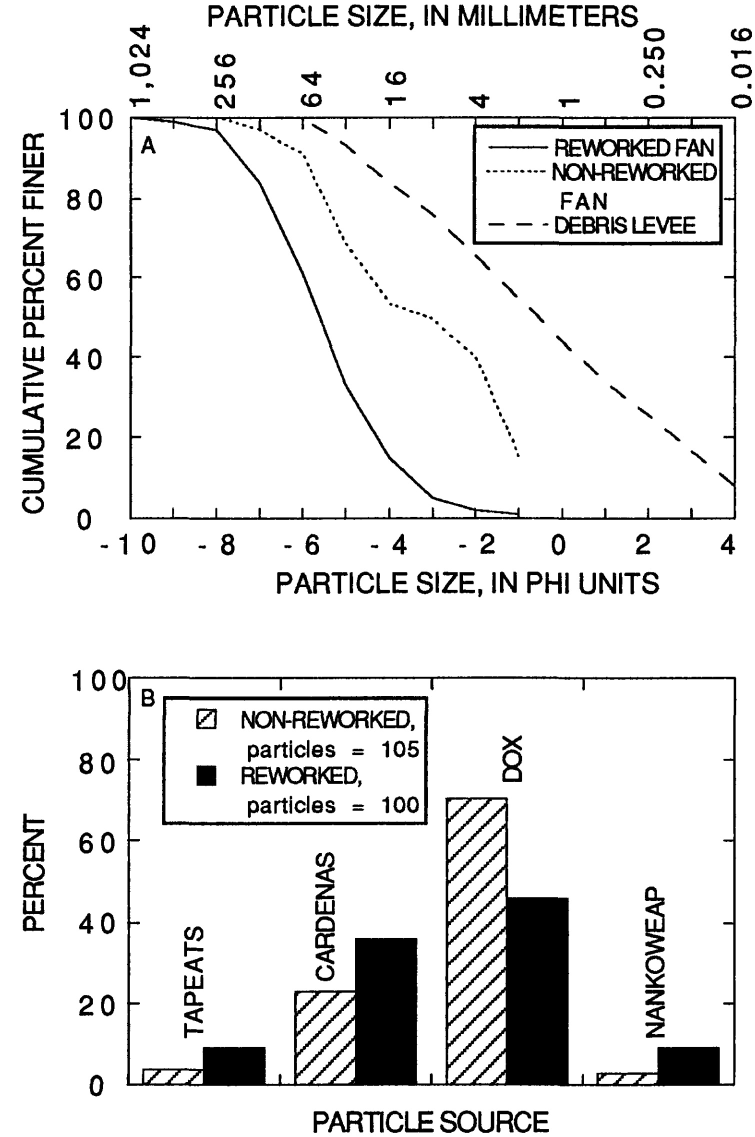


Figure 26. Particle-size and source distributions for various sediment deposits associated with the debris flow of 1984 in an unnamed tributary of the Colorado River at river mile 71.2-R in Grand Canyon. *A*, Particle-size distributions of the undisturbed surface of the 1984 debris fan, part of the 1984 debris fan reworked by river discharges of at least 790 m3/s between 1984 and 1993, and an undisturbed levee deposited during the 1984 debris flow. *B*, Source distributions of particles on the surface of the undisturbed 1984 debris fan and the reworked part of the debris fan inundated by river flows of at least 790 m^3/s between 1984 and 1993.

several small side channels or scoured channel-terrace deposits.

Site D

At site D, peak discharge was estimated just upstream from the debris fan and downstream from the waterfall (site G). Site D consists of a right-hand bend with evidence of runup and superelevation. The debris flow flowed over the waterfall and struck the opposing wall of Dox Sandstone, causing a rockfall at site G. As a result, the debris flow subsequently entrained many large, angular boulders from this rockfall. Debris-flow levees and fan deposits downstream from the waterfall-rockfall failure are comprised mostly of large, angular Dox Sandstone clasts, whereas upstream from site G, Tapeats Sandstone clasts dominate debris-flow levees.

Peak discharges were estimated using both superelevation and runup evidence. A discharge of 120 m^3/s was obtained using both methods (table 26). This estimate indicates that peak discharge decreased in the reach below the waterfall despite bulking-up of the debris flow that resulted from the rockfall. This may be partly explained by a bedrock plunge-pool at the base of the waterfall. The plunge pool may have served as a hydraulic energy dissipator or drop-structure to dampen the peak discharge of the initial debris-flow pulse.

Deposition and Reworking of the 1984 Debris Fan

A significant part of the original 1984 debris fan (fig. 25), surveyed in August 1991, was reworked by relatively high dam releases between 1984 and 1991. An erosional cut-face along the distal edge of the 1984 debris fan, approximately 1.3-m high, provides evidence of reworking by Colorado River discharges between 850 and 1,415 m^3/s. Whereas most of the finer matrix of the deposit has been eroded by the river, large angular clasts of Dox Sandstone persist on the reworked debris fan.

Part of an existing separation bar was eroded and (or) buried by the 1984 debris flow; the sand bar has remained in that condition since 1984. Releases from Glen Canyon Dam between 1984 and 1994 were not large enough to inundate and redeposit the separation bar on the debris fan. The surface of the debris fan was aggraded by about 1.2 m near its apex and the new sediment is comprised of sand- to cobble-size clasts from the Dox Sandstone.

Test pits were excavated on the 1984 debris fan deposit to determine the thickness of the sediment deposited by the debris flow. Test pits across the widest section of the debris fan spaced every 20 m and, at two places along the medial axis of the fan, pits were excavated to the pre-1984 fan surface. A cut-face along the front of the debris fan also revealed the thickness of the deposit. Examined in cross section, the debris-fan deposit was massive and lacked sedimentary structures. The subsurface of the 1984 debris fan contained mainly Dox Sandstone with some Tapeats Sandstone cobbles and boulders. On the basis of the depths of the test pits (thickness of the deposit varied by 0.3 m), the average thickness of the new deposit is 1.5 m.

The 1984 debris-fan deposit has an area of 3,000 m^2 and a volume of at least 4,500 m^3. On the basis of particle-size data for the <16 mm fraction of the debris flow, 45 percent, or 2,000 m^3, of sand-and-finer sediment was deposited on the debris fan. The volume removed by river reworking between 1984 and 1991 was 650 to 1,000 m^3. Using the particle-size distribution for the debris-flow sample, 300 to 450 m^3 of the reworked deposit was probably sand-and-finer sediment.

Sediment Characteristics

A 20-kg sediment sample was collected from sediments deposited on the debris fan during the 1984 debris flow. The part of the sample <64 mm was dry sieved to obtain a particle-size distribution for the finer component of the debris flow deposit (fig. 27A and 27B). On the basis of the sample collected from a debris-flow levee, the 1984 debris flow contained about 45 percent sand-and-finer sediment. The <16 mm fraction was reconstituted, yielding a water content of 16 to 20 percent by weight. An activity of 0.291 pCi/g of ^{137}Cs was measured in one sample of debris-flow matrix.

Particle-size data were also collected from point counts made on the preserved debris-flow levee at site C, upstream from the rockfall at site G, and at three sites where we identified hyperconcentrated-flow deposits (fig. 27A and

Table 24. Indirect peak-discharge estimate for the August 1984 debris flow in an unnamed tributary at river mile 72.1-R, site B

[Thalweg distance, was measured for individual cross sections relative to the cross section at which ΔH_s max occurred. Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Type of estimate procedure used: superelevation in a right-hand bend
Outside high-water mark: discontinuous mudline
Inside high-water mark: discontinuous debris flow levee
Visually estimated percentage of channel controlled by bedrock: 90 percent

Superelevation data

Radius of curvature (R_c) = 18 m
Elevation difference (ΔH_s) = 1.7 m
Mean velocity (V_s) = 6.1 m/s
Channel top width (W) = 8 m
Channel slope (S) = 0.23

Cross-section data

Cross-section location	Thalweg distance, in meters	Area, in square meters	Hydraulic radius, in meters	Hydraulic depth, in meters	Flow-elevation difference, in meters	Top width, in meters
Downstream	14	9	1.0	1.0	1.3	10
Superelevation	0	16	0.2	2.0	1.7	8
Upstream	19	4	0.6	0.7	1.1	6

Q_s = [1]24 m^3/s
Site rating for estimating discharge: Good

[1]Final discharge estimate based on minimum flow-elevation difference, L to R.

27B). The hyperconcentrated-flow deposits have similar particle-size distributions. Source data collected from the 1984 debris-flow levees (site C) and the debris-fan deposit (site E) show a clear contrast between the lithologic composition of debris-flow deposits upstream and downstream from the site G rockfall (fig. 27C). These data further support the idea that the rockfall played a significant role bulking-up the debris flow, and in the formation of the coarse debris-fan deposit. Many large, angular boulders were transported by the debris flow from site G to the debris fan and into the Colorado River.

Particle-size distributions for the 1984 debris fan were measured along several different elevations related to stages of the Colorado River (fig. 27D). During a unique period of constant 142 m^3/s discharge lasting for 72 hours in May 1991, we measured particle-size distributions on the debris fan above the 1,000 m^3/s level, between the 850 and 142 m^3/s levels, and at about the 85 m^3/s level (fig. 27D). In addition, we were able to measure many of the boulders deposited in the river channel during the 1984 debris flow and determine their lithologies and weights (appendix 8). The largest boulders ranged in weight from 7 to 25 Mg. The source distributions of the reworked debris fan above the 142 m/s stage contrasts strongly with that at about the 85 m^3/s stage (fig. 27E); all of the persistent clasts in the river are Dox Sandstone.

Frequency

No historical photographs show the debris fan at the mouth of this unnamed tributary. Low-elevation aerial photographs taken between 1965 and 1984 show no significant changes to the debris fan which would indicate the occurrence of debris flows, and no debris flows have occurred between 1984 and 1994.

Preserved twigs were extracted from mud plastered under an overhanging wall just

Table 25. Indirect peak-discharge estimate for the August 1984 debris flow in an unnamed tributary at river mile 72.1-R, site C

[Thalweg distance, was measured for individual cross sections relative to the cross section at which ΔH_s max occurred. Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Type of estimate procedure used: superelevation in a right-hand bend with a runup
Outside high-water mark: continuous scourline, damaged plant remains, also discontinuous mud
Inside high-water mark: continuous debris flow sediments
Visually estimated percentage of channel controlled by bedrock: 75 percent

Superelevation and runup data

Radius of curvature (R_c) = 12 m
Elevation difference (ΔH_s) = 5.5 m
Mean velocity (V_s) = 5.7 m/s
Channel slope (S) = 0.11

Channel top width (W) = 20 m
Elevation difference (ΔH_r) = 1.3 m
Mean velocity (V_r) = 5.0 m/s

Cross-section data

Cross-section location	Thalweg distance, in meters	Area, in square meters	Hydraulic radius, in meters	Hydraulic depth, in meters	Flow-elevation difference, in meters	Top width, in meters
Downstream	21	44	2.2	2.7	2.1	16
Superelevation	0	86	0.6	4.1	5.0	21
Upstream #1	6	49	0.4	2.5	4.5	20
Upstream #2	18	20	0.2	1.0	2.1	21
Upstream #3	38	34	0.3	1.5	1.6	21
Upstream #4	44	59	0.3	2.7	1.9	22

Q_s = [1]190 m^3/s and Q_r = [1]170 m^3/s
Site rating for estimating discharge: Good

[1]Final discharge estimates were based on minimum flow-elevation difference, L to R.

Table 26. Indirect peak-discharge estimate for the August 1984 debris flow in an unnamed tributary at river mile 72.1-R, site D

[Thalweg distance, was measured for individual cross sections relative to the cross section at which ΔH_s max occurred. Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Type of estimate procedure used: superelevation in a right-hand bend with a runup
Outside high-water mark: semicontinuous mudline
Inside high-water mark: continuous scourline
Visually estimated percentage of channel controlled by bedrock: 50 percent

Superelevation and runup data

Radius of curvature (R_C) = 11 m
Elevation difference (ΔH_S) = 4.3 m
Mean velocity (V_S) = 5.6 m/s
Channel slope (S) = 0.089

Channel top width (W) = 15 m
Elevation difference (ΔH_r) = 1.6 m
Mean velocity (V_r) = 5.6 m/s

Cross-section data

Cross-section location	Thalweg distance, in meters	Area, in square meters	Hydraulic radius, in meters	Hydraulic depth, in meters	Flow-elevation difference, in meters	Top width, in meters
Upstream	9	21	1.2	1.2	0.0	17

Q_s = 120 m^3/s and Qr = 120 m^3/s
Site rating for estimating discharge: Good

downstream from site C. These twigs were radiocarbon dated to check the association between organic debris and the known date of the transporting debris flow. A radiocarbon date of 130.6±1.3 percent of modern carbon supports a post-1950s age for the 1984 debris flow. Using the post-bomb ^{14}C relation, the twigs were killed in either 1959 or 1976. Assuming the latter year is correct, the plant material transported by the flood died about 8 years before the debris flow. Sediment samples for ^{137}Cs analysis were collected from the overhanging wall, the debris fan, and a test pit through the debris fan. The activities of these samples were 0.282±0.017, 0.0151±0.015, and 0.122±0.013 pCi/g, which are consistent with the date of the flood and show the variability in ^{137}Cs activity in debris-flow deposits.

75-Mile Creek (River Mile 75.5-L)

75-Mile Creek (fig. 28) had debris flows in August 1987 and September 1990; the dates of these floods were determined from the accounts of professional river guides (Glenn Rink, written commun., 1990). This tributary drains 11.47 km^2 on the south side of Grand Canyon. The drainage of 75-Mile Creek faces west and has headwaters at the edge of the South Rim near the Desert View watchtower (fig. 28). The lower parts of the drainage basin contain Shinumo Quartzite and Dox Sandstone; these crop out at the confluence with the Colorado River and are present in the higher elevations of the drainage.

The eastern section of the Seventy-Five-Mile Fault trends northeast through 75-Mile Creek (Huntoon and others, 1986). This fault controlled the asymmetric evolution of the 75-Mile Creek drainage (fig. 28); most tributaries in Grand Canyon formed along ancient faults (Dolan and others, 1978). The relation of faults and the frequency of rockfalls and debris flows in 75-Mile Creek lies in the increased deformation of rocks contained in the footwall of the fault, which is on the south side of the drainage (fig. 28). All second-order channels and gullies in the drainage basin are on the south side of the basin. Although colluvial wedges are widespread in the drainage, all recent debris flows have been initiated on the footwall-side of the fault.

The complex stratigraphy of bedrock exposed in 75-Mile Creek provides many initiation mechanisms for debris flows. The footwall of Seventy-Five-Mile Fault is incised with five small drainages on the south side of the tributary. No well-developed channels are present on the north side of the drainage basin, although steep pourovers occur along the top of Redwall Limestone cliffs. Rockfalls and failures of hillslopes are common; during aerial reconnaissance, we observed that both the 1987 and 1990 debris flows were initiated primarily in colluvial-wedge failures on the south side of the drainage basin. Runoff generated above the South Rim drains away from 75-Mile Creek because the strata on the south side of the river dips 2 to 3 degrees to the south. The small amount of headwaters near or above the rim reduces the probability of bedrock failures in the Hermit Shale.

The Debris Flow of 1987

The debris flow of 1987 was initiated during a thunderstorm centered over the watershed. Precipitation records from Desert View ranger station, on the South Rim at the head of the drainage, show that August 24 is the most-likely date for the debris flow. A total of 13 mm of rain fell on the South Rim, which was the highest 24-hour total for that month. Although the rainfall was not unusual, it was enough to generate significant runoff on slopes above the Coconino Sandstone. The runoff eroded material from colluvial wedges in the six tributaries to 75-Mile Creek. Many of the resulting debris flows flowed short distances and stopped; the water and fine-sediment fraction segregated from the coarser material, and streamflow and (or) hyperconcentrated-flow continued downstream. The 1987 debris flow in 75-Mile Creek offers the best example of the flow transformations that occur in small debris flows with insufficient energy and mass to flow from their initiation points to the Colorado River.

Discharge Estimates

Canyon 1 and Canyon 2 (fig. 28) had debris flows during the 1987 event, but both debris flows stopped near the juncture of the two canyons. The resulting flow in 75-Mile Creek was streamflow downstream from this juncture. At site C, 3.8 km upstream from the Colorado River and just upstream from the mouth of Canyon 3, we estimated streamflow to be 0.7 to 1.0 m^3/s, using the slope-area estimation technique (table 27).

The peak discharge for a debris flow that debouched from Canyon 3 was estimated at two sites. Site A, in Canyon 3 above a waterfall, consisted of a left-hand bend. The discharge estimated at this site using superelevation evidence was 52 m^3/s (table 28). At site B, the juncture of Canyon 3 and 75-Mile Creek, the debris flow issued from Canyon 3, crossed 75-Mile Creek, and impinged directly on a vertical bedrock wall. Using runup evidence, we estimated a peak discharge of 19 m^3/s (table 29). The debris flow then turned the bend into 75-Mile Creek and stopped 200 m downstream. Hyperconcentrated-flow evidence was present along the channel downstream from where the debris flow stopped.

Canyon 4 generated streamflow during August 1987. Between Canyon 4 and Canyon 5 (fig. 28), the channel-bed sediments of 75-Mile Creek were mostly well-sorted sand and gravel. No evidence of debris flow passage was evident; even trees in the middle of the channel, which would have been destroyed by debris flows, were still standing although slightly damaged by the streamflow flooding. We surveyed high-water evidence in a straight reach at site D, 2.7 km upstream from the Colorado River. Using the slope-area method, we estimated a peak discharge of 3 m^3/s for streamflow in 75-Mile Creek (table 30).

Canyon 5 only had streamflow during the August 1987 flood. At site E, which consists of a straight reach, floored with bedrock, we surveyed water-surface elevations along the channel margins using lines of organic debris. Using the slope-area method, we estimated a peak discharge of 23 m^3/s (table 31).

The debris flow initiated in Canyon 6 combined with streamflow or hyperconcentrated flow in 75-Mile Creek to flow to the Colorado River. At site F, in Canyon 6, we used superelevation evidence in a reach with a bedrock floor and bedrock sides to estimate a peak discharge of 60 m^3/s (table 32). At site G, at the mouth of Canyon 3, the debris flow crossed 75-Mile Creek and impinged on a bedrock wall. Using this runup evidence, we estimated a peak discharge of 250 m^3/s for the debris flow of 1987 in 75-Mile Creek (table 33).

Sediment Characteristics

Particle-size data were collected for debris-flow, hyperconcentrated-flow, and streamflow deposits left by the 1987 event (fig. 29A). A source distribution of the debris flow was obtained from point-count data that were collected from the newly aggraded debris fan (fig. 29B). The clay minerals present in three <2 mm samples of debris-flow matrix show a dominance of undifferentiated micas and kaolinite with no montmorillonite detected (table 9). We estimated a volume at 3,000 to 4,000 m^3 for the aggradation on the debris fan. In addition, we measured the largest boulders deposited by the 1987 debris flow on the debris fan (appendix 8); these ranged in weight from 1 to 18 Mg.

The Debris Flow of 1990

The most recent debris flow in 75-Mile Creek was initiated by fire-hose effects and several small hillslope failures. The 1990 debris flow must have occurred between September 16 and 24, 1990, based on precipitation records at the Desert View Ranger station. A total of 61 mm of rainfall occurred on the South Rim between those dates, with high daily totals of 19 and 12 mm occurring on the 18th and 24th, respectively. A total of 92 mm of rainfall was recorded at Desert View during the month of September 1990.

Most of the hillslope scour and failures occurred in Canyon 6, a tributary of 75-Mile Creek. Canyon 6 is about 1.3 km upstream from the Colorado River (fig. 28). We observed that runoff and small amounts of sediment were also supplied from other areas near the head of the tributary. The pattern of deposition on the debris fan and in the channel of 75-Mile Creek indicate that at least two pulses of debris flow occurred during the 1990 debris flow.

Discharge Estimates

Three indirect peak-discharge estimates were made for the 1990 debris flow. Site A is in Canyon 3 (fig. 28), which produced the largest debris flow during the 1990 flood. Sites H and I are in the lower reaches of the main tributary channel (fig. 28) and preserved good evidence of superelevated flow consisting of mudlines and damaged plants; site H also has evidence of runup.

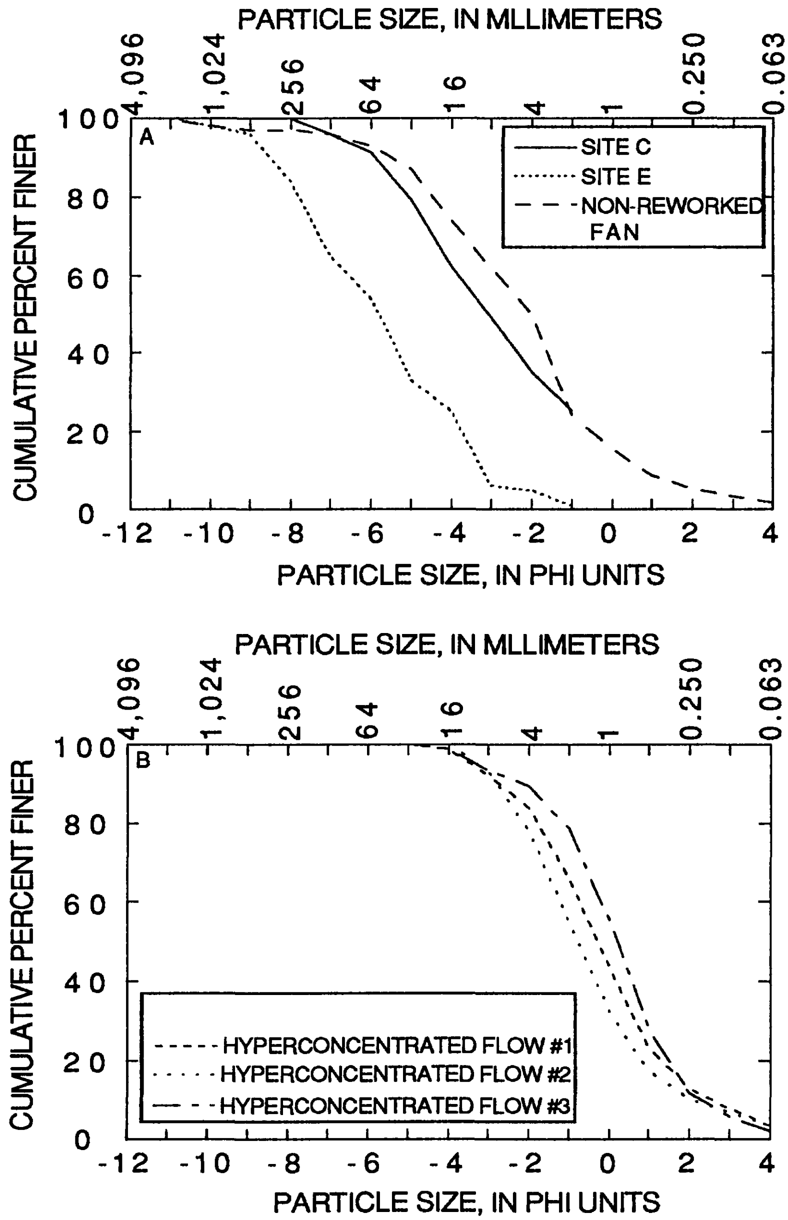
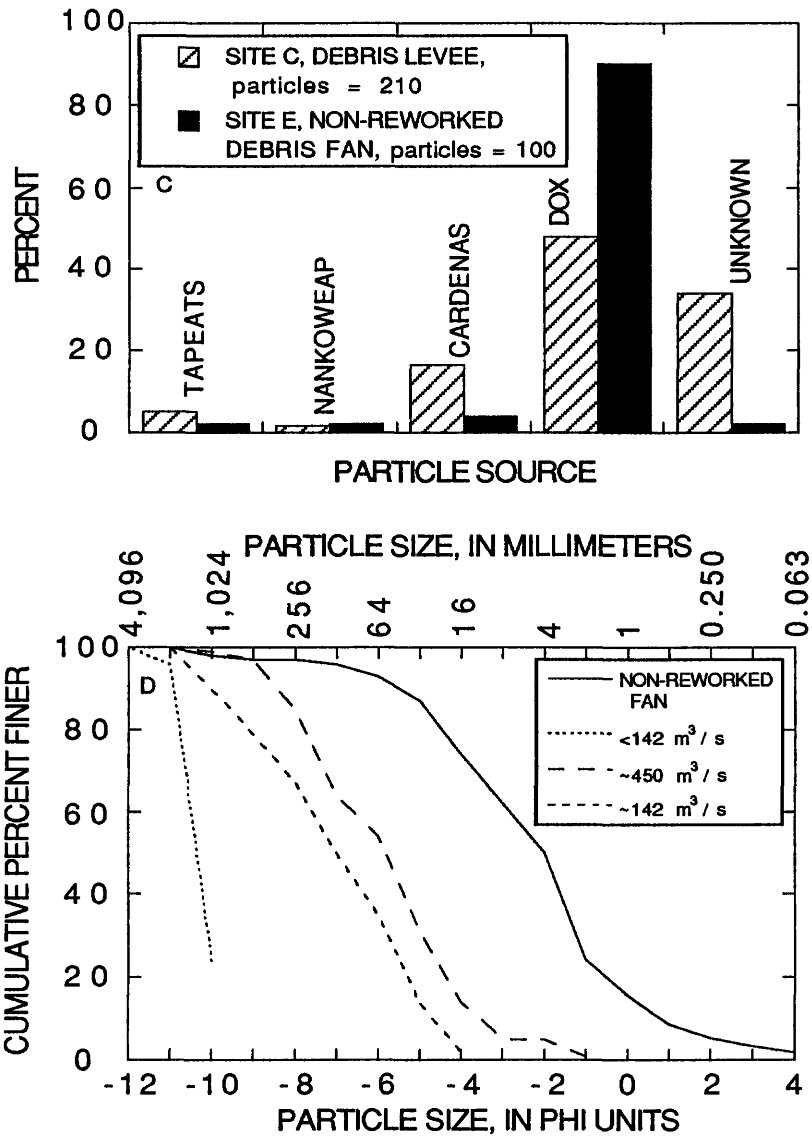
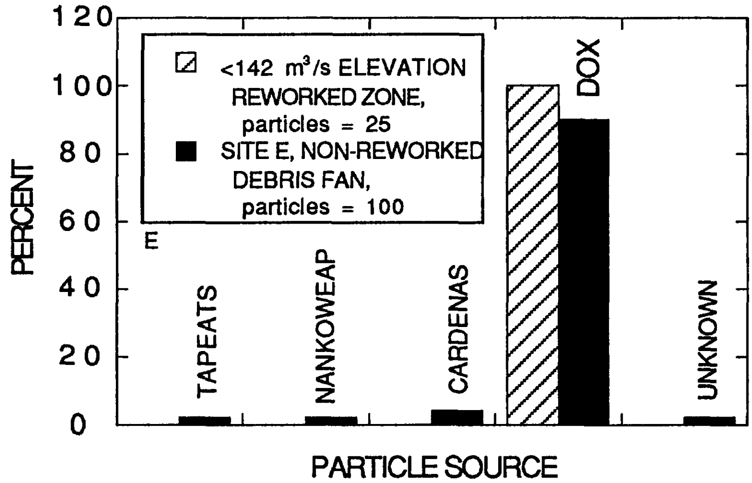


Figure 27. Particle-size and source distributions of various sediment deposits associated with the debris flow of 1984 in an unnamed tributary of the Colorado River at river mile 72.1-R. *A*, Particle-size distributions of the undisturbed 1984 deposit on the debris fan surface sampled at site E; the reworked part of the 1984 debris fan inundated by river discharges of at least 790 m^3/s between 1984 and 1993 at site E; and an undisturbed 1984 debris-flow levee at site C. *B*, Particle-size distributions of three 1984 hyperconcentrated-flow deposits.



C, Source distributions of particles sampled on the undisturbed 1984 debris fan at site E and an undisturbed 1984 debris-flow levee at site C. *D*, Particle-size distributions of the undisturbed 1984 debris fan at site E and the debris fan surfaces reworked by discharges of approximately 450, 142, and < 142 m^3/s.

Figure 27. Continued.



E, Source distributions of particles on the undisturbed debris fan at site E and the reworked debris surface at the < 142 m^3/s stage.

Figure 27. Continued.

At site A, a debris flow that was initiated in the upper parts of Canyon 3 travelled through a left-hand bend immediately upstream from the juncture with 75-Mile Creek. Evidence of superelevated flow is preserved as mudlines and scour of hillslopes along the flow margins of the channel. Using this evidence, we estimated that the debris flow attained a peak- discharge of 310 m^3/s as it entered 75-Mile Creek (table 34).

From superelevation evidence we estimated a peak discharge for the 1990 debris flow at site H of 110 m^3/s (table 35). At site I, only 0.1 km downstream, the peak discharges estimated using superelevation and runup evidence were 260 and 210 m^3/s, respectively (table 36).

Sediment Characteristics

Sediment samples of the 1990 debris flow collected for particle-size analyses included a 17-kg sample from the aggraded debris fan, a 2-kg sample of hyperconcentrated-flow deposit collected from the main channel, and a 2-kg sample of streamflow deposit collected from the main channel of 75-Mile Creek. On the basis of the dry-sieve analysis of the <64 mm component of the debris-fan sample, the 1990 debris flow contained 11 percent sand-and-finer sediment and 84 percent gravel (fig. 30A). A source distribution of the debris fan deposit (fig. 30B) indicated that the coarser component of the debris flow consisted of mainly Unkar Group rocks (fig. 3) eroded from the lower elevations of the drainage basin. The larger clasts deposited on the debris fan were probably stored in the channel and transported by the debris flow as it scoured the channel bed of 75-Mile Creek. The debris flow contained 11 to 13 percent water by weight.

Deposition on the Debris Fan

The debris-fan deposit of the 1990 debris flow had an area of 10,000 m^2, which is nearly three times larger than the 1987 debris-flow deposit. Deposition occurred mainly on the upstream part of

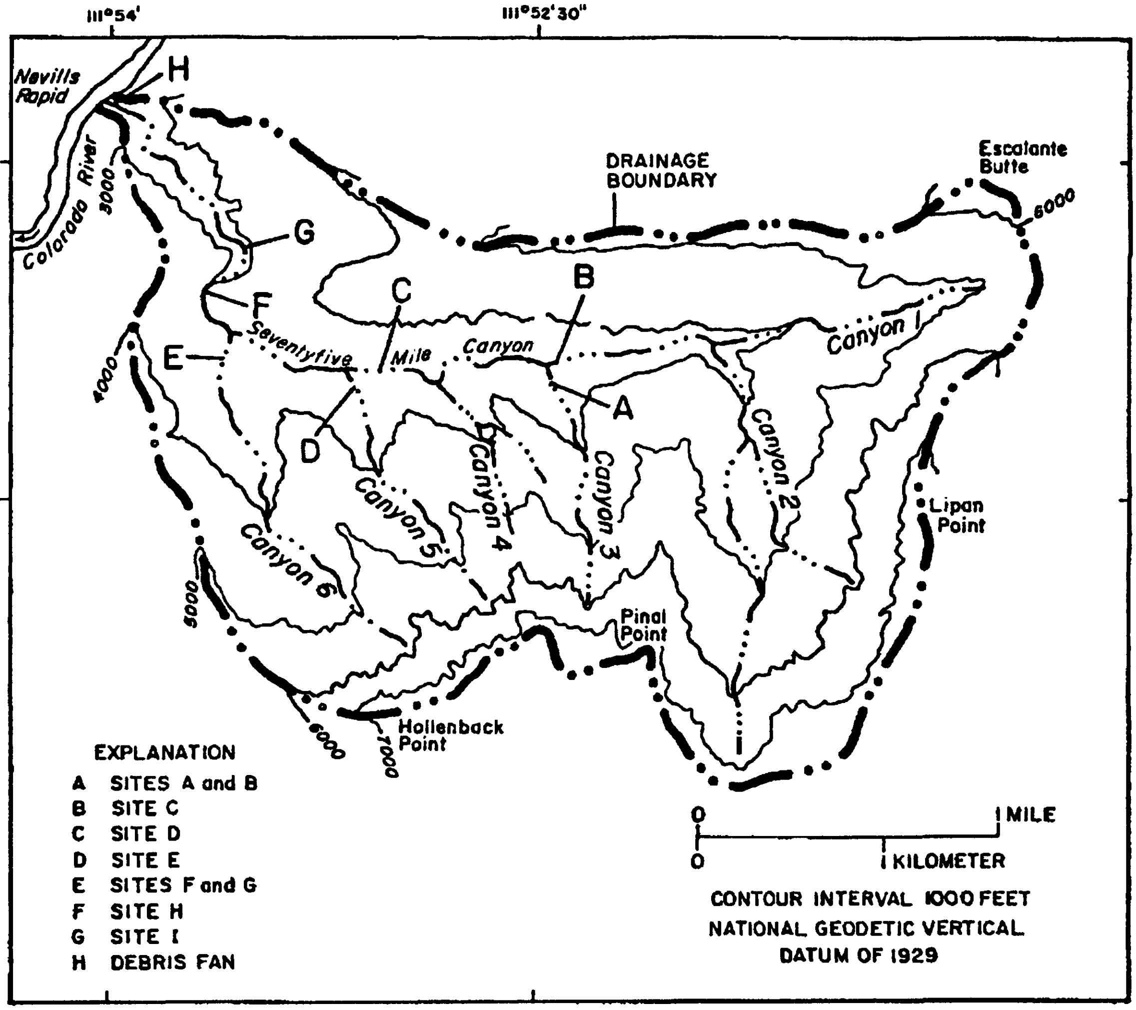


Figure 28. The drainage basin of 75-Mile Canyon (river mile 75.5-L), a tributary of the Colorado River in Grand Canyon.

Table 27. Indirect peak-discharge estimate for the streamflow flood of August 1987 in 75-Mile Creek (river mile 75.5-L), site C

Site description

Location: 75-Mile Creek, 3.8 km upstream from the Colorado River
Mean basin elevation: 1,545 m
Drainage area: 11.50 km^2
Reach description: Straight channel lined with boulders, no bedrock control present. Value represents the combined runoff from "Canyon 1" and "Canyon 2" during the debris flow of 1987.

Slope-area discharge estimate

Cross-section	Manning n-value	Area (m^2)	Conveyance	Velocity (m/s)	Froude number	Discharge (m^3/s)	Slope (m/m)
1	0.070	1.0	6.1	0.8	0.37	0.8	
2	0.070	1.2	6.4	0.8	0.35	1.0	0.08
3	0.070	1.0	4.4	0.7	0.47	0.7	

Q = 0.7 to 1.0 m^3/s (streamflow)
Site rating for estimating discharge: Fair

Table 28. Indirect peak-discharge estimate for the August 1987 debris flow in 75-Mile Creek (river mile 75.5-L), site A

[Thalweg distance, was measured for individual cross sections relative to the cross section at which ΔH_s max occurred. Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Type of estimate procedure used: superelevation in a left-hand bend
Outside high-water mark: continuous scour line with damaged plants, driftwood, and mud
Inside high-water mark: continuous scour line with mud and damaged plants
Visually estimated percentage of channel controlled by bedrock: 0 percent (alluvial channel)

Superelevation data

Radius of curvature (R_c) = 20.1 m
Maximum elevation difference (ΔH_s) = 1.6 m
Mean Velocity (V_s) = 4.0 m/s

Channel top width (W) =20.1 m
Channel slope (S) = 0.08

Cross-section data

Cross-section location	Thalweg distance, in meters	Area, in square meters	Hydraulic radius, in meters	Hydraulic depth, in meters	Flow-elevation difference, in meters	Top width, in meters
Downstream #1	23	12	0.8	0.8	0.1	15
Superelevation	0	25	1.0	2.3	1.6	24
Upstream #1	10	22	1.2	1.7	1.1	16
Upstream #2	33	14	1.1	1.4	0.7	13

Q_s = [1]52 m^3/s
Site rating for estimating discharge: Fair

[1]Based on the mean of the two cross sections with the least flow-elevation differences, L to R.

Table 29. Indirect peak-discharge estimate for the August 1987 debris flow in 75-Mile Creek (river mile 75.5-L), site B

[Thalweg distance, was measured for individual cross sections relative to the cross section at which ΔH_s max occurred. Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Location: at the juncture of "Canyon 5" and 75-Mile Creek, peak discharge is from "Canyon 5"
Estimate procedure used: runup
Outside high-water mark: mudline
Inside high-water mark: mudline
Visually estimated percentage of channel controlled by bedrock: 100 percent

Runup data

Elevation difference (ΔH_r) = 0.5 m
Mean velocity (V_s) = 3.1 m/s
Channel slope (S) = 0.05

Cross-section data

Cross-section location	Thalweg distance, in meters	Area, in square meters	Hydraulic radius, in meters	Hydraulic depth, in meters	Flow-elevation difference, in meters	Top width, in meters
Downstream #1	21	21	0.4	1.3	0.7	16
Downstream #2	11	6	0.5	0.6	0.3	14

Q_r = [1]19 m^3/s
Site rating for estimating discharge = Good

[1]Final discharge estimate based on minimum flow-elevation difference, L to R.

Table 30. Indirect peak-discharge estimate for the streamflow flood of August 1987 in 75-Mile Creek (river mile 75.5-L), site D

Site description

Location: site D, located in 75-Mile Creek between "Canyon 4" and "Canyon 5," 2.7 km upstream from the Colorado River
Mean basin elevation: 1,545 m
Drainage area: 11.50 km^2
Reach description: straight reach with about 50 percent bedrock control

Slope-area discharge estimate

Cross-Section	Manning n-value	Area (m2)	Conveyance	Velocity (m/s)	Froude number	Discharge (m^3/s)	Slope (m/m)
1	0.065	3.9	42	0.8	0.31	3	
2	0.065	3.8	43	0.8	0.31	3	0.04
3	0.065	4.3	48	0.7	0.28	3	

Q = 3 m^3/s (streamflow)
Site rating for discharge estimate: Good

Table 31. Indirect peak-discharge estimate for the streamflow flood of August 1987 in 75-Mile Creek (river mile 75.5-L), site E

Site description

Location: site E in "Canyon 5"
Mean basin elevation: 1,545 m
Drainage area: 11.50 km^2
Reach description: straight reach, 100 percent bedrock control

Slope-area discharge estimate

Cross-Section	Manning n-value	Area (m^2)	Conveyance	Velocity (m/s)	Froude number	Discharge (m^3/s)	Slope (m/m)
1	0.065	39	699	0.6	0.17	23	
2	0.065	30	494	0.8	0.23	24	0.03

Q = 23 m^3/s (streamflow)
Site rating for estimation of discharge: Fair

the debris fan between the mouth of the tributary and the river channel. An average thickness for the 1990 deposit was 1.2 m, which was determined from replicated photographs that show large boulders that were not moved during the debris flow (fig. 31). On the basis of this thickness, we estimate a minimum volume for the 1990 debris flow of 12,000 m^3. The volume of sand-and-finer sediment contained in the aggraded debris fan is 1,320 m^3, based on the 11-percent sand-and-finer sediment content of the debris-flow deposit.

Despite considerable aggradation on the debris fan, the 1990 debris flow had no obvious effect on Nevills Rapid, which is created by the debris fan of 75-Mile Creek (fig. 28). The peak discharge of the debris flow was not of sufficient magnitude or duration to transport boulders across the unconfined channel on the debris fan and into the Colorado River. The reworked appearance of the debris fan indicates that a sizable, recessional flood followed the debris flow.

Frequency

The frequency of debris flows in 75-Mile Creek is high compared to other drainages in Grand Canyon. We used mainly repeat photography to estimate the frequency of debris flows in this tributary. Historical photographs of the debris fan at this tributary show significant aggradation during the last 103 years by debris flows from 75-Mile Creek. An 1890 photograph of the debris fan that was replicated in February 1990 and February 1991 (fig. 31) shows considerable aggradation on the debris fan. In addition to deposition from the 1987 and 1990 debris flows, a pile of boulders (in the foreground of figure 31A) was most probably eroded by an earlier debris flow of unknown age.

A total of 12 historical photographs are available of Nevills Rapid and the debris fan at the mouth of 75-Mile Creek (table 37). No changes are evident in the debris fan in aerial photographs taken between 1935 and 1984; although changes associated with small debris flows might have been obliterated by river flows. On the basis of the two recent debris flows and possibly a third that may have occurred 30 to 40 years ago, 75-Mile Creek may have a debris-flow frequency of one debris flow every 10 to 15 years.

Monument Creek (River Mile 93.5-L)

The 1984 debris flow in Monument Creek has been previously described by Webb and others (1988, 1989). A large debris fan at the mouth of Monument Creek constricts the Colorado River, forming Granite Rapid (Stevens, 1990). Monument Creek drains 9.73 km^2 on the south side of the Colorado River (fig. 1). On July 25, 1984, runoff from a thunderstorm centered over the eastern part of Monument Creek caused a slope failure in the Esplanade Sandstone. The failure became an avalanche that fell 650 m and mobilized into a debris flow upon reaching the channel of Monument Creek. The debris flow traveled 4.5 km

Table 32. Indirect peak-discharge estimate for the August 1987 debris flow in 75-Mile Creek (river mile 75.5-L), site F

[Thalweg distance, was measured for individual cross sections relative to the cross section at which ΔH_s max occurred. Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Location: in "Canyon 6"
Type of estimate procedure used: superelevation in a right-hand bend
Outside high-water mark: continuous mudline
Inside high-water mark: continuous mudline
Visually estimated percentage of channel controlled by bedrock: 100 percent

Superelevation data

Radius of curvature (R_c) = 62 m
Elevation difference (ΔH_s) = 0.345 m
Mean velocity (V_s) = 4.3 m/s
Channel top width (W) = 11.2 m
Channel slope (S) = 0.07

Cross-section data

Cross-section location	Thalweg distance, in meters	Area, in square meters	Hydraulic radius, in meters	Hydraulic depth, in meters	Flow-elevation difference, in meters	Top width, in meters
Upstream	36	10	0.9	1.2	0.0	20
Superelevation	0	20	1.2	4.0	2.3	20
Downstream	14	18	1.1	1.1	0.3	21

Q_s = [1]60 m^3/s
Site rating for estimating discharge: Good

[1]Based on mean area of the two cross sections with the least flow-elevation differences, L to R

Table 33. Indirect peak-discharge estimate for the August 1987 debris flow in 75-Mile Creek (river mile 75.5-L), site G

[Thalweg distance, was measured for individual cross sections relative to the cross section at which ΔH_s max occurred. Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Location: juncture of "Canyon 3" and 75-Mile Creek
Type of estimate procedure used: runup
Channel left high-water mark: mudline
Channel right high-water mark: line of boulders and mudline
Visually estimated percentage of channel controlled by bedrock: 100 percent

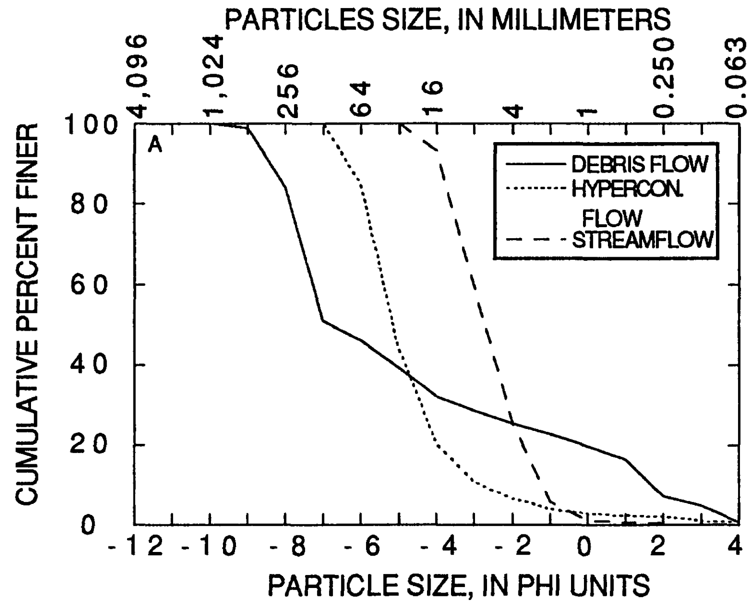
Runup data

Elevation difference (ΔH_r) = 3.0 m
Mean velocity (V_r) = 7.6 m/s
Channel slope (S) = 0.11

Cross-section data

Cross-section location	Thalweg distance, in meters	Area, in square meters	Hydraulic radius, in meters	Hydraulic depth, in meters	Flow-elevation difference, in meters	Top width, in meters
Upstream	35	32	1.3	1.4	0.5	23

Q_r = 250 m^3/s
Site rating for estimating discharge: Fair



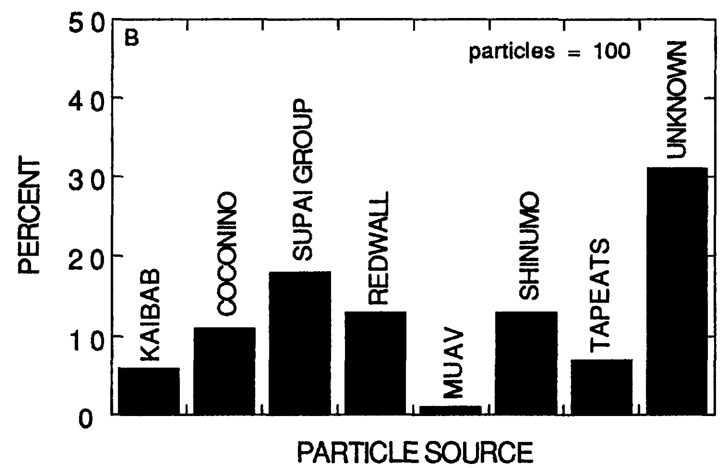


Figure 29. Particle-size and source distributions of various sediment deposits associated with the debris flow of 1987 in 75-Mile Canyon (river mile 75.5-L). *A*, Particle-size distributions of the undisturbed 1987 debris fan, a 1987 hyperconcentrated-flow deposit, and a 1987 streamflow deposit. *B*, Source distribution of particles on the 1987 debris fan.

to the Colorado River where deposition of debris on the debris fan significantly altered flow in Granite Rapid (Webb and others, 1988).

Webb and others (1989) estimated a peak discharge of about 100 to 120 m^3/s for the 1984 debris flow. The water content of the 1984 debris flow was estimated to be about 27 to 34 percent by volume. Deposition on the debris fan had an estimated volume of 6,800 m^3, of which 35 percent, or about 2,400 m^3, was sand-and-finer sediment. The clay minerals present were mainly undifferentiated micas and kaolinite with no detected montmorillonite (table 9). The activity of ^{137}Cs in one sample of debris-flow matrix from the 1984 debris flow was 0.08±0.05 pCi/g, which is consistent with the post-1952 age of this debris flow.

The frequency of debris flows in Monument Creek was determined using radiocarbon dates and a combination of repeat photography and analysis of aerial photography (table 38). One debris flow deposit of unknown magnitude yielded a radiocarbon date of 170±90 yrs BP which corresponds to a calendric age range of AD 1647 to 1955. This debris flow may have left the fresh-looking deposits that are visible in an 1872 photograph (Webb and others, 1988, 1989; appendix 6). Another debris flow that significantly aggraded the debris fan occurred between 1935 and 1973. Examination of historical photographs indicates that no debris flows occurred between 1890 and 1967. A relatively small debris flow occurred between March 1967 and September 1968 (table 38), slightly aggrading the debris fan at Granite Rapid.

The combination of photographic analysis and radiocarbon analysis indicates that debris flows have been relatively infrequent in Monument Creek in the recent geologic past. Since 1967, two debris flows have occurred, but no debris flows occurred between 1890 and 1967. The long-term average frequency of debris flows in this tributary is probably about one debris flow every 50 to 100 years.

Boucher Creek (River Mile 96.7-L)

Boucher Creek drains 16.79 km^2 on the south side of the Colorado River (fig. 1). As a result of our 1992 match of two 1890 photographs of the Boucher Canyon debris fan (appendix 4), we determined that a large, fan-forming debris flow occurred in this drainage basin. Debris-flow levees deposited by this 20th-century debris flow and three other debris flows were identified in the channel of Boucher Creek just upstream from the confluence with the Colorado River.

By examining aerial photographs taken in 1935, 1965, and 1984, we determined that the second largest debris flow in Boucher Creek occurred between 1935 and 1965. A river runner confirmed that the debris flow occurred in 1951 or 1952 (Robert Rigg, personal commun., 1994). The 1965 photograph shows many new boulders not seen in the 1935 view, and also shows a larger and different-shaped debris fan. Driftwood collected on one of the debris-flow levees was radiocarbon dated at 560±90 yrs BP, which correlates to a calendric age of AD 1295 to 1432 (appendix 7). This radiocarbon date indicates that organic material has a long residence time in the drainage basin of Boucher Creek. The ^{137}Cs activity of debris-flow sediment was 0.090±0.010 pCi/g, which is consistent with the age of the deposit. The 1951-52 debris flow deposited many large boulders on the debris fan; most are still present. The aggraded debris fan was partly reworked by Colorado River flows before closure of Glen Canyon Dam based on the bouldery texture that we measured in 1994.

Another, younger-looking, debris-flow deposit is present at the mouth of Boucher Creek. Aerial photographs indicate that the small debris flow that left the deposit occurred in the summer of 1984. Fresh-looking, non-reworked deposits are preserved above the 1,275 m^3/s stage, which also indicates the debris flow occurred after June 1983. The debris flow may have occurred on the same date as the Monument Creek debris flow of 1984 (Webb and others, 1988). A small debris flow that travelled only a short distance in 1993 was also identified. The ^{137}Cs activity of this deposit was 0.052±0.007 pCi/g.

We identified a prehistoric debris flow that occurred before the 1951 event. Driftwood collected from levees deposited by this earlier debris flow were radiocarbon dated at 375±75 yrs BP, which correlates to a calendric age of AD 1436 to 1638. The radiocarbon results from Boucher Creek do not support our interpretation of the order

Table 34. Indirect peak-discharge estimate for the September 1990 debris flow in 75-Mile Creek (river mile 75.5-L), site A

[Thalweg distance, was measured for individual cross sections relative to the cross section at which ΔH_s max occurred. Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Type of estimate procedure used: superelevation in a left-hand bend
Outside high-water mark: continuous scourline
Inside high-water mark: continuous scourline with damaged plants
Visually estimated percentage of channel controlled by bedrock: 50 percent

Superelevation data

Radius of curvature (R_c) = 17 m
Elevation difference (ΔH_s) = 7.9 m
Mean velocity (V_s) = 6.1 m/s
Channel top width (W) = 35 m
Channel slope (S) = 0.08

Cross-section data

Cross-section location	Thalweg distance, in meters	Area, in square meters	Hydraulic radius, in meters	Hydraulic depth, in meters	Flow-elevation difference, in meters	Top width, in meters
Downstream	27	35	0.3	2.2	0.9	16
Superelevation	0	116	0.8	3.4	1.5	34
Upstream	50	51	0.4	2.3	0.2	22
Average		67				

Q_s = [1]310 m^3/s
Site rating for estimating discharge: Good

[1]Final discharge estimate based on minimum flow-elevation difference, L to R.

Table 35. Indirect peak-discharge estimate for the September 1990 debris flow in 75-Mile Creek (river mile 75.5-L), site H

[Thalweg distance, was measured for individual cross sections relative to the cross section at which ΔH_s max occurred. Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Type of estimate procedure used: superelevation in a right-hand bend
Outside high-water mark: continuous mudline
Inside high-water mark: scourline with damaged plants
Visually estimated percentage of channel controlled by bedrock: 75 percent

Superelevation data

Radius of curvature (R_c) = 15 m
Elevation difference (ΔH_s) = 2.4 m
Mean velocity (V_s) = 4.8 m/s
Channel top width (W) = 15 m
Channel slope (S) = 0.054

Cross-section data

Cross-section location	Thalweg distance, in meters	Area, in square meters	Hydraulic radius, in meters	Hydraulic depth, in meters	Flow-elevation difference, in meters	Top width, in meters
Downstream	47	22	0.2	1.5	0.4	15
Superelevation	0	31	1.2	2.0	2.4	15
Upstream	21	19	1.3	1.4	0.8	13
Average		24				

Q_s = [1]110 m^3/s
Site rating for estimating discharge: Good

[1]Final discharge estimate based on minimum flow-elevation difference, L to R.

Table 36. Indirect peak-discharge estimate for the September 1990 debris flow in 75-Mile Creek (river mile 75.5-L), site I

[Thalweg distance, was measured for individual cross sections relative to the cross section at which ΔH_S max occurred. Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Type of estimate procedure used: superelevation in a left-hand bend with a runup
Outside high-water mark: continuous mudline
Inside high-water mark: continuous scourline with damaged plants
Visually estimated percentage of channel controlled by bedrock: 75 percent

Superelevation and runup data

Radius of curvature (R_c) = 26 m
Elevation difference (ΔH_S) = 2.3 m
Mean velocity (V_S) = 6.5 m/s
Channel slope (S) = 0.03

Channel top width (W) = 14 m
Elevation difference (ΔH_r) = 1.4 m
Mean velocity (V_r) = 5.2 m/s

Cross-section data

Cross-section location	Thalweg distance, in meters	Area, in square meters	Hydraulic radius, in meters	Hydraulic depth, in meters	Flow-elevation difference, in meters	Top width, in meters
Downstream	32	56	1.7	4.5	1.0	12
Superelevation	0	30	0.3	2.4	2.3	12
Upstream	40	23	0.2	0.6	1.0	38

Q_s = [1]260 m^3/s and Q_r = [1]210 m^3/s

Site rating for estimating discharge: Good

[1]Based on the mean area of upstream and downstream cross sectional areas

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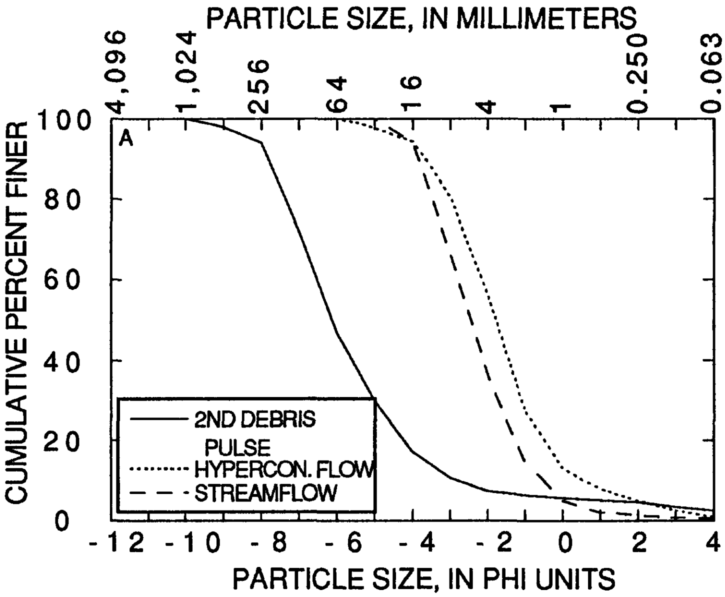
Table 37. Historical photographs of Nevills Rapid (river mile 75.5) and the debris fan at the mouth of 75-Mile Creek (75.5-L)

[For photographs taken before 1921, the discharge is estimated from known stage-discharge relations at Nevills Rapid. For photographs taken between 1921 and 1963, discharge is estimated from daily discharge records of the Colorado River at Lees Ferry. After 1963, discharge is estimated from known stage-discharge relations at Nevills Rapid. These estimates are perhaps accurate to ±1,000 ft3/s. (AV), vertical aerial photography.; (AL), photograph is an oblique aerial taken from the left side of the river; (AR), photograph is an oblique aerial taken from the right side of the river; (RL), photograph was shot from river-left; (RR), photograph was shot from river-right; (US), upstream view; (DS), downstream view; (AC), view across the river; (UC), view looking up the tributary channel or away from the river; (R), view shows a rapid; (DF), view shows debris fan(s); (SB), view shows sand bar(s); (n.d.), no data; (n.m.), the photograph was analyzed, but not matched]

Year	Date	Photographer	Original number	Stake number	Side	Direction	Subject	Discharge (ft^3/s)
1890	Jan 25	Stanton	407	1445	RL	US	R,DF,SB	4,000
	Jan 25	Stanton	408	2252	RL	DS	R,SB	4,000
1923	Aug 16	LaRue	413	1093	RL	DS	R,DF,SB	28,000
	Aug 16	Kolb	5136	1447	RL	DS	R,DF,SB	28,000
1935	Nov	Maxon	98	n.m.	AV	AV	R,DF,SB	~6,000
1963	Jun 17	Reilly	L64-33	n.m.	AL	AC	R,DF,SB	2,520
1965	May 14	WRD	139	n.m.	AV	AV	R,DF,SB	~25,000
1973	Jun 16	WRD	219	n.m.	AV	AV	R,DF,SB	~7,000
1983	Oct 23	Turner	1093	1093	RL	DS	R,DF,SB	n.d.
1984	Oct 22	GCES	3-146	n.m.	AV	AV	R,DF,SB	5,000
1990	Jan 25	Brownold	1445	1445	RL	US	R,DF,SB	n.d.
1991	Feb 10	Melis	1445	1445	RL	US	R,DF,SB	n.d.



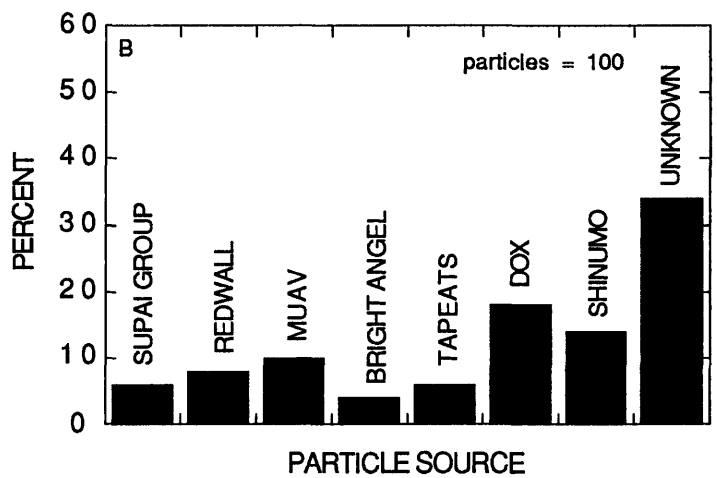


Figure 30. Particle-size and source distributions of various deposits associated with the debris flow of 1990 in 75-Mile Canyon (river mile 75.5-L). *A*, Particle-size distributions of a 1990 hyperconcentrated-flow deposit, a 1990 streamflow deposit, and the undisturbed debris fan deposited by the second debris pulse of the 1990 debris flow. *B*, Source distribution of particles sampled from the undisturbed 1990 debris fan.

in which the last two large debris flows occurred, which was based on stratigraphic superposition and aerial photography. However, this may be explained by the fact that the tree branch preserved in the stratigraphically younger, inset deposits may have had a long residence time in the drainage basin after the plant died and before it was transported by the debris flow. Radiocarbon ages of debris-flow deposits are difficult to interpret with confidence.

We measured particle-size and source distributions from the 1951 debris-fan surface and levee; the 1984 debris-flow fan deposit; a 1993 debris-flow levee deposit; and a 1993 streamflow deposit (figs. 32A, 32B, and 32C). The particle-size data for the two debris-fan surfaces and the 1993 streamflow sediments contrast greatly, as expected. Comparison of the debris-fan surfaces provides a good example of pre-dam as compared with post-dam reworking of deposits on the debris fan. We measured the ten largest boulders deposited on the debris fan by the larger debris flow and determined their lithologies (appendix 8). Most of these large particles consisted of Redwall Limestone and had b-axis diameters ranging from 1 to 4 m.

Effects on the River Channel

The 1984 debris flow had virtually no effect on Boucher Rapid. The aggradation of the debris fan consisted mainly of sand- to cobble-sized sediment. However, the debris flow that occurred between 1935 and 1965 significantly aggraded the debris fan; a reworked deposit consisting mainly of large boulders is still present. The replicate of a 1909 photograph (appendix 6) shows that the tailwaves at the bottom of Hermit Rapid (river mile 95.0-L) are no longer present (drowned out), even at nearly identical discharges in the Colorado River; Hermit Rapid is otherwise virtually unchanged. We concluded that the increased constriction of the river channel at Boucher Rapid caused by the 1951 debris flow drowned out the bottom of Hermit Rapid by increasing the base level of the river at Boucher Rapid (Webb, in press). The phenomenon of drowning out of tailwaves was originally reported at Boucher Rapid because of the debris flow of 1966 in Crystal Creek (98.2-R) (Webb, in press).

Crystal Creek (River Mile 98.2-R)

Crystal Creek, which drains 111.64 km^2 on the north side of Grand Canyon, is one of the largest tributaries of the Colorado River (fig. 1). The debris fan of Crystal Creek forms Crystal Rapid, one of the most severe reaches of whitewater in the western United States (Stevens, 1990). Intense and prolonged precipitation totalling 355 mm fell on the North Rim in early December 1966 and caused a large amount of runoff in the Crystal Creek drainage basin. In the headwaters of Dragon Creek, a major tributary of Crystal Creek, 11 failures in Hermit Shale, the Supai Group, and Muav Limestone initiated a large debris flow as a result of the storm. Cooley and others (1977), using the slope-area method, estimated a peak discharge of 822 m^3/s for the debris flow in Dragon Creek, which is the major tributary of Crystal Creek. Using superelevation and runup evidence, Webb and others (1989) estimated a peak discharge of between 260 and 400 m^3/s. Major inconsistencies and exaggerations concerning the reported hydrology of the Crystal Creek debris flow of 1966 are documented by Webb (in press).

Sediment Characteristics

The debris flow of 1966 in Crystal Creek left considerable depositional evidence. The largest boulder known to have moved during the debris flow weighed an estimated 44 Mg, and boulders with diameters in excess of 2 m are common in debris levees along Crystal Creek (Webb and others, 1989). Twenty percent of the particles in the debris flow were sand-and-finer sediment, and the water content was 24 to 33 percent. Undifferentiated micas and kaolinite dominated the suite of clay minerals in the debris flows matrix; no montmorillonite was detected (table 9). No detectable activity of ^{137}Cs was present in two samples of debris-flow matrix collected from matrix deposits of the 1966 debris flow.

We collected particle-size and source data from the reworked debris fan of the 1966 event (fig. 33A and B). The debris fan formed by the 1966 debris flow is composed mostly of Supai Group rocks with lesser amounts of Redwall Limestone clasts; its particle-size distribution is significantly coarser

Figure 31. A time series of replicate photographs showing the debris fan at 75-Mile Canyon (river mile 75.5-L). *A,* The original view was taken on January 24, 1890 (Robert Brewster Stanton, number 407, National Archives). Gravel, cobbles, and lack of sand in foreground indicates that a debris flow occurred before this view was made, but probably no earlier than June 1884, when 8,500 m^3/s reportedly flowed in the Colorado River.

B. The first replicate view was taken on January 27, 1990 (Ralph Hopkins, U.S. Geological Survey, stake 1445). The debris flow of 1987 deposited on the mid-ground; note the deposition of debris around the base of the prominent boulder at right-center in the view. Changes to boulders in the extreme foreground occurred during a debris flow on an unknown date.

Figure 31. Continued.

C. The second replicate view was taken on February 10, 1991 (T.S. Melis, stake 1445). The debris flow of 1990 deposited 12,000 m^3 of sediment on the debris fan. Deposition is particularly obvious around the prominent boulder at right center.

Figure 31. Continued.

Table 38. Historical photographs of Granite Rapid (river mile 93.5) and the debris fan at the mouth of Monument Creek (river mile 93.5-L)

[For photographs taken before 1921, the discharge is estimated from known stage-discharge relations at Granite Rapid. For photographs taken between 1921 and 1963, discharge is estimated from daily discharge records of the Colorado River near Grand Canyon. After 1963, discharge is estimated from known stage-discharge relations at Granite Rapid. These estimates are perhaps accurate to ±1,000 ft3/s. (AV), vertical aerial photography; (AL), photograph is an oblique aerial taken from the left side of the river; (AR), photograph is an oblique aerial taken from the right side of the river; (RL), photograph was shot from river-left; (RR), photograph was shot from river-right; (US), upstream view; (DS), downstream view; (AC), view across the river; (UC), view looking up the tributary channel or away from the river; (R), view shows a rapid; (DF), view shows debris fan(s); (SB), view shows sand bar(s); (n.d.), no data; (n.m.), the photograph was analyzed, but not matched]

Year	Date	Photographer	Original number	Stake number	Side	Direction	Subject	Discharge (ft^3/s)
1872	Sep 1	Hillers	871	1462	RL	US	R,DF,SB	~32,000
	Sep 1	Hillers	872	1257	RL	US	R,DF	~32,000
1890	Feb 7	Stanton	464	1458	RL	US	R,DF,SB	~5,000
	Feb 7	Stanton	465	1460	RL	AC	R,DF,SB	~5,000
	Feb 7	Stanton	466	1459	RL	DS	R,DF,SB	~5,000
1909	Nov 5	Cogswell	822	n.m.	RL	AC	R,DF	n.d.
	Nov 5	Cogswell	823	n.m.	RL	AC	R	n.d.
	Nov 5	Cogswell	824	n.m.	RL	AC	R,DF	n.d.
	Nov 5	Cogswell	825	n.m.	RL	AC	R	n.d.
	Nov 5	Cogswell	826	n.m.	RL	US	R,DF	n.d.
	Nov 5	Cogswell	827	n.m.	RL	US	R	n.d.
	Nov 5	Cogswell	828	n.m.	RL	US	R,DF	n.d.
1935	Nov	Maxon	96	n.m.	AV	AV	R,DF,SB	~6,000
1938	Jul 23	Clover	2:14:07	2735	RL	AC	R,SB,DF	n.d.
	Oct 26	Burg	n.d.	2346	RL	US	R,DF,SB	10,400
	n.d.	n.d.	16116	n.m.	RL	AC	R,DF,SB	n.d.
1941	Jul 23	Heald	5011	n.m.	RL	US	R,DF	21,300
1949	Jul	Wright	5509	n.m.	RL	AC	R	n.d.
1950	Jul 19	Reilly	R02-03	2538	RL	AC	R,DF	22,700
1955	Mar 19	Reilly	L11-22	n.m.	AR	DS	R,DF,SB	17,600
1957	Apr 14	Reilly	L28-1	n.m.	AL	AC	R,DF,SB	8,690
1962	Aug 29	Butchart	1227	2646	RL	DS	R,DF,SB	5,520
	Aug 29	Butchart	1226	2647	RL	US	R,DF,SB	5,520
1965	n.d.	WRD	n.d.	n.m.	AV	AV	R,DF,SB	28,000
1967	Mar 9	Davis	442a	n.m.	AL	AC	R,DF,SB	n.d.
	Mar 9	Davis	441a	n.m.	AR	DS	R,DF,SB	n.d.
1968	Sep 16	Stephens	871	1462	RL	US	R,DF,SB	n.d.
	Sep 16	Stephens	872	1257	RL	US	R,DF	n.d.
1973	Jun 16	WRD	266	n.m.	AV	AV	R,DF,SB	n.d.
1986	Mar 27	Turner	1257	1257	RL	US	R,DF	27,800

than undisturbed debris-flow levee deposits sampled by Webb and others (1989) from upstream on Crystal Creek.

Most of this large debris fan was inundated by dam releases up to 2,700 m^3/s between 1983 and 1986. Significant reworking of the debris fan occurred during June 1983 (Kieffer, 1985). The rock garden, a significant navigational hazard, coalesced during the 1983 dam releases. This debris bar consists mainly of large boulders of Supai Group rocks.

Analysis of historical photographs (table 39) reveals that the debris flow of 1966 was the only significant debris flow to reach the Colorado River during the last century. However, on the basis of radiocarbon dating of preserved debris-flow deposits, Webb and others (1989) found that a minimum of three debris flows have reached the Colorado River in the last 200 years. The frequency of debris flows is higher in Dragon Creek, but the debris flows occurring in this major tributary usually stop before reaching the Colorado River.

Waltenberg Canyon (River Mile 112.2-R)

Waltenberg Rapid is formed by the opposing debris fans of Waltenberg Canyon (river mile 112.2-R), which drains 14.27 km^2 on the north side of the river, and an unnamed tributary (river mile 112.2-L), which drains 1.78 km^2 on the south side of the river (fig. 1). This rapid is the most severe reach of whitewater between Crystal and Dubendorff Rapids (river miles 98 to 132; Stevens, 1990). A total of 26 historical photographs were used to reconstruct the occurrence of debris flows in Waltenberg Canyon and their effects on the Colorado River (table 40).

The largest debris flow of the last century in Waltenberg Canyon occurred between 1890 and 1923. The debris fan visible in a 1923 photograph protrudes much further into the Colorado River than it did in the 1890 view, despite a lower stage in 1890. Between 1938 and 1942, a small deposit of cobbles that appeared on the debris fan is indicative of a small debris flow. Between 1973 and 1984, another debris flow occurred that obliterated the separation bar on the downstream side of the debris fan. The historical photographs indicate that debris flows in Waltenberg Canyon may occur between one every 30 years and one every 50 years. No debris flows have occurred in the unnamed tributary at river mile 112.2-L in the last century.

119-Mile Creek (River Mile 119.0-R)

119-Mile Creek drains 2.77 km^2 on the north side of the Colorado River (fig. 1). Comparison of an 1890 photograph and a 1990 replicate view indicates that no debris flows have occurred in this tributary during the last century. Three ^{14}C samples, consisting of twigs, were collected from mudcoats preserved under overhanging bedrock walls in the main tributary channel 0.3 km upstream from the river. At this site, two distinct levels of mud coats were preserved and could be distinguished easily by color; the lower was reddish-orange and the higher was brown. Two wood samples, consisting of small twigs collected from the lower-elevation mudline, yielded radiocarbon dates of 485±105 and 420±80 yrs BP, which correspond to calendric dates of AD 1327 to 1479 and AD 1421 to 1619, respectively. Combining these samples and calibrating them yields a calendric range of AD 1421 to 1619 for the debris flow. The third sample, collected from the higher-elevation mudline, consisted of a single fragment of wood that was too small for a standard ^{14}C analysis and was analyzed using a tandem mass accelerator. A radiocarbon date of 1,032±64 yrs BP was obtained from this sample, which calibrates to a calendric range of AD 912 to 1027. Assuming we were able to date the most recent debris flows in 119-Mile Creek, two debris flows have occurred in about 1,000 years. Therefore, the frequency of debris flows in this tributary may be one debris flow every 500 years.

Forster Canyon (River Mile 122.7-L)

A debris flow occurred in Forster Canyon during September 1991 determined from reports of river guides (John Toner, oral commun., 1991) and field investigation. This tributary drains 10.04 km^2 on the south side of the Colorado River (fig. 34). The tributary drains to the northeast and has a simple configuration consisting of a main channel that bifurcates into two steeper channels near the middle portion of the drainage basin. Tapeats Sandstone and Bright Angel Shale are exposed at the confluence with the Colorado River along with extensive deposits of gravel. The eastern end of the Fossil Monocline trends southeast through the lower part of Forster Canyon. Another smaller fault trends east through the eastern part of the upper drainage; this fault is down-thrown to the south (Huntoon and others, 1986).

The source sediments for the 1991 debris flow in Forster Canyon were scoured from the higher-elevation areas of the tributary. Most of the source areas consist of talus slopes comprised of debris eroded from Supai Group rocks, Redwall Limestone, and Hermit Shale. Erosion of unconsolidated sediments has produced numerous small rills in the hillslopes throughout the drainage, particularly on those deposits overlying Hermit Shale. No evidence of rockfalls or major failures were observed in the bedrock walls of the canyon. The 1991 debris flow was initiated during intense, localized thunderstorms embedded in a pulse of regional precipitation that occurred during the first two weeks of September. Three sites were used to estimate peak discharge of the debris flow. They are all in the lower reaches of the drainage and occur in channels incised into Bright Angel Shale and Tapeats Sandstone. The recent debris flow damaged many catclaw trees growing in the streambed and deposited reddish-brown mud on the walls of the channel.

Discharge Estimates

Site A

The first of three sites used to estimate peak discharge for the 1991 debris flow occurs in a right-hand bend (fig. 34). The channel, which cuts through Tapeats Sandstone and Bright Angel Shale, is irregular, contains several large boulders, and appears to have been slightly eroded by the recent debris flow. Debris-flow deposits were completely

Table 39. Historical photographs of Crystal Rapid (river mile 98.3) and the debris fan at the mouth of Crystal Creek (river mile 98.2-R)

[For photographs taken before 1921, the discharge is estimated from known stage-discharge relations at Crystal Rapid. For photographs taken between 1921 and 1963, discharge is estimated from daily discharge records of the Colorado River near Grand Canyon. After 1963, discharge is estimated from known stage-discharge relations at Crystal Rapid. These estimates are perhaps accurate to ±1,000 ft3/s. (AV), vertical aerial photography; (AL), photograph is an oblique aerial taken from the left side of the river; (AR), photograph is an oblique aerial taken from the right side of the river; (RL), photograph was shot from river-left; (RR), photograph was shot from river-right; (US), upstream view; (DS), downstream view; (AC), view across the river; (UC), view looking up the tributary channel or away from the river; (R), view shows a rapid; (DF), view shows debris fan(s); (SB), view shows sand bar(s); (n.d.), no data; (n.m.), the photograph was analyzed, but not matched]

Year	Date	Photographer	Original number	Stake number	Side	Direction	Subject	Discharge (ft^3/s)
1890	Feb 8	Stanton	478	1471	RR	DS	R,DF,SB	~5,000
	Feb 8	Stanton	479	1472	RR	UC	DF	n.d.
	Feb 9	Stanton	480	1473	RR	UC	R,DF	n.d.
	Feb 9	Stanton	481	1467	RR	DS	R,DF	~5,000
	Feb 9	Stanton	482	1578	RR	DS	R	~5,000
	Feb 9	Stanton	482.5	1578	RR	DS	R	~5,000
	Feb 9	Stanton	483	1469	RR	DS	R,DF,SB	~5,000
1923	Aug 30	LaRue	460	2349	RR	DS	SB	15,400
	Aug 31	LaRue	461	2056	RR	AC	SB	n.d.
	Aug 30	LaRue	462	2348	RR	UC	DF	15,400
1935	Nov	Maxon	104	n.m.	AV	AV	R,DF,SB	~5,500
1958	May 21	Reilly	L38-23	2347	RR	UC	DF	n.d.
1963	Mar	Turner	n.d.	n.m.	AL	US	R,DF,SB	~5,000
	Mar	Turner	n.d.	n.m.	AL	AC	R,DF,SB	n.d.
1965	May	WRD	n.d.	n.m.	AV	AV	R,DF,SB	n.d.
1966	May 31	Butchart	2366	1466	RR	AC	R,DF	n.d.
	May 31	Butchart	2366	1268	RR	AC	R,DF	n.d.
1967	Feb 6	Aldridge	n.d.	2736	RR	AC	R,DF	n.d.
	Feb 6	Aldridge	n.d.	2737	RR	AC	R,DF	n.d.
	Mar 9	Davis	443A	n.m.	AL	US	R,DF,SB	n.d.
	Mar 9	Davis	444A	n.m.	AR	DS	R,DF,SB	n.d.
1973	Jun 16	WRD	279	n.m.	AV	AV	R,DF,SB	n.d.
1986	Apr 4	Turner	1268	1268	RR	AC	R,DF	n.d.

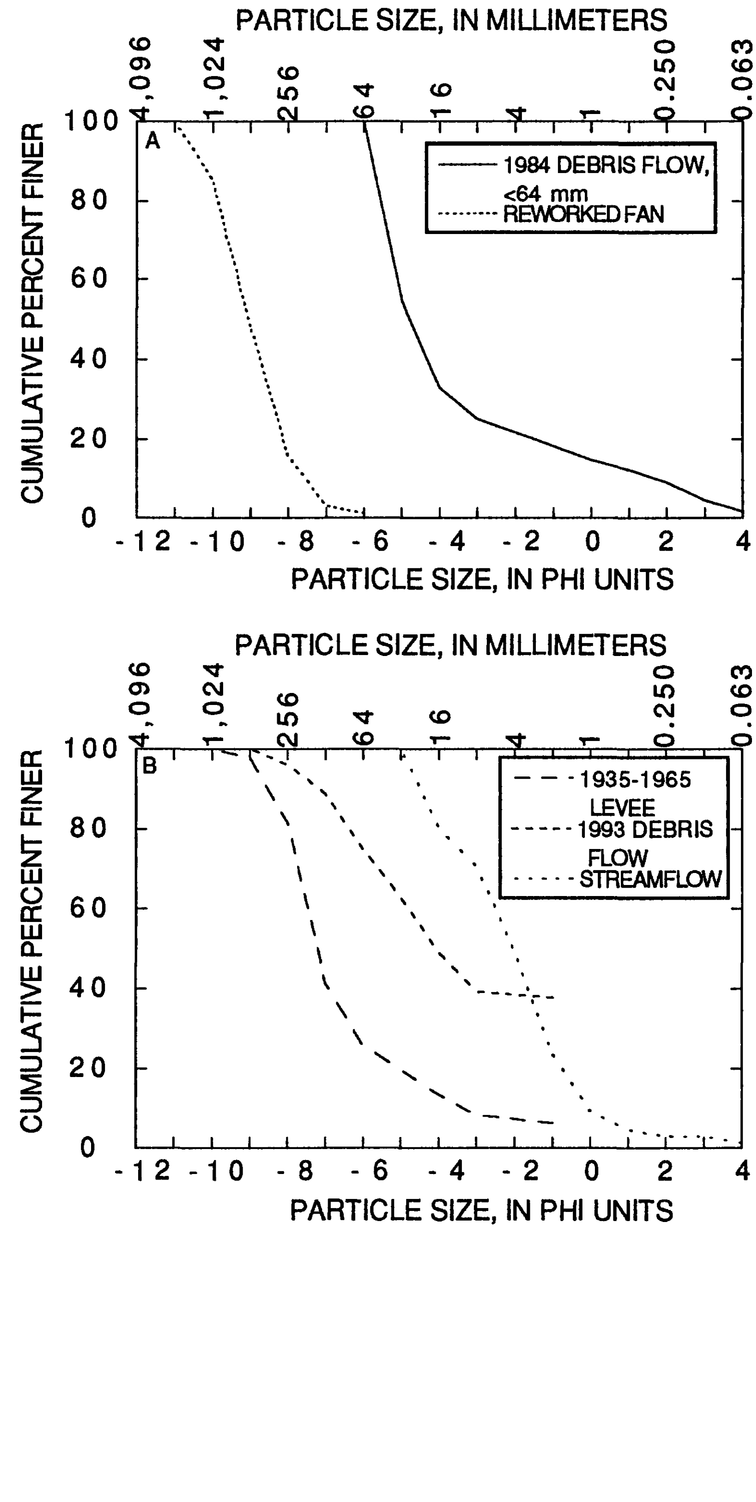
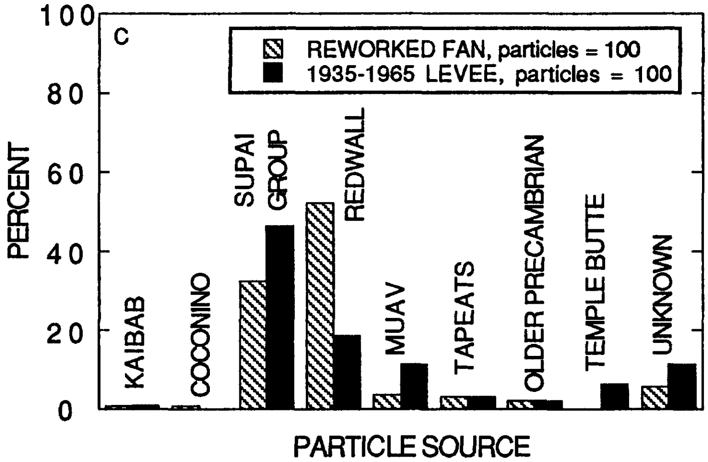


Figure 32. Particle-size and source distributions of various sediment deposits associated with debris flows that have recently occurred at Boucher Canyon (river mile 96.7-L), a tributary of the Colorado River in Grand Canyon. *A,* Particle-size distributions of an undisturbed 1984 debris-flow levee and the pre-existing, reworked debris fan. *B,* Particle-size distributions of an undisturbed debris-flow levee deposited between 1935 and 1965, a debris-flow levee deposited by the debris flow of 1993, and a 1993 streamflow deposit.



C. Source distributions of particles sampled from the pre-existing, river reworked debris-fan surface, and an undisturbed debris-flow levee deposited between 1935 and 1965.

Figure 32. Continued.

reworked by recessional streamflow. The lower parts of the mudlines on the walls were also removed by these flood waters, indicating that recessional streamflow flooding did not exceed the stage of the initial debris flow.

A mudline preserved on the outside of the bend at site A was discontinuous but clearly showed evidence of superelevated flow through the reach. The stage of recessional streamflow was indicated by an irregular scour line on the inside of the bend, mud deposits, and damaged plants. The peak discharge of the debris flow at this site was 180 m^3/s (table 41).

Site B

Site B is upstream from site A (fig. 34). This site is a moderately-uniform reach of channel with a slight, left-hand bend incised into Bright Angel Shale. A continuous mudline preserved beneath an overhanging channel wall provided evidence of superelevated debris flow. Inside flow elevations consist of a continuous scour line with damaged plants. Sediments stored in the channel also show evidence of substantial reworking owing to streamflow flooding that followed the debris flow. The peak discharge estimated from superelevation evidence was 470 m^3/s (table 42). The difference between the peak discharges estimated at sites A and B is large and cannot be explained by deposition or erosion of the channel. The apparent reduction in peak discharge indicates the high margin of error possible in estimating peak discharges at marginally suitable sites such as those in Forster Canyon.

Site C

Site C is in a left-hand bend incised into Muav Limestone (fig. 34). This bend is fairly uniform and shows little sign of erosion from the recent debris flow. Evidence of superelevated flow is preserved on the outside of the bend as a continuous mudline beneath the overhanging walls of the channel. Lowered water-surface elevations are indicated by an irregular scour line on the inside of the bend, along with deposits of mud and damaged plants. The peak discharge estimated from the superelevation evidence at this site was 170 m^3/s (table 43). Site C was judged to be a good reach for

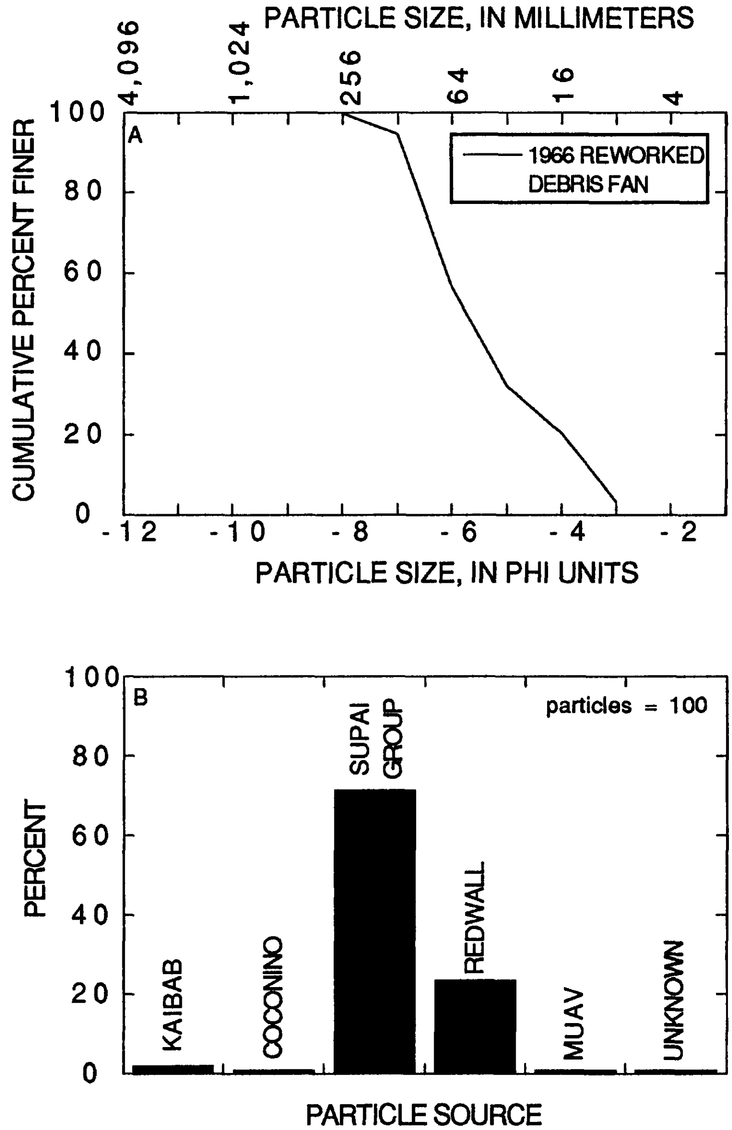


Figure 33. Particle-size and source distributions of the partially reworked debris fan deposited in 1966 at the mouth of Crystal Creek (river mile 98.2-R), a tributary of the Colorado River in Grand Canyon. *A*, Particle-size distribution of the 1966 debris fan that was reworked by discharges of the Colorado River ranging from < 142 to about 2,700 m^3/s between 1966 and 1994. *B*, Source distribution of particles on the surface of the 1966 debris fan after reworking between 1966 and 1994.

Table 40. Historical photographs of Waltenberg Rapid (river mile 112.2) and the debris fan at the mouth of Waltenberg Canyon (river mile 112.2-R)

[For photographs taken before 1921, the discharge is estimated from known stage-discharge relations at Waltenberg Rapid. For photographs taken between 1921 and 1963, discharge is estimated from daily discharge records of the Colorado River near Grand Canyon. After 1963, discharge is estimated from known stage-discharge relations at Waltenberg Rapid. These estimates are perhaps accurate to ±1,000 ft3/s. (AV), vertical aerial photography; (AL), photograph is an oblique aerial taken from the left side of the river; (AR), photograph is an oblique aerial taken from the right side of the river; (RL), photograph was shot from river-left; (RR), photograph was shot from river-right; (US), upstream view; (DS), downstream view; (AC), view across the river; (UC), view looking up the tributary channel or away from the river; (R), view shows a rapid; (DF), view shows debris fan(s); (SB), view shows sand bar(s); (n.d.), no data; (n.m.), the photograph was analyzed, but not matched]

Year Date	Date	Photographer	Original number	Stake number	Side	Direction	Subject	Discharge (ft^3/s)
1890	Feb 18	Stanton	528	2608	RR	US	SB	~6,000
	Feb 19	Stanton	529	1757	RL	AC	SB	~6,000
	Feb 19	Stanton	530	1482	RL	DS	SB	~6,000
	Feb 19	Stanton	531	1481a	RL	US	R,DF	~6,000
	Feb 19	Stanton	532	1481b	RL	DS	R,DF	~6,000
1909	Nov 7	Cogswell	872	n.m.	RL	DS	R,DF	n.d.
	Nov 7	Cogswell	873	n.m.	RR	US	R,DF	n.d.
1911	Dec 24	Kolb	294	n.m.	RL	DS	R,DF	n.d.
1923	Sep 4	LaRue	492	1789	RR	DS	R,SB	15,100
	Sep 4	LaRue	493	2350	RR	US	R,DF	15,100
	Sep 5	LaRue	494	2230	RL	DS	R,DF	13,700
	Sep 5	LaRue	496	1758	RL	DS	R,SB	13,700
	Sep 5	LaRue	497	2594	RL	DS	R	13,700
	Sep 5	LaRue	498	2229	RL	US	R,DF,SB	13,700
1927	Dec 5	LaRue	J5-J10	n.m.	RR	DS	R,DF,SB	9,370
1934	Jul 19	Fahrni	3-26	n.m.	RR	US	R,DF	1,450
	Jul 19	Fahrni	3-27	n.m.	RR	US	R,DF	1,450
1935	Nov	Maxon	135	n.m.	AV	AV	R,DF,SB	~6,000
1938	Oct 28	Burg	n.d.	3004	RL	US	R,DF	9,870
1942	Jul 22	Wilson	4:14:19	3003	RL	DS	R,DF	19,900
1962	Nov 3	Reilly	L61-22	n.m.	AR	DS	R,DF,SB	7,930
	Nov 3	Reilly	L61-20	n.m.	AL	US	R,DF,SB	7,930
1965	n.d.	WRD	n.d.	n.m.	AV	AV	R,DF,SB	28,000
1973	Jun 16	WRD	325	n.m.	AV	AV	R,DF,SB	n.d.
	n.d.	Weeden	II-60	2231	RR	DS	R,DF,SB	~5,000
1984	n.d.	GCES	n.d.	n.m.	AV	AV	R,DF,SB	~5,000

estimating peak discharge by the superelevation method and the discharge at site C is similar to the discharge estimate at site A.

Sediment Characteristics

Particle-size distributions were measured by point counts on the surfaces of the debris fan reworked before 1991; a debris-flow deposit interpreted to represent the second of two debris-flow pulses in 1991 channel-stored sediments deposited during the recessional flood; and a debris bar in the river channel immediately downstream from Forster Rapid (fig. 35A). Lateral boulder levees that were likely deposited by the initial debris-flow pulse were reworked by the recessional streamflow. The source distribution for the existing debris fan at the mouth of Forster Canyon (fig. 35B) indicates that the larger particles transported in prehistoric, fan-forming debris flows were mostly

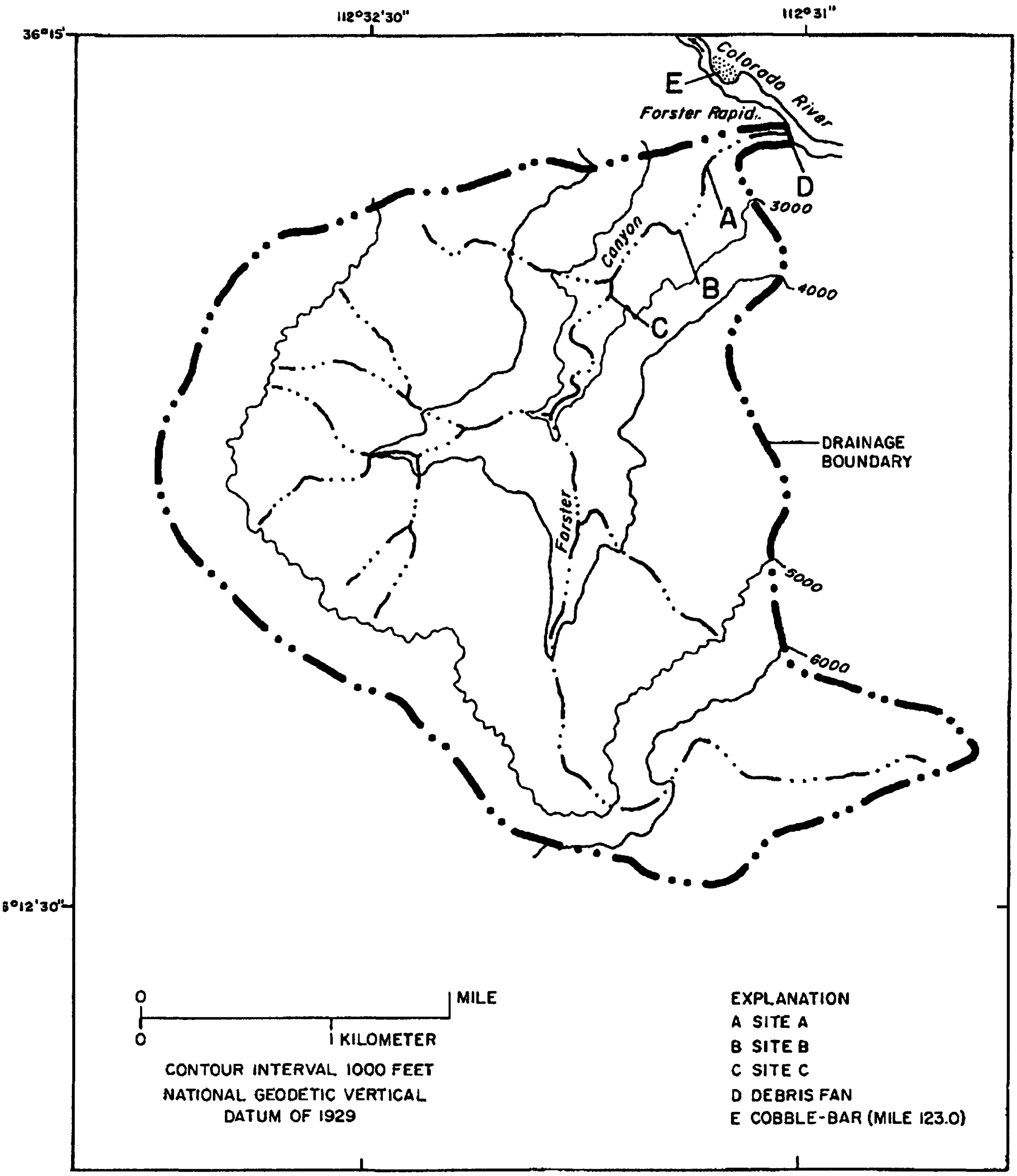


Figure 34. The drainage basin of Forster Canyon (river mile 122.7-L), a tributary of the Colorado River.

Supai Group rocks and Muav and Redwall Limestone in about equal amounts. The source distributions of the reworked debris fan and the debris bar, on river right immediately downstream from Forster Rapid (fig. 35B), show similar percentages of both Redwall Limestone and Supai Group rocks. However, the debris bar contains clasts of Kaibab Limestone, Coconino Sandstone, Bright Angel Shale, Tapeats Sandstone, and Temple Butte Limestone, which were not recorded in the surface of the reworked debris fan at Forster Creek.

Effect on the Debris Fan and River

The 1991 debris flow caused a small amount of deposition on the debris fan and did not alter Forster Rapid. The debris flow deposited poorly-sorted sediment over the existing debris-fan surface; the initial surge of the debris flow did not reach the Colorado River. Recessional streamflow reworked the debris-flow deposits and transported the finer component into the Colorado River. The volume of aggradation was not estimated owing to its small size.

Frequency

The frequency of debris flows at Forster Canyon is unknown. Although four separate photographs were taken by Robert Stanton in the vicinity of Forster Canyon in 1890, none of them clearly shows the debris fan, rapid or tributary channel mouth. No major changes in the rapid or debris fan are visible in aerial photographs taken between 1965 and 1990.

Fossil Canyon (River Mile 125.0-L)

Fossil Canyon, which drains 34.39 km^2 on the south side of the river (fig. 36), had a debris flow in early September 1989 that was followed by a much larger streamflow flood. All evidence of flow elevations for the debris flow were eroded by the recessional streamflow, although large boulders deposited at the toe of the debris fan and in Fossil Rapid (river mile 125.0) were still present in 1994. Initial debris-flow and hyperconcentrated-flow deposits are commonly completely reworked by recessional streamflow, making it difficult to estimate the peak discharge of the debris flow. Debris flows from Fossil Canyon have produced one of the largest debris fans in this reach of the Colorado River (Reach 7, river miles 115.8 to 125.0), yet the geomorphic history of this debris fan is unknown.

Boulder Transport

The ten largest boulders deposited at the river by the 1989 debris flow were measured and classified by stratigraphic source (appendix 8). These boulders ranged in weight from 5 to 25 Mg. Several of the largest boulders transported by the debris flow were deposited in the upper-left side of Fossil Rapid and therefore could not be accurately measured. These clasts constricted the top of the rapid, creating new lateral waves at the head of the rapid.

Frequency

About 0.3 km upstream from the Colorado River, a series of debris-flow deposits are preserved in an alcove on the left side of Fossil Creek (fig. 36). Twigs lying on the surface of the highest debris flow deposit were deposited there during large streamflow that preceded the 1989 flood. These twigs were radiocarbon dated at 240±100 yrs BP (fig. 37), which calibrates to a calendric date range of AD 1516 to 1955. Two debris-flow deposits contained organic material consisting of small woody twigs (fig. 37). Several twigs contained in the highest deposit were collected and randomly split into three samples that yielded radiocarbon dates of 410±100, 395±80, and 380±100 yrs BP. By averaging and calibrating these radiocarbon dates, we obtained a calendric age range of AD 1437 to 1618 (appendix 7). We therefore conclude that the last major debris flow at Fossil Canyon before 1989 occurred 350 to 400 years ago. A large stick buried in a debris-flow levee from a stratigraphically lower deposit (fig. 37) was radiocarbon dated at 865±60 yrs BP, which calibrates to a calendric date of AD 1041 to 1255. These two units appear stratigraphically distinct; the radiocarbon dates support this interpretation. Therefore, we conclude that at least three debris flows have occurred in

Table 41. Indirect peak-discharge estimate for the September 1991 debris flow in Forster Canyon (river mile 122.7-L), site A

[Thalweg distance, was measured for individual cross sections relative to the cross section at which ΔH_s max occurred. Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Type of estimate procedure used: superelevation in a right-hand bend
Outside high-water mark: discontinuous mudline
Inside high-water mark: continuous scourline
Visually estimated percentage of channel controlled by bedrock: 75 percent

Superelevation data

Radius of curvature (R_c) = 23 m
Elevation difference (ΔH_s) = 3.3 m
Mean velocity (V_s) = 6.1 m/s
Channel top width (W) = 20 m
Channel slope (S) = 0.041

Cross-section data

Cross-section location	Thalweg distance, in meters	Area, in square meters	Hydraulic radius, in meters	Hydraulic depth, in meters	Flow-elevation difference, in meters	Top width, in meters
Downstream	21	29	0.3	2.7	2.7	11
Superelevation	0	80	0.6	4.0	3.3	20
Upstream	14	90	0.7	4.4	3.0	21

Q_s = [1]180 m^3/s
Site rating for estimating discharge: Poor

[1]Final discharge estimate based on minimum flow-elevation difference, L to R

Table 42. Indirect peak-discharge estimate for the September 1991 debris flow in Forster Canyon (river mile 122.7-L), site B

[Thalweg distance, was measured for individual cross sections relative to the cross section at which ΔH_s max occurred. Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Type of estimate procedure used: superelevation in a left-hand bend
Outside high-water mark: discontinuous mudline
Inside high-water mark: continuous scourline
Visually estimated percentage of channel controlled by bedrock: 50 percent

Superelevation data

Radius of curvature (R_c) = 23 m
Elevation difference (ΔH_s) = 2.5 m
Mean velocity (V_s) = 6.3 m/s
Channel top width (W) = 14 m
Channel slope (S) = 0.045

Cross-section data

Cross-section location	Thalweg distance, in meters	Area, in square meters	Hydraulic radius, in meters	Hydraulic depth, in meters	Flow-elevation difference, in meters	Top width, in meters
Downstream	15	49	2.7	3.6	2.3	14
Upstream	6	74	0.3	5.0	2.0	15

Q_s = [1]470 m^3/s
Site rating for estimating discharge: Poor

[1]Final discharge estimate based on minimum flow-elevation difference, L to R

Table 43. Indirect peak-discharge estimate for the September 1991 debris flow in Forster Canyon (river mile 122.7-L), site C

[Thalweg distance, was measured for individual cross sections relative to the cross section at which ΔH_s max occurred. Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Type of estimate procedure used: superelevation in a left-hand bend
Outside high-water mark: discontinuous mudline
Inside high-water mark: discontinuous scourline.
Visually estimated percentage of channel controlled by bedrock: 75 percent

Superelevation data

Radius of curvature (R_c) = 26 m
Elevation difference (ΔH_s) = 3.4 m
Mean velocity (V_s) = 6.6 m/s
Channel top width (W) = 20 m
Channel slope (S) = 0.036

Cross-section data

Cross-section location	Thalweg distance, in meters	Area, in square meters	Hydraulic radius, in meters	Hydraulic depth, in meters	Flow-elevation difference, in meters	Top width, in meters
Downstream	21	26	1.6	2.2	2.5	12
Upstream	17	44	0.4	2.4	3.1	18

Q_s = [1]170 m^3/s

Site rating for estimating discharge: Good

[1]Final discharge estimate based on minimum flow-elevation difference, L to R.

Fossil Canyon during the last millennium at a frequency of about one every 300 to 400 years.

Unnamed Tributary at River Mile 126.9-L

A debris flow occurred in a small, unnamed tributary at river mile 126.9-L (fig. 38) in late August 1989. The debris flow was initiated in colluvium at the base of cliffs of Redwall Limestone and deposited a lobe of sediment over an existing debris fan at the Colorado River. This tributary, which drains 0.57 km^2 on the west side of the river, is directly across from Hundred and Twenty-Seven-Mile Creek. The unnamed tributary consists of a main channel formed by the coalescence of two small, steep channels that head beneath cliffs of Redwall Limestone (fig. 38). No major geologic structures have been mapped in this tributary, although a small west-trending reverse fault crosses the Colorado River immediately upstream from the drainage basin (Huntoon and others, 1986).

Discharge Estimate

At site A, the channel bends to the right just above a waterfall in Tapeats Sandstone (fig. 38). Superelevation evidence here is preserved as discontinuous mudlines under overhanging ledges of this sandstone on both sides of the channel. Using this evidence, we estimated a peak discharge of 180 m^3/s for the debris flow of 1989 (table 44).

Sediment Characteristics

Particle-size and source data were collected from the surface of an undisturbed debris-flow levee preserved at site A and from the distal edge of the reworked debris fan (fig. 39A). The initial pulse of debris flow contained only about 3 to 4 percent sand-and-finer sediment; the reworked particle-size data reflects the effects of dam releases between about 90 and 850 m^3/s that occurred from autumn 1989 to summer 1991 and flows of between 142 and 566 m^3/s from autumn 1991 to spring 1994. The coarser particles sampled from the debris-flow levee are mostly of Muav Limestone with smaller

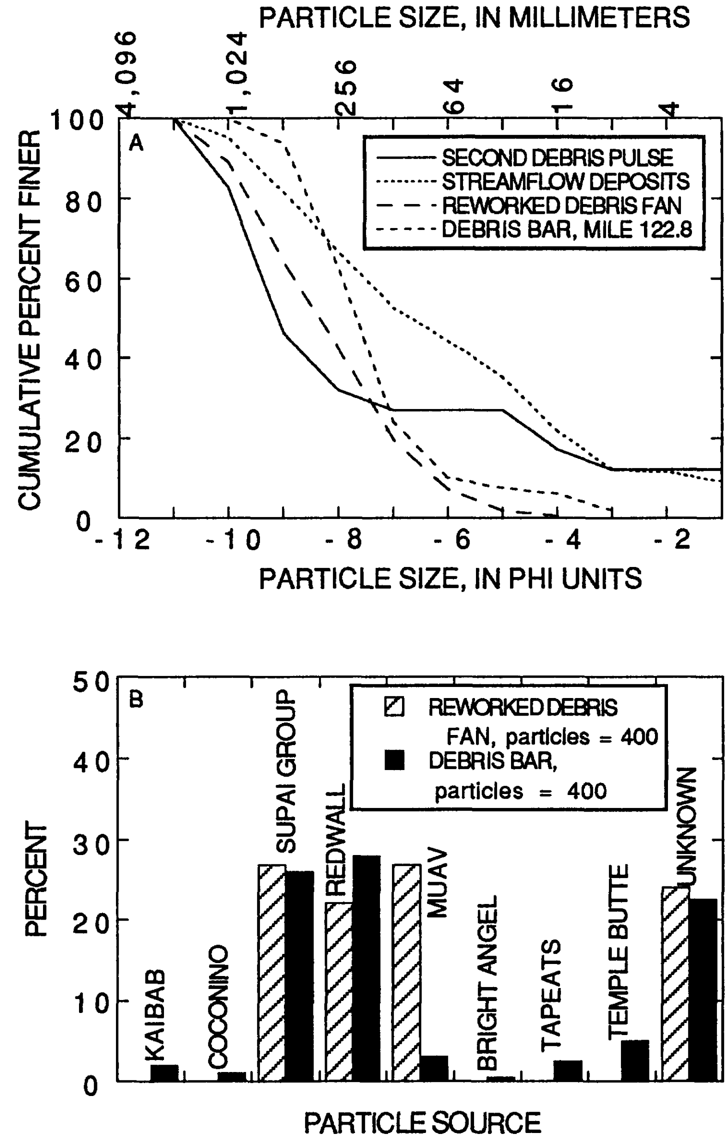


Figure 35. Particle-size and source distributions of various sediment deposits associated with the debris flow of 1991 in Forster Canyon (river mile 122.7-L). *A*, Particle-size distributions of the undisturbed 1991 deposit associated with the second debris-flow pulse, a 1991 streamflow deposit, the pre-existing, reworked debris fan and the debris bar downstream at river mile 122.8. *B*, Source distributions of particles on the pre-existing, reworked debris fan and the debris bar downstream at river mile 122.8.

but equal amounts of Supai Group and Redwall Limestone (fig. 39B). The largest boulders deposited on the debris fan ranged in weight from 3 to 24 Mg (appendix 8).

Frequency

The frequency of debris flows in this tributary was determined using aerial photography. By analyzing aerial photographs taken in 1935, 1965, 1973, and 1984, we concluded that no debris flows had occurred in the 64 years preceding the 1989 flood. Therefore, the recurrence interval for debris flows in the unnamed tributary at river mile 126.9-L may be one debris flow per 60 years, and is probably on the order of one debris flow per century, based on debris-flow frequency data collected from other drainage basins in this part of Grand Canyon.

Unnamed Tributary at River Mile 127.3-L

A debris flow occurred in an unnamed tributary at river mile 127.3-L (fig. 40) during the first two weeks of September 1989. The debris flow was initiated during the same storm that caused the debris flow at river mile 126.9-L. The debris flow deposited a small, new debris fan at the Colorado River. This tributary drains 0.76 km^2 on the west side of the river, with headwaters stretching to the top of Stanton Point. The drainage basin has a main channel formed from two smaller, steeper channels directly below Redwall Limestone cliffs (fig. 40).

Source sediment for the 1989 debris flow was derived from both the upper and lower elevations of the drainage basin, based on aerial reconnaissance in 1991. Colluvium deposited in the lower areas of the drainage basin provided most of the sediment for the debris flow. These source sediments were eroded from colluvial wedges deposited over bedrock hillslopes of Muav Limestone. Most of the sediment was eroded and mobilized by cascading streamflow and debris flow originating from above the cliffs of Redwall Limestone. The debris flow was initiated above these cliffs on the north side of the basin. Comparison of aerial photographs showing the lower reaches of the basin taken in May 1988 and October 1989 and test pits showed up to 3 to 4 m of aggradation in the main channel of the tributary. Aerial photographs taken in 1935 show that no debris fan was present at river mile 127.3-L and presumably no debris fan was present between 1935 and 1988 because none is visible in subsequent photographs up to October 1988.

Estimate of Sediment Yield from Hillslopes

An estimate was made for sediment yielded from the lower source areas of the drainage. Scour, indicated by plant damage and fresh slope cuts, is obvious on the talus slopes and was the basis of the estimates. A minimum of 4,000 to 5,000 m^3 of sediment was removed from the hillslope deposits overlying Muav Limestone; channel slopes in these source areas have gradients of 20 to 30 degrees and debris flows were mobilized by fire-hose effects.

Test pits excavated into the alluvial channel immediately upstream from the debris fan revealed an alternating sequence of matrix-supported debris-flow sediments and open-matrix gravel and sand. Approximately 6,000 to 7,000 m^3 of gravel was deposited in the main channel of the creek between the sediment source areas and the debris fan. The surface of the channel deposits was clearly reworked by recessional flow, but the interior of the deposits consisted of a finer-matrix sediment to a depth of 0.20 m. Further excavation showed depositional evidence of an intermediate period of reworking between two periods of debris flow surge.

Discharge Estimate

Only one site, in the main channel of the tributary, was suitable for estimating a peak discharge for the 1989 debris flow. Site A (fig. 40) consists of superelevated mudlines preserved on the outside of a right-hand bend. Debris-flow evidence includes abundant deposits, scoured terraces, and damaged plants on the inside of the channel. The channel is bedrock-controlled (Tapeats Sandstone) at this site and is fairly uniform in shape and size. At site A, a continuous mudline is preserved on the outside of the bend under overhanging ledges of Tapeats Sandstone. We estimated a peak discharge for the debris flow of 260 m^3/s (table 45).

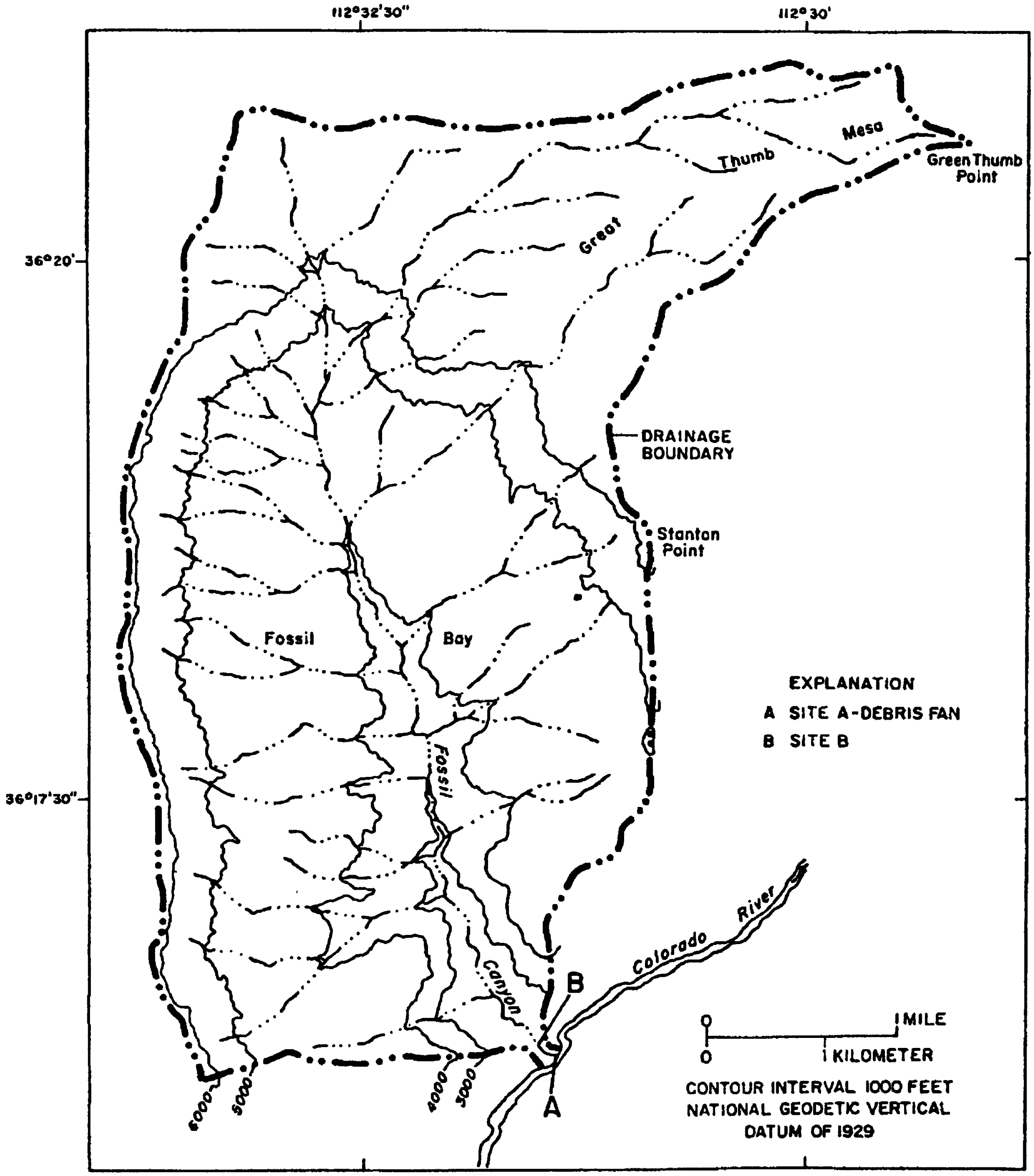


Figure 36. The drainage basin of Fossil Canyon (river mile 125.0-L), a tributary of the Colorado River in Grand Canyon.

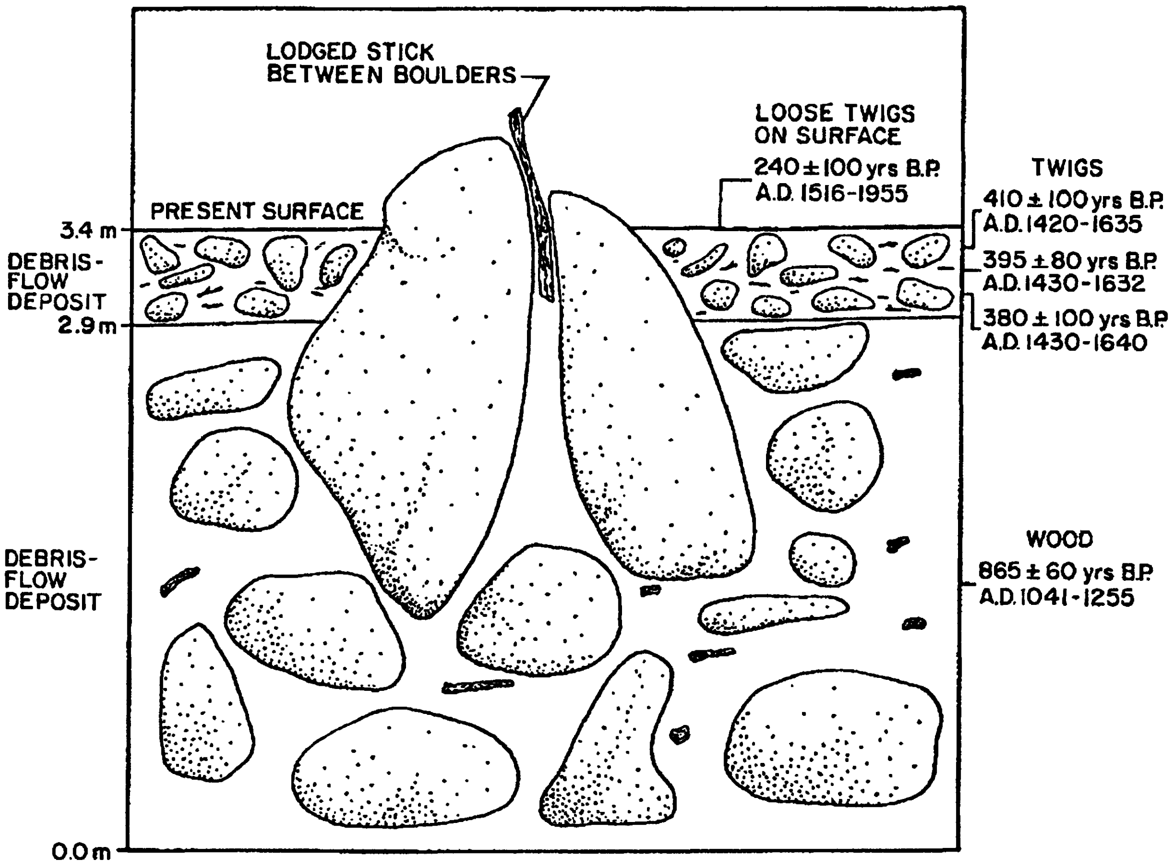


Figure 37. Stratigraphic diagram of debris-flow deposits in Fossil Canyon.

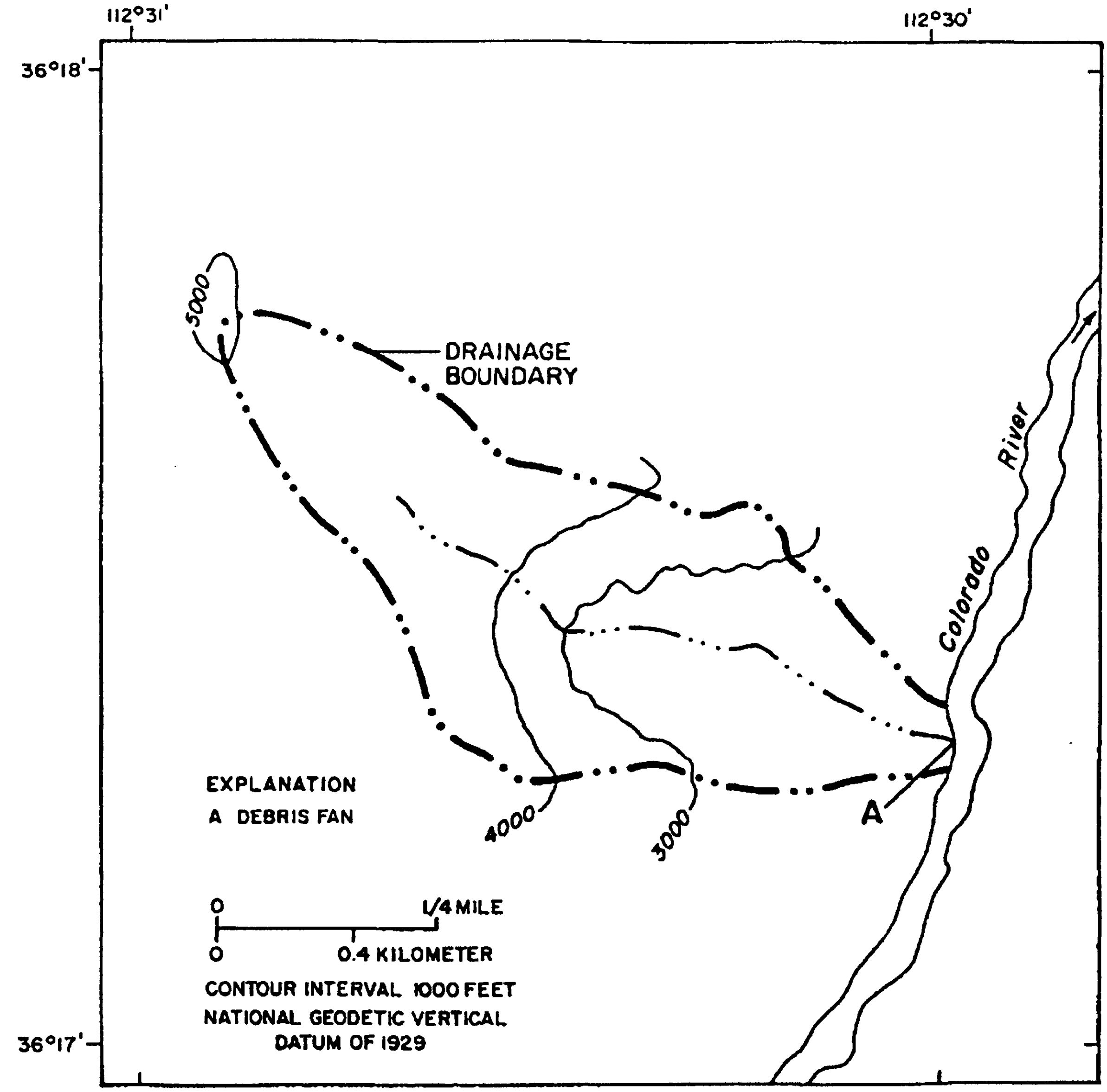


Figure 38. The drainage basin of an unnamed tributary of the Colorado River at river mile 126.9-L in Grand Canyon.

Table 44. Indirect peak-discharge estimate for the September 1989 debris flow in an unnamed tributary at river mile 126.9-L, site A

[Thalweg distance, was measured for individual cross sections relative to the cross section at which ΔH_s max occurred. Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Type of estimate procedure used: superelevation in a right-hand bend
Outside high-water mark: discontinuous mudline
Inside high-water mark: discontinuous mudline
Visually estimated percentage of channel controlled by bedrock: 100 percent

Superelevation data

Radius of curvature (R_c) = 8 m
Elevation difference (ΔH_s) = 3.8 m
Mean velocity (V_s) = 5.2 m/s

Channel top width (W) = 11
Channel slope (S) = 0.14

Cross-section data

Cross-section location	Thalweg distance, in meters	Area, in square meters	Hydraulic radius, in meters	Hydraulic depth, in meters	Flow-elevation difference, in meters	Top width, in meters
Superelevation	0	27	0.2	2.5	3.7	11
Upstream	12	35	0.3	3.4	1.9	10

Q_s = [1]180 m^3/s
Site rating for estimating discharge: Good

[1]Final discharge estimate based on minimum flow-elevation difference, L to R.

Sediment Characteristics

Several sediment samples were collected from the 1989 debris-flow deposits. These included an 11-kg debris-flow sample collected from a debris-flow levee in the main tributary channel upstream from the debris fan; point-count data for the undisturbed surface of the debris fan; and samples of both hyperconcentrated-flow and streamflow sediments. The fraction of the sample <64 mm collected from the debris fan contained 20 percent sand-and-finer sediment. Particle-size data collected from the non-reworked debris fan surface, the reworked distal edge of the debris fan, and other related deposits, in March 1994 indicate that significant reworking of the deposit has occurred since 1989 (fig. 41A and 41B). A source distribution for the coarse part of the debris flow (fig. 41C) indicates that the debris flow consisted mainly of Muav and Redwall Limestone clasts, with lesser amounts of Supai Group rocks. On the basis of reconstitution, the debris flow sample contained 14 to 17 percent water by weight. Five of the largest boulders deposited on the debris fan, which were Redwall Limestone, had an average b-axis diameter of about 1.4 m and ranged in weight from 2.6 to 23 Mg (appendix 8).

Deposition of the Debris Fan

The 1989 debris flow deposited a new debris fan at the confluence of the tributary and the Colorado River. Aerial photographs taken of the site in 1988 show only a small deposit of boulders before the 1989 debris flow; two small sand bars present in 1988 were buried by the new deposits. The surface of the present debris-fan deposit contains well-sorted gravel. No intact debris-flow deposits were found on the debris-fan surface; however, intact debris-flow deposits were found 0.4 m beneath the surface. The new debris fan was first visited about five weeks after the debris flow occurred. Point counts of the 1989 debris-fan surface revealed a particle-size distribution for the coarser component of the debris flow which was partly reworked by streamflow that followed the initial pulse of the debris flow (fig. 41A). After 1989, several occurrences of streamflow and (or) hyperconcentrated flow from the tributary deposited additional sediments on the debris fan.

A test pit with an area of 0.5 m² was excavated into the 1989 debris fan. The stratigraphy of sediments in the debris fan showed an upper 0.2 m of streamflow deposits underlain by 0.4 m of transitional sediments indicative of hyper-

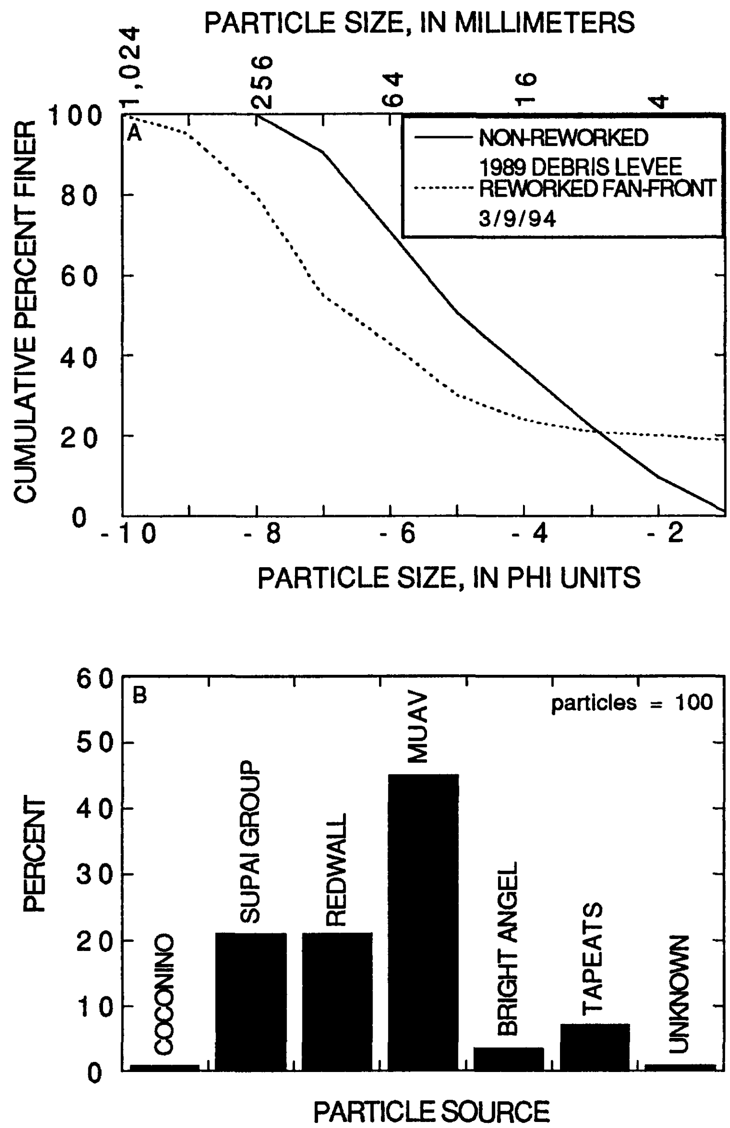


Figure 39. Particle-size and source distributions of various sediment deposits associated with the debris flow of 1989 that occurred in an unnamed tributary of the Colorado River at river mile 126.9-L. *A*, Particle-size distributions of an undisturbed 1989 debris-flow levee and the reworked, distal edge of the 1989 debris fan that was inundated by Colorado River discharges of < 142 to about 935 m^3/s between 1989 and 1994. *B*, Source distribution of particles on the undisturbed 1989 debris fan.

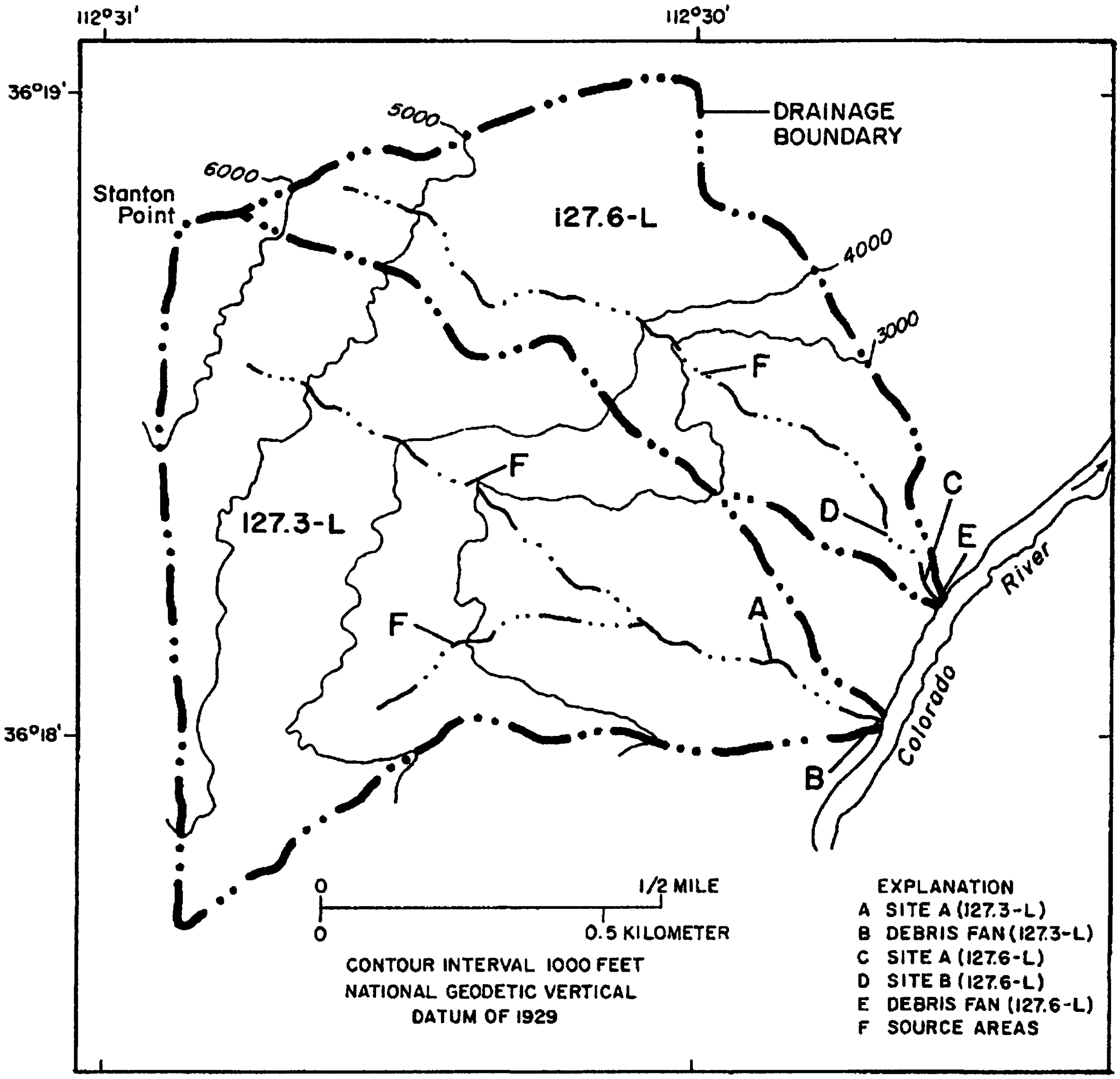
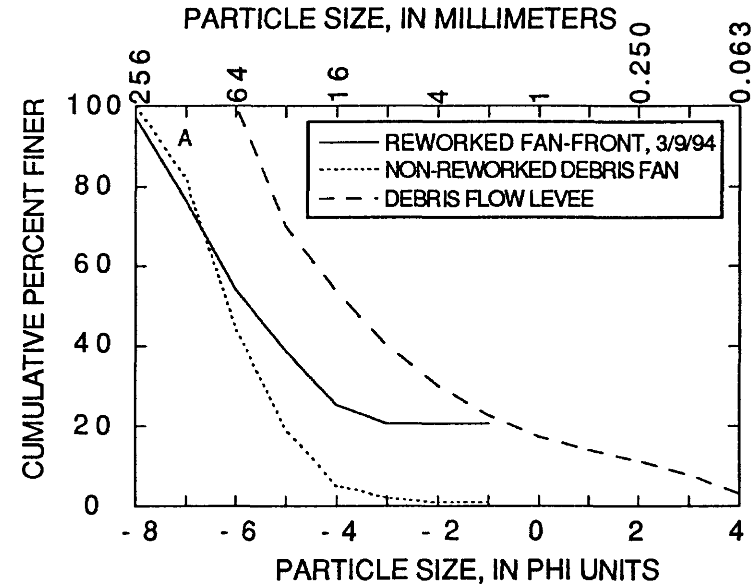


Figure 40. The drainage basins of unnamed tributaries of the Colorado River at river miles 127.3-L and 127.6-L in Grand Canyon.



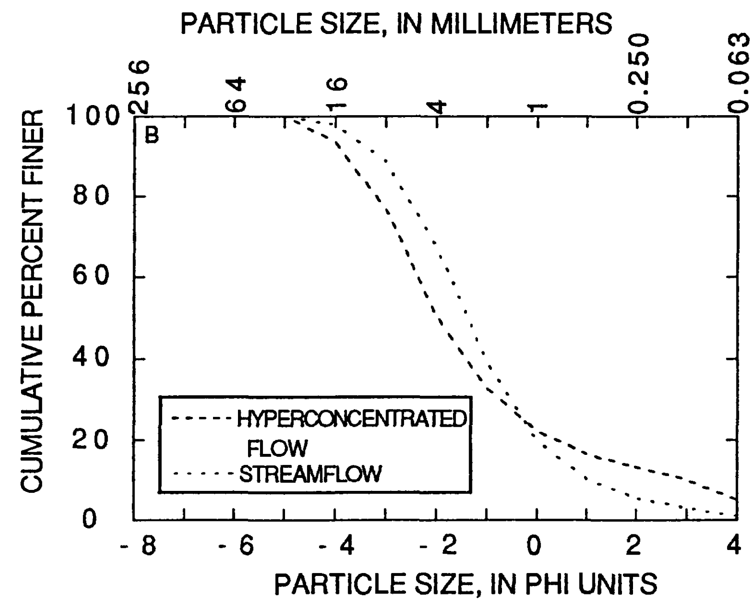
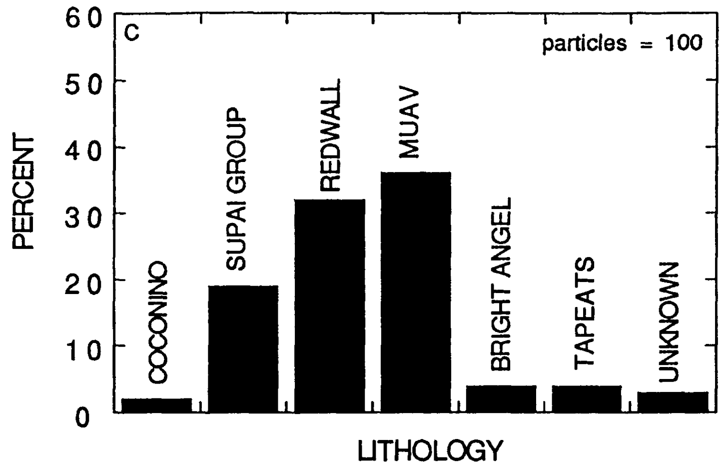


Figure 41. Particle-size and source distributions of various sediment deposits associated with the debris flow of 1989 in an unnamed tributary of the Colorado River at river mile 127.3-L. *A*, Particle-size distributions of the reworked, distal edge of the 1989 debris fan, the undisturbed 1989 debris-flow deposit, and an undisturbed 1989 debris-flow levee. *B*, Particle-size distributions of a 1989 hyperconcentrated-flow deposit and a 1989 streamflow deposit.



C, Source distribution of particles on the undisturbed 1989 debris-flow deposit.

Figure 41. Continued.

concentrated flow. Underlying these strata was a layer of matrix-supported debris-flow deposits containing large boulders; the lower limit of this layer could not be determined by excavation. Point-count data collected at a depth of 0.4 m beneath the surface of the test pit indicated that most of the particles in the hyperconcentrated flow were Muav Limestone (fig. 41B).

Estimated Volume of the 1989 Debris Fan

The area of the 1989 debris-fan deposit at the mouth of the unnamed tributary at river mile 127.3-L was 1,600 m^3. The elevations measured along the front of the debris fan were made at about the elevation of 250 to 300 m^3/s discharge in the Colorado River. The average thickness of the debris fan was estimated to be about 5.3 m, using the estimated burial depth of prominent bedrock outcrops visible in pre-1989 aerial photographs. The estimated volume of the new debris fan is about 8,500 m^3; 1,700 m^3 of the deposit is sand-and-finer sediment.

Frequency

The frequency of debris flows in the unnamed tributary at river mile 127.3-L was estimated using a combination of aerial photography and radiocarbon dating. Aerial photographs taken between 1935 and 1988 show no significant changes to the stream channel or the debris fan. The 1935 photograph clearly shows a prominent outcropping of amphibolite rock surrounded by sand in the present location of the new debris fan. On the basis of these photographs, no debris flows had occurred at this drainage between 1935 and 1989. In addition, the 1935 photographs show no evidence that a debris flow had occurred before that date. Therefore, the frequency of debris flows in this tributary may be one debris flow per 60 years or less.

Debris flows in the unnamed tributary at river mile 127.3-L periodically buried packrat middens that were built on a vertical wall downstream from site A. Burial occurred at least three times; after the midden was initially buried by a thin layer of matrix mud, the rodents reoccupied the location and continued accumulating organic materials until the next debris flow occurred. This stratigraphic arrangement of packrat middens and debris-flow deposits was used to estimate the frequency of debris flows in this tributary. The lowermost packrat midden had a radiocarbon age of 3,050±130 yrs BP, which calibrates to a calendric date range of BC 1488 to 1110. The radiocarbon date, therefore, signifies a record length of 3,015 to 3,538 years in this tributary. The two intermediate packrat middens were radiocarbon dated at 2,945±130 and 2,685±150 yrs BP, which calibrate to BC 1387 to 943 and BC 1010 to 664, respectively (appendix 7). During the period represented by these packrat middens, the frequency of debris flows is about one every 200 years. The stage of the 1989 debris flow was only slightly lower in elevation than the packrat midden and did not inundate that location. However, it did dislodge the large boulder that shielded the midden, exposing it to weathering.

"127.6-Mile Canyon" (River Mile 127.6-L)

In 1989, a debris flow occurred in 127.6-Mile Canyon, a tributary that drains 1.75 km^2 on the west side of the river on the eastern flank of Stanton Point (fig. 40). This ephemeral stream has a main channel that splits into two smaller, steep channels immediately downstream from cliffs formed by Redwall Limestone. No major geologic structures have been mapped in this drainage (Huntoon and others, 1986).

The 1989 debris flow in 127.6-Mile Canyon probably occurred during the same storm that initiated the debris flows in the unnamed tributaries at river miles 126.9-L and 127.3-L. The debris flow caused significant aggradation on an existing debris fan and formed a new rapid in the Colorado River. The debris flow was mostly initiated above the Redwall Limestone, apparently in talus slopes overlying Hermit Shale. Additional source sediment for the debris flow was eroded from the lower section of the drainage. Fire-hose effects, from runoff falling over cliffs of Redwall Limestone, initiated failures in colluvial wedges deposited on slopes of Muav Limestone, and significantly contributed to the debris flow. Aerial photographs taken in May 1988 and October 1989 showed that the main channel of the basin was also aggraded by at least 3 m during the debris flow.

Estimates of Sediment Yielded from Hillslopes

The sediment yield from 127.6-Mile Canyon was estimated from zones of scour in the colluvial wedges overlying Muav Limestone in the lower basin. Scour was obvious in the colluvial wedges, and erosional evidence included fresh gullies, damaged plants, and exposed roots. On the basis of several estimates from different parts of the basin, 4,000 to 5,000 m^3 of sediment was eroded from the colluvial wedges.

Test pits excavated in the channel upstream from the debris fan revealed a transition between matrix-supported debris-flow deposits and open-matrix gravel and sand, which is indicative of hyperconcentrated flow. A total of 5,000 to 7,000 m^3 of gravel-sized sediment was deposited in the main channel between the colluvial wedges and the debris fan. The channel deposits were reworked on their surfaces, although test pits revealed that the underlying deposits contained finer-matrix material 0.2 m below the surface. Deeper excavation showed depositional evidence of an intermediate period of reworking that occurred between two pulses of debris flow.

Sediment Characteristics

Sediment samples collected from the 1989 debris-flow deposits included a 23.5-kg sample excavated from an undisturbed debris-flow levee in the main channel upstream from the debris fan; a 27.7-kg sample collected from the 1989 deposits on the debris fan; and three samples of hyperconcentrated-flow sediments deposited during recessional flow in 1989 and separate floods in 1991 and 1993 (fig. 42A). The <64 mm fractions of the debris-flow samples contained 13 percent sand-and-finer sediment. A source distribution for the coarse component of the debris flow indicates that the debris flow contained mostly clasts of Redwall Limestone, Supai Group rocks, and Muav Limestone (fig. 42B). The <16 mm fraction of the debris fan sample contained a minimum of 11 to 15 percent water by weight. In addition to these particle-size samples, the ten largest boulders deposited on the debris fan were 1.2 and 2.9 m in diameter and ranged in weight from 11 to 111 Mg (appendix 8).

Particle-size data collected from the reworked, distal edge of the 1989 debris fan were repeatedly collected from the same sampling area on six different occasions between February 1990 and March 1994 (fig. 42C). These data show a significant coarsening of the distal edge in comparison with the intact surface of the debris fan (fig. 42D). Following the initial pulse of the 1989 debris flow, two hyperconcentrated flows deposited mostly gravel-sized sediment on the debris fan. The most recent of these floods occurred during the summer of 1993.

Discharge Estimates

Site A

At site A, immediately upstream from the debris fan, superelevated flow occurred in a left-hand bend (fig. 40). Flow-surface elevations on the outside of the bend are preserved as a continuous mudline and cobble-sized sediment deposited along the right-channel margin. Flow-surface elevations on the inside of the bend are indicated by discontinuous debris-flow deposits, a discontinuous mudline, and damaged plants. Using the superelevation method, the peak discharge for the 1989 debris flow was 220 m^3/s (table 46).

Site B

Site B, in a left-hand bend incised into Tapeats Sandstone upstream from site A (fig. 40), had evidence of superelevated flow on the outside of the bend as a continuous mudline. Depression of the flow-surface elevation on the inside of the bend is indicated by a discontinuous mudline and damaged plants; evidence of runup is also preserved at site B. We estimated peak discharges of 330 m^3/s and 380 m^3/s at site B using the superelevation and runup evidence, respectively (table 47).

Twigs were collected from mud deposited by the debris flow of 1989 on a protected bedrock ledge immediately upstream from site B. Radiocarbon dates on this material of 109.2±1.4 and 108.2±0.8 percent of modern carbon indicate a post-1950s date for this debris flow (appendix 7). Using the post-bomb ^{14}C relation, dates in 1957 or 1988 are obtained; the latter is consistent with the 1989 date of the debris flow.

Effects of the 1989 Debris Flow on the River

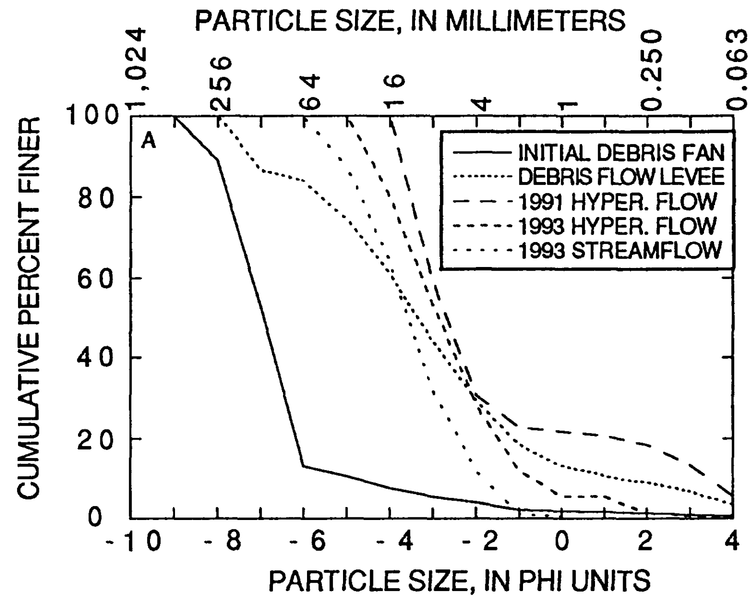
The 1989 debris flow aggraded the debris fan and formed a new rapid on the Colorado River. On the basis of a photograph of the debris fan taken in 1973 (Harmer Weeden, appendix 6), the existing debris fan was aggraded by 2 m during the 1989 event (fig. 43). In addition, small sand bars on the upstream and downstream sides of the debris fan were buried by debris-flow deposits. Point-count data collected on the debris fan shortly after the debris flow indicates that the fluctuating-flows released from Glen Canyon Dam between 1989 and 1994 reworked a significant amount of sediment finer than about 0.90 m (b-axis diameter) along the distal-edge of the debris fan (fig. 42C). Most of this reworking occurred in the first 12 months after the debris flow and during high water caused by a January 1993 flood discharge from the Little Colorado River which equaled or exceeded the peak powerplant discharges.

Volume of the 1989 Debris Fan

The newly aggraded area of the debris fan has an area of 2,500 m^2. On the basis of repeat photography of the debris fan from 1973 and aerial photographs taken between 1935, 1984, and 1990, which show partial burial of existing boulders at the site, the average thickness of the aggraded debris fan is about 2.0 m. On the basis of these measurements and estimates, the total volume of the 1989 debris flow is estimated at about 5,000 m^3. The volume of sand-and-finer sediment contained in the newly aggraded debris fan is about 650 m^3, based on a sand-and-finer sediment content of 13 percent.

During September 1991 and January 1993, additional floods in this tributary deposited hyperconcentrated-flow deposits over most of the debris fan and a newly deposited separation bar. The particle-size distributions of the 1991 and 1993 deposits consist of mostly well-sorted gravel (fig. 42A).

The effects of post-1989 floods in 127.6-Mile Canyon include aggradation of the debris fan and



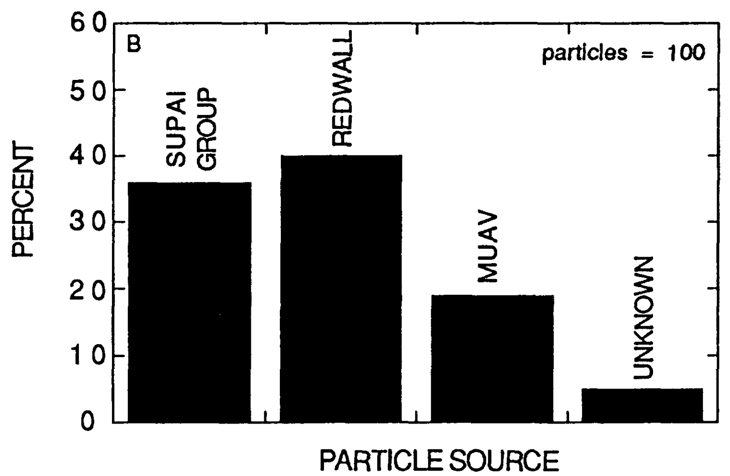
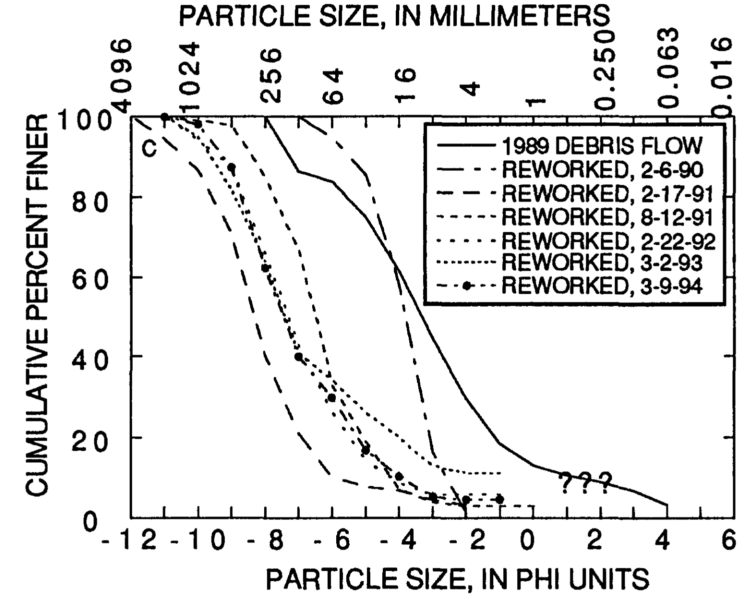
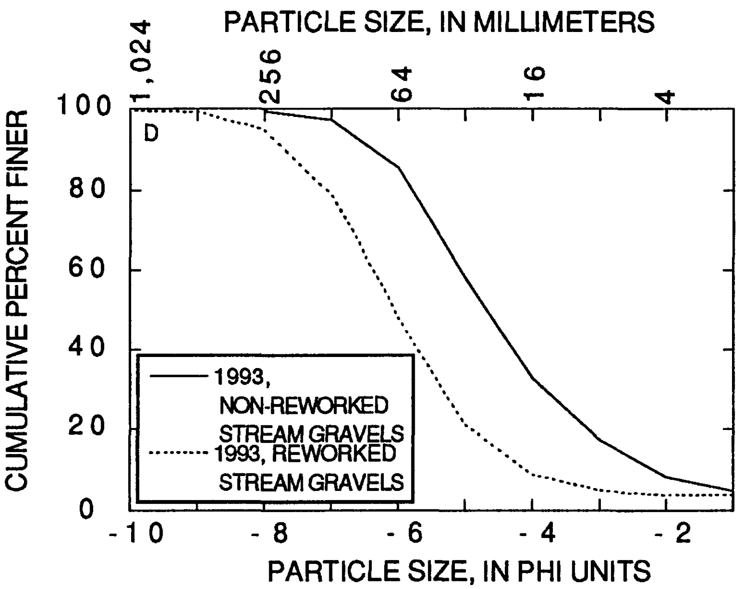


Figure 42. Particle-size and source distributions of various sediment deposits associated with the debris flow and streamflow floods that occurred between 1989 and 1993 in "127.6-Mile Canyon" (river mile 127.6-L). *A*, Particle-size distributions of the undisturbed 1989 debris-flow deposit, an undisturbed 1989 debris-flow levee, a 1991 hyperconcentrated-flow deposit, a hyperconcentrated-flow deposit of 1993, and a 1993 streamflow deposit. *B*, Source distribution of particles on the undisturbed 1989 debris-flow deposit.





C, Time series of changes in particle-size distributions showing reworking of the distal edge of the 1989 debris-flow fan exposed at discharges of 140 to about 935 m^3/s sampled between 1990 and 1994. *D,* Particle-size distributions of an undisturbed, 1993 streamflow deposit and a river-reworked, 1993 streamflow deposit.

Figure 42. Continued.

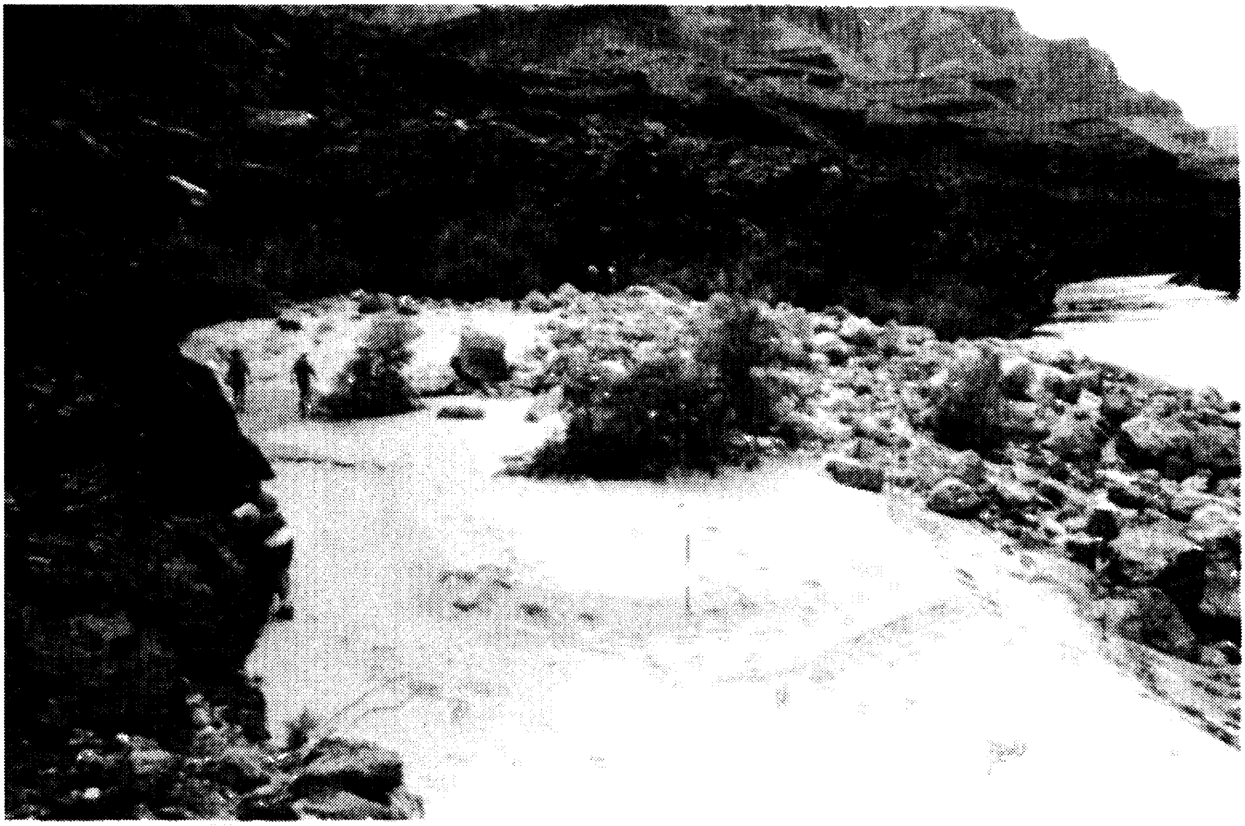


Figure 43. Replicate photographs of the debris fan at "127.6-Mile Canyon" (river mile 127.6-L). *A,* The original view, which is looking downstream, shows the debris fan at "127.6-Mile Canyon" as it appeared in the summer of 1973 (Harmer Weeden, Pennsylvania State University, Weeden slide III-3, Grand Canyon National Park).

B, The replicate view was taken on October 19, 1991 (Liz Hymans, U.S. Geological Survey, stake 2236). The debris flow of 1989 has buried the former sand bar and aggraded the debris fan by 2 m.

Figure 43. Continued.

Table 46. Indirect peak-discharge estimate for the September 1989 debris flow in "127.6 Mile Canyon" (river mile 127.6-L), site A

[Thalweg distance, was measured for individual cross sections relative to the cross section at which ΔH_s max occurred. Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Type of estimate procedure used: superelevation in a left-hand bend
Outside high-water mark: continuous scourline with damaged plants
Inside high-water mark: discontinuous debris flow deposit and mudlines
Visually estimated percentage of channel controlled by bedrock: 50 percent

Superelevation data

Radius of curvature (R_c) = 36 m
Elevation difference (ΔH_s) = 4.1 m
Mean velocity (V_s) = 6.4 m/s
Channel top width (W) = 35 m
Channel slope (S) = 0.14

Cross-section data

Cross-section location	Thalweg distance, in meters	Area, in square meters	Hydraulic radius, in meters	Hydraulic depth, in meters	Flow-elevation difference, in meters	Top width, in meters
Downstream	66	97	3.5	3.0	2.1	32
Superelevation	0	180	3.8	3.8	4.1	47
Upstream	64	34	0.9	1.6	1.5	16

Q_s = [1]220 m^3/s
Site rating for estimating discharge: Good

[1]Final discharge estimate based on minimum flow-elevation difference, L to R.

Table 47. Indirect peak-discharge estimate for the September 1989 debris flow in "127.6 Mile Canyon" (river mile 127.6-L), site B

[Thalweg distance, was measured for individual cross sections relative to the cross section at which ΔH_s max occurred. Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Type of estimate procedure used: superelevation in a left-hand bend with a runup
Outside high-water mark: continuous mudline
Inside high-water mark: discontinuous mudline with damaged plants
Visually estimated percentage of channel controlled by bedrock: 75 percent

Superelevation and runup data

Radius of curvature (R_c) = 20 m
Elevation difference (ΔH_s) = 3.9 m m
Mean velocity (V_s) = 6.9 m/s m
Channel slope (S) = 0.10
Channel top width (W) = 16 m
Elevation difference (ΔH_r) = 3.2 m
Mean velocity (V_r) = 7.9 m/s

Cross-section data

Cross-section location	Thalweg distance, in meters	Area, in square meters	Hydraulic radius, in meters	Hydraulic depth, in meters	Flow-elevation difference, in meters	Top width, in meters
Superelevation	0	81	2.9	4.2	3.9	20
Upstream	36	48	0.4	2.9	1.1	17

Q_s = [1]330 m^3/s and Q_r = [1]380 m^3/s
Site rating for estimating discharge: Good

[1]Final discharge estimates based on minimum flow-elevation differences, L to R

reduction in the size of the remaining separation bar. The former surface of the sand bar was covered by about 0.3 m of hyperconcentrated-flow sediments and streamflow transported gravels by March 1994. The separation bar was surveyed repeatedly between February 1990 and March 1994; comparison of the August 1991 and October 1991 surveys indicate that approximately 50 percent of the sand bar was buried by the hyperconcentrated-flow deposit of September 1991.

Aerial photographs taken of the pre-1989 debris fan in May 1988 indicate that the 1989 debris flow was responsible for burying a significant part of the separation bar on the downstream side of the debris fan. An indirect effect of the 1989 debris flow has been alteration of the size and shape of the flow-separation zone downstream from the debris fan and associated recirculating flow patterns that have altered deposition of fine sediment on the separation bar. Aerial photographs taken of the debris fan and separation bar between May 1988 and June 1990 show that the altered depositional pattern is the result of the increased constriction of the Colorado River. During that time period, the separation bar increased in size laterally before it was eventually buried by the 1991 flood deposits.

Frequency

The frequency of debris flows in 127.6-Mile Canyon was estimated using two historical photographs of the debris fan taken in 1973 and aerial photographs taken between 1935 and 1990. The 1935 aerial photograph shows a debris fan at the mouth of 127.6-Mile Canyon that is similar to the debris fan shown in the 1988 aerial photograph; minor changes in the size of the separation bar had occurred in the intervening 55 years. This indicates that no debris flows affecting the separation bar had occurred at the site between 1935 and September 1989. The 1973 photographs also show that no debris flows occurred between 1973 and 1989. The replicate views (fig. 43) provide an excellent example of how sand bars may be directly affected by debris flows through burial. In summary, none of the replicate or aerial photographs show evidence of debris flows between 1935 and 1989. The debris flow of 1989 and the hyperconcentrated flows of 1991 and 1993 were probably the first significant occurrences of sediment transport in this drainage basin in about 60 years.

Specter Chasm (River Mile 129.0-L)

Specter Chasm drains 8.25 km^2 on the west side of the Colorado River (fig. 1). A small debris flow occurred in this drainage basin during the same storm in 1989 that triggered other debris flows between river miles 126 and 130. Using a photograph taken of the Specter Chasm debris fan and rapid by Eddy in 1927 that we matched in 1993 (appendix 6), we concluded that the 1989 debris flow was the first in Specter Chasm to reach the Colorado River in 62 years (figs. 44A and 44B). Aerial photographs taken between 1965 and 1988 indicated no changes to the rapid or debris fan during that time period.

We estimated particle-size and source distributions for the pre-1989 debris fan, which had been reworked by the Colorado River, and the mostly undisturbed debris deposited by the 1989 event (figs. 45A and 45B). Both the debris-flow sediments from the 1989 flood and the reworked debris-fan surface are composed mostly of Redwall Limestone (fig. 45B). The 1989 deposit on the debris fan has been only slightly reworked by river flows that have ranged from less than 142 to about 990 m^3/s since 1989.

The discharge of the 1989 debris flow could not be estimated because no suitable sites were found in the tributary. However, several large boulders were transported into Specter Rapid during the flood; these increased the severity of the rapid by constricting the left side of the river channel and forcing flow toward a bedrock wall on river right. Large standing waves in the center of the channel are now difficult to avoid. River flows since 1989 have not removed a significant number of the new boulders from the rapid.

Bedrock Canyon (River Mile 130.5-R)

Bedrock Canyon drains 21.41 km^2 on the north side of the Colorado River (fig. 1). Bedrock Rapid is formed by a combination of a debris fan at the mouth of the canyon and a Precambrian bedrock outcrop in the center of the Colorado River channel

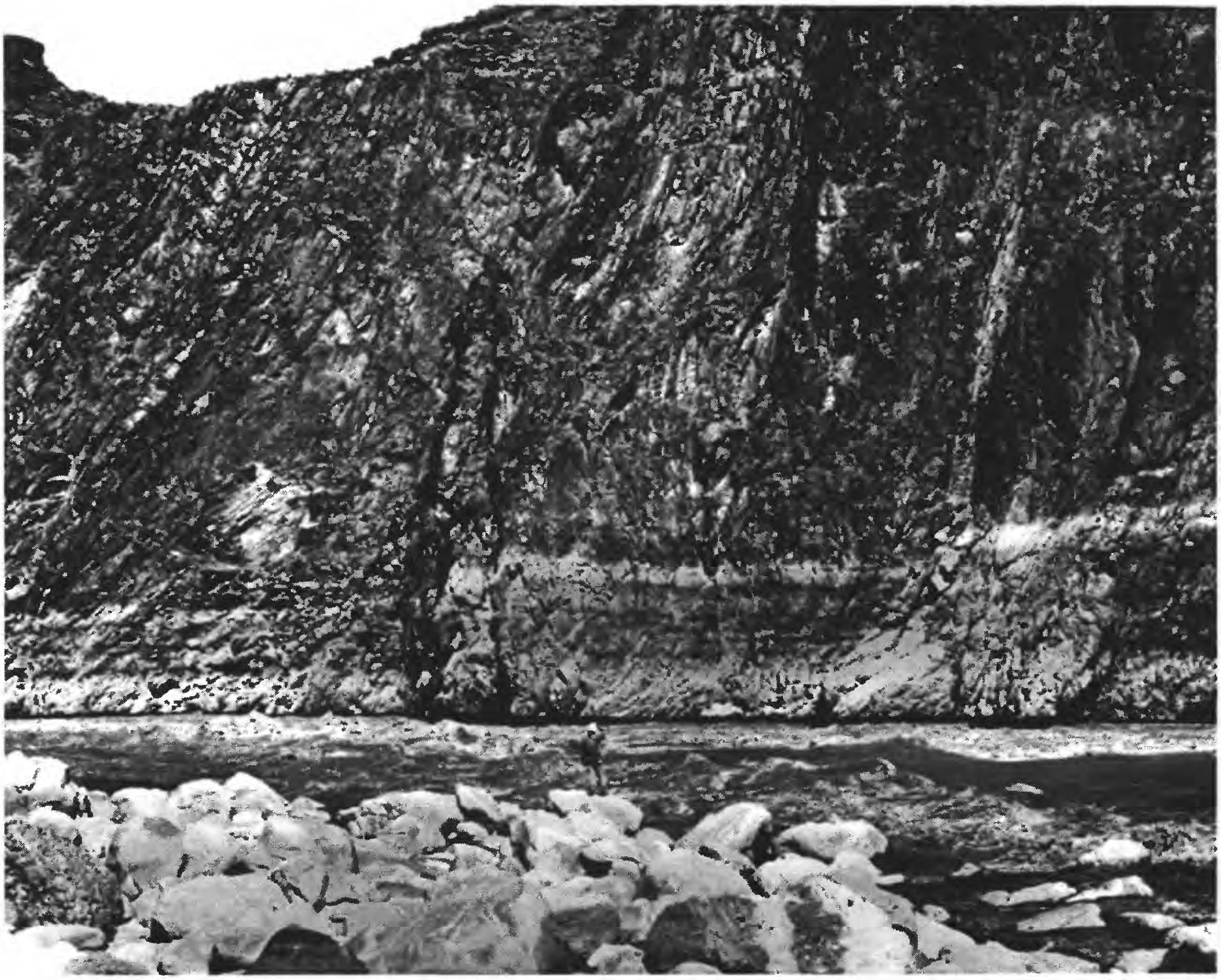
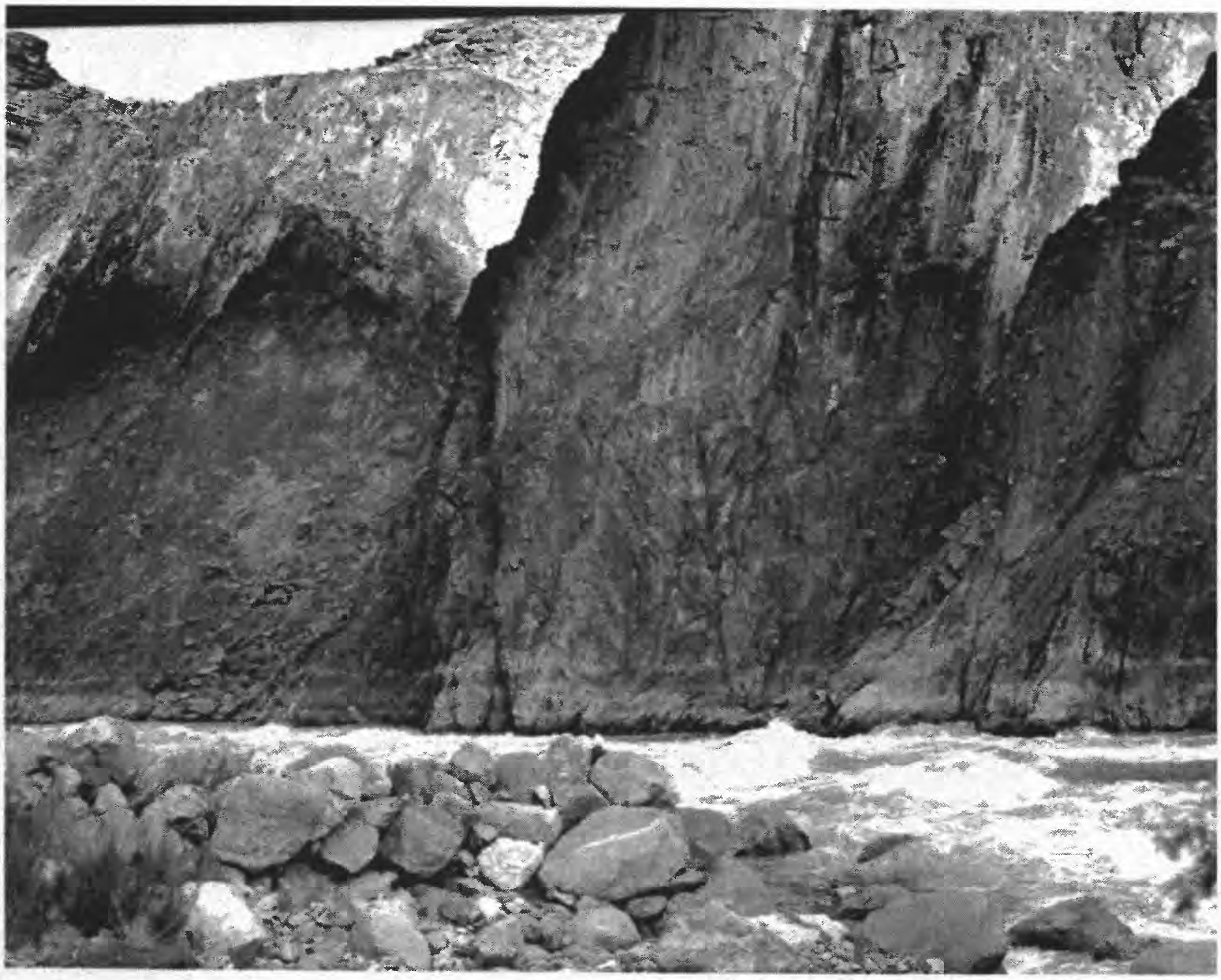


Figure 44. Replicate photographs of the debris fan at Specter Chasm (river mile 129.0-L), a tributary of the Colorado River. *A*, The original view, which is downstream and across the river, shows the debris fan and rapid at the mouth of Specter Chasm as it appeared on July 27, 1927 (Clyde Eddy, photograph 76, Huntington Library).



B, The replicate view was taken on September 25, 1993 (Ted Melis, U.S. Geological Survey, stake 2624). The debris flow of 1989 has deposited large boulders on the debris fan and in the rapid.

Figure 44. Continued.

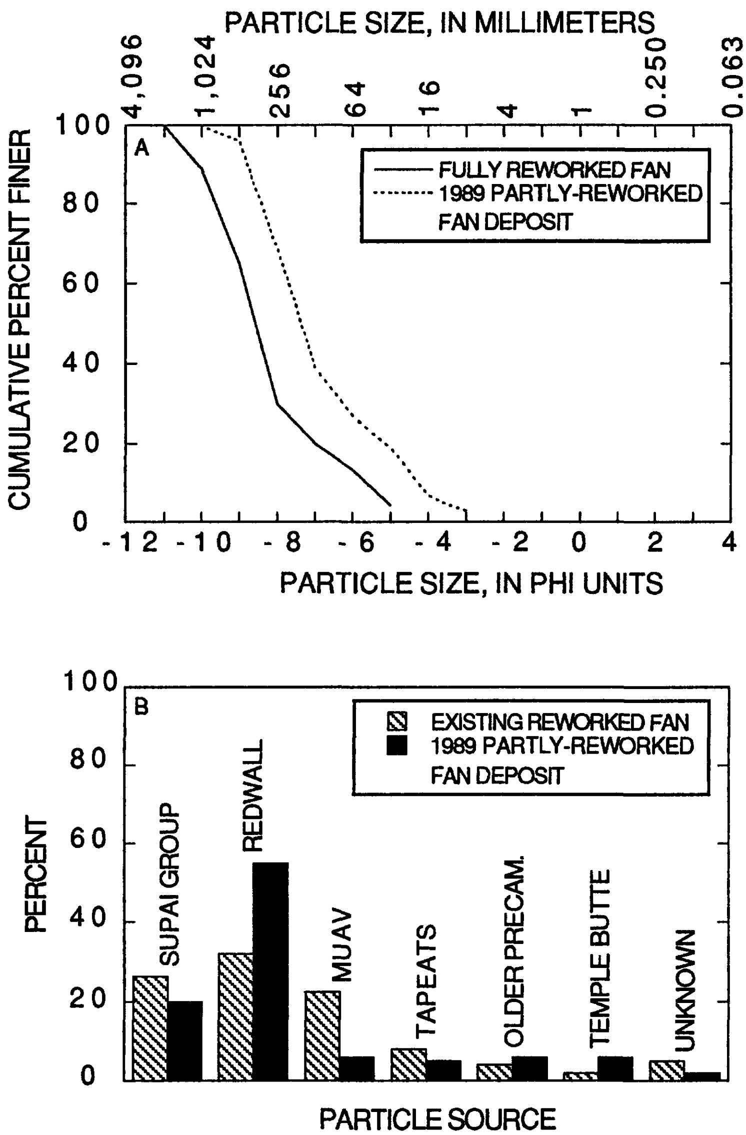


Figure 45. Particle-size and source distributions of various sediment deposits associated with the debris flow of September 1989 in Specter Chasm (river mile 129.0-L). *A*, Particle-size distributions of the pre-existing, reworked debris fan and the partially reworked, 1989 debris-flow deposit that was inundated by river discharges of < 142 to about 935 m^3/s between 1989 and 1994. *B*, Source distributions of particles on the pre-existing, reworked debris fan surface, and the partially reworked, 1989 debris-flow deposit.

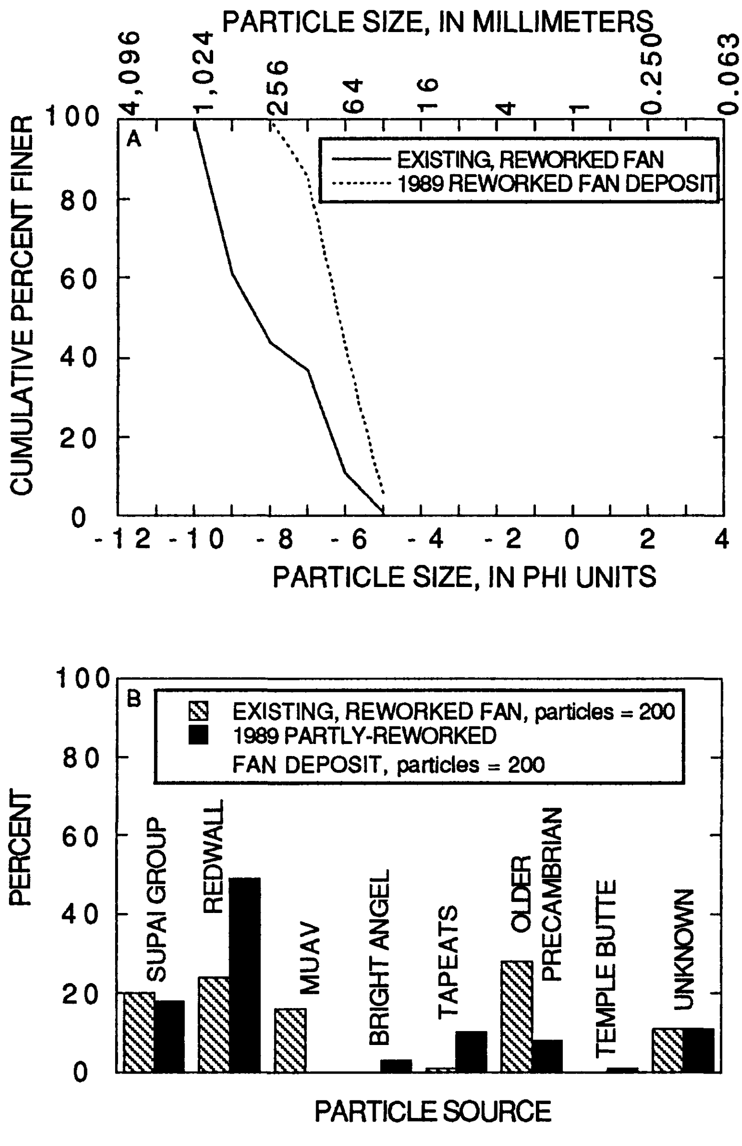


Figure 46. Particle-size and source distributions of various sediment deposits associated with the debris flow of September 1989 that occurred in Bedrock Canyon (river mile 130.5-R), a tributary of the Colorado River in Grand Canyon. A, Particle-size distributions of the pre-existing, reworked debris fan and the partially reworked, 1989 debris-flow deposit inundated by river discharges of < 142 to about 935 m^3/s between 1989 and 1994. B, Source distributions of particles on the pre-existing, reworked debris fan and the partially reworked, 1989 debris-flow deposit.

immediately downstream from the mouth of the canyon. According to the account of a river guide (Larry Stevens, oral commun., 1989), a small debris flow occurred in Bedrock Canyon during late August to early September 1989. The debris flow likely was triggered by the same storm that initiated debris flows between river miles 126 and Specter Chasm (river mile 129.0-L). On the basis of aerial photographs, the 1989 debris flow was the first to occur in Bedrock Canyon and reach the Colorado River since 1965.

Particle-size and source distributions were determined from point-count data collected from the existing debris-fan surface and partly reworked debris-flow deposits deposited at the debris fan during the 1989 debris flow. We were unable to sample the initial debris-flow sediments before they were inundated during powerplant releases during the autumn of 1989. Figure 46A shows the contrast in particle-size distributions between the pre-1989, reworked debris fan and the partly reworked debris fan of 1989. The source distributions of the 1989 and pre-1989 debris-fan surfaces are shown in figure 46B.

The most significant result of the 1989 debris flow was deposition of a small, bouldery debris fan on the downstream side of the existing, reworked debris fan. The new debris-flow deposit initially constricted the right side of the river channel by about 8 to 10 m. This deposit greatly increased the difficulty of navigating Bedrock Rapid because river runners had great difficulty avoiding the bedrock outcrop in the center of the rapid. The enlarged debris fan has been reworked substantially by river flows since 1989, but a residual deposit of boulders remains on the fan, which makes Bedrock Rapid a greater challenge for private and commercial boaters than the rapid was before 1989. Because of the size of this drainage basin, and the unusual bedrock outcrop in the rapid, the potential for additional debris flows to further increase navigational hazard in Bedrock Rapid is great in the post-dam era.

140-Mile Canyon (River Mile139.9-L)

140-Mile Canyon drains 25.76 km^2 on the south side of the river (fig. 47). We examined a recent-looking debris-flow lobe on the downstream side of the debris fan. On the basis of its elevation and bouldery texture, the debris-flow deposit had been reworked by large, pre-dam Colorado River floods, indicating that it was deposited before 1963. The flood of 1983 (about 2,700 m^3/s) may have inundated the deposit, although we could not determine the amount of reworking that may have occurred in 1983. We did not find sufficient evidence to determine either the peak discharge or volume of this debris flow.

Some indication of the frequency of debris flows in this tributary was determined using radiocarbon dating. A piece of driftwood partly buried in the surface of the most recent debris-flow fan deposit yielded a radiocarbon age of 255±100 yrs BP. This date indicates that the last debris flow in 140-Mile Canyon likely occurred between AD 1490 and 1955 (appendix 7). No historic photography is available for 140-Mile Canyon, and aerial photography was insufficient to evaluate the frequency of debris flows in this tributary.

The particle-size distribution for the deposit of the AD 1490 to 1955 debris flow was similar to that of the fully reworked debris-fan surface (fig. 48A). Most of the matrix (sand-and-finer sediment) had been removed from the debris fan, but cobbles and small boulders are numerous. The source distribution of the AD 1490 to 1955 debris flow indicates that the deposit consists mostly of Redwall and Muav Limestones (fig. 48B).

Kanab Creek (River Mile 143.5-R)

Kanab Creek is a major tributary of the Colorado River, draining 6,076 km^2 of northern Arizona and southern Utah (fig. 1). Most flow in this creek, which is perennial at its mouth, is streamflow. However, debris flows are initiated in Kanab Creek in its lower reaches. Stream terraces lining the channel margins along its lower 20 km consists of poorly-sorted debris-flow deposits including large boulders (Webb and others, 1991).

Considerable historical photography exists of Kanab Creek, beginning with images taken in 1872 (Webb and others, 1991). In particular, the debris fan at the mouth of Kanab Creek has been frequently photographed (table 48). Previous analysis of historical photographs indicated that a large debris flow initiated in a tributary of Kanab

Creek had flowed to the Colorado River (Webb and others, 1991). Although the date of this debris flow had been constrained between 1923 and 1953 (Webb and others, 1991), a 1942 photograph (table 48) indicates the debris flow occurred between 1923 and 1942. A 1934 photograph exists, but does not include the upper part of the debris fan.

Unnamed Tributary at River Mile 157.6-R

Widespread, convective thunderstorms over western Grand Canyon on or about August 20, 1993, triggered a debris flow in an unnamed tributary at river mile 157.6-R (fig. 49). This tributary drains 11.11 km^2 on the north side of the Colorado River. We could not access the upper reaches of this drainage during our fieldwork; therefore, the peak discharge was not estimated for the debris flow. River runners camped downstream in the vicinity of National Canyon (river mile 166.4-L) on the day of the debris flow reported about three hours of intense thunderstorms during the afternoon of the August 20, dropping from 50 to 75 mm of rain.

A relatively-small debris fan was present at mile 157.6-R before the 1993 debris flow. A popular camping beach commonly known as the "First Chance" camp is used often by river runners owing to its close proximity to Havasu Creek (river mile 156.8-L), which is a popular stop for river parties. Fortunately, the debris flow occurred during the day when the camp was unoccupied.

Volume of the 1993 Debris Dan and Sediment Characteristics

On the basis of a topographic survey of the 1993 debris fan, we estimated a minimum volume for the new debris-flow deposit at river mile 157.6-R of 10,000 to 13,000 m^3. Point-count data collected from the surface of the new fan deposit indicates that the debris flow is very-poorly sorted, contains 25 to 35 percent sand-and-finer sediment (fig. 50A) and consists mainly of Muav and Redwall Limestones, with lesser amounts of Supai Group rocks (figs. 50B). Particle-size distributions for the initial debris-flow pulse were compared with three point-count transects made across the later-stage sediment deposits (fig. 50C). These data show the contrast between the coarser, initial surge of the debris flow and the finer sediment that was transported by recessional flow. Such differences between initial and late-stage surges are common in Grand Canyon debris flows.

The distal edge of the 1993 debris fan was slightly reworked by river flows of 142 to 566 m^3/s that occurred between August and September 1993. However, the remainder of the debris fan probably will not be substantially reworked by flows of 850 to 1,500 m^3/s. Large boulders deposited on the debris-flow fan were measured and classified by source in order to determine their individual and total volumes; most of these boulders were Muav Limestone that ranged in weight from 1 to 7.5 Mg (appendix 8).

Effects on the River Channel

Most of the sand bars on the upstream and downstream margins of the debris fan were buried under 2 to 4 m of poorly sorted debris. Burial of sand bars by debris flows is common, but this was an exceptional example of how a heavily-used camping beach can be rendered unusable by a debris flow. The 1993 debris flow constricted the river channel by about 15 m, which increased the drop through an existing riffle.

Frequency

The frequency of debris flows in this unnamed tributary was determined by examining aerial photographs taken between 1965 and 1993. These photographs indicate that the 1993 debris flow was the first since at least 1963 when Glen Canyon Dam was closed. Twigs deposited in the 1993 debris fan deposit were analyzed for ^{14}C to test the accuracy of the radiocarbon dating recent debris flows using the ultra modern, post-bomb curve. This material radiocarbon dated at 116.2±1.2 percent of modern carbon, which corresponds to a calendric date of either 1958 or 1993 (appendix 7). The sediment had a ^{137}Cs activity of 0.057±0.008 pCi/g, which is consistent with the date of the flow.

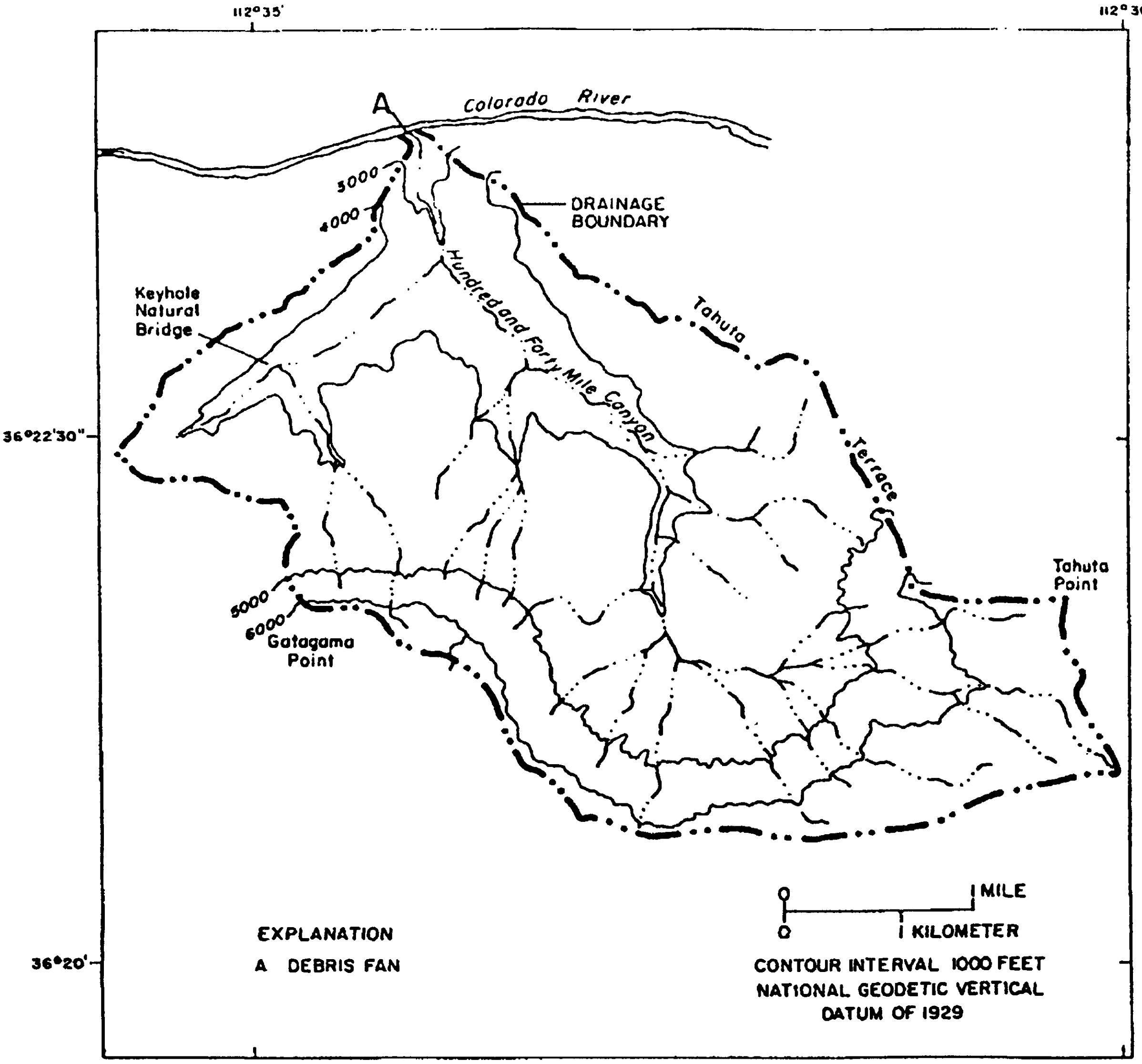


Figure 47. The drainage basin of 140-Mile Canyon (river mile 139.9-L), a tributary of the Colorado River in Grand Canyon.

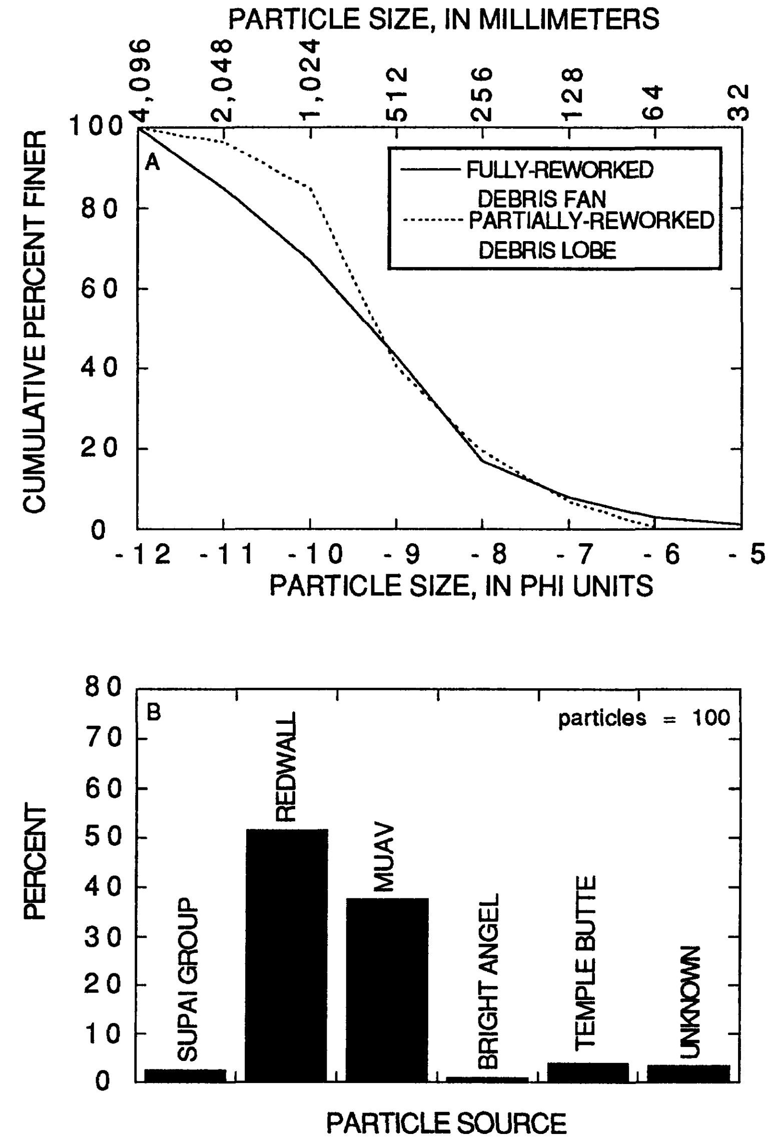


Figure 48. Particle-size and source distributions of various sediment deposits associated with a debris flow that occurred between AD 1490 and 1955 in 140-Mile Canyon (river mile 139.9-L). *A*. Particle-size distributions of the pre-existing, reworked debris fan and the reworked deposit of the AD 1490 and 1955 debris flow. *B*, Source distribution of the reworked deposit of the AD 1490 and 1955 debris flow.

Table 48. Historical photographs of Kanab Creek Rapid (river mile 143.5) and the debris fan at the mouth of Kanab Canyon (river mile 143.5-R)

[For photographs taken before 1921, the discharge is estimated from known stage-discharge relations at Kanab Rapid. For photographs taken between 1921 and 1963, discharge is estimated from daily discharge records of the Colorado River at Lees Ferry. After 1963, discharge is estimated from known stage-discharge relations at Kanab Rapid. These estimates are perhaps accurate to ±1,000 ft3/s. (AV), vertical aerial photography; (AL), photograph is an oblique aerial taken from the left side of the river; (AR), photograph is an oblique aerial taken from the right side of the river; (RL), photograph was shot from river-left; (RR), photograph was shot from river-right; (US), upstream view; (DS), downstream view; (AC), view across the river; (UC), view looking up the tributary channel or away from the river; (R), view shows a rapid; (DF), view shows debris fan(s); (SB), view shows sand bar(s); (n.d.), no data; (n.m.), the photograph was analyzed, but not matched]

Year	Date	Photographe r	Original number	Stake number	Side	Directio n	Subject	Discharge (ft^3/s)
1871	Apr	Beaman	399	1793	RR	DS	R,DF	n.d.
1872	Sep 10	1Hillers	692	695	RR	DC	DF	(3)
	n.d.	Bell	225	2652	RR	US	DF	n.d.
	n.d.	Bell	216	2653	RR	DS	R,DF	n.d.
	n.d.	Bell	178	2654	RR	UC	DF	(3)
	n.d.	Bell	III-269	1792	RR	UC	DF	(3)
	n.d.	Bell	II-11	1096	RR	DC	DF	(3)
	n.d.	Bell	II-5	1794	RR	DS	DF	n.d.
	n.d.	Bell	V-5	694	RR	DS	DF	n.d.
1890	Feb 24	[1]Stanton	597	1504a	RR	DS	R,DF	~8,000
1923	Sep 10	LaRue	552	1791	RL	US	SB	10,600
	Sep 10	LaRue	553	718	RL	US	R,DF,SB	10,600
	Sep 10	LaRue	554	2041	RR	DC	DF	10,600
	Sep 10	Larue	555	n.m.	RR	US	R,DF,SB	10,600
1934	Jul 30	Fahrni	3-226	n.m.	RR	DS	SB	2,050
1942	Jul	Wilson	4:08:21	2595	RR	DS	R,DF	19,900
1953	Jul 6	Reilly	R42-7	2040	RR	DC	DF	20,200
1964	May 10	Reilly	L70-24	2038	RR	DC	DF	(3)
	May 10	Reilly	L70-19	2042	RR	DC	DF,SB	n.d.
	May 10	Reilly	L70-17	2042b	RR	DS	DF,SB	n.d.
1968	Sep 22	[2]Stephens	692	695	RR	DC	DF	(3)
1972	Jul 2	Turner	n.d.	695	RR	DC	DF	(3)

[1]Photograph was published in Webb and others (1991).

[2]Photograph was published in Stephens and Shoemaker (1987).

[3]Indicates that the river was not visible in the photograph.

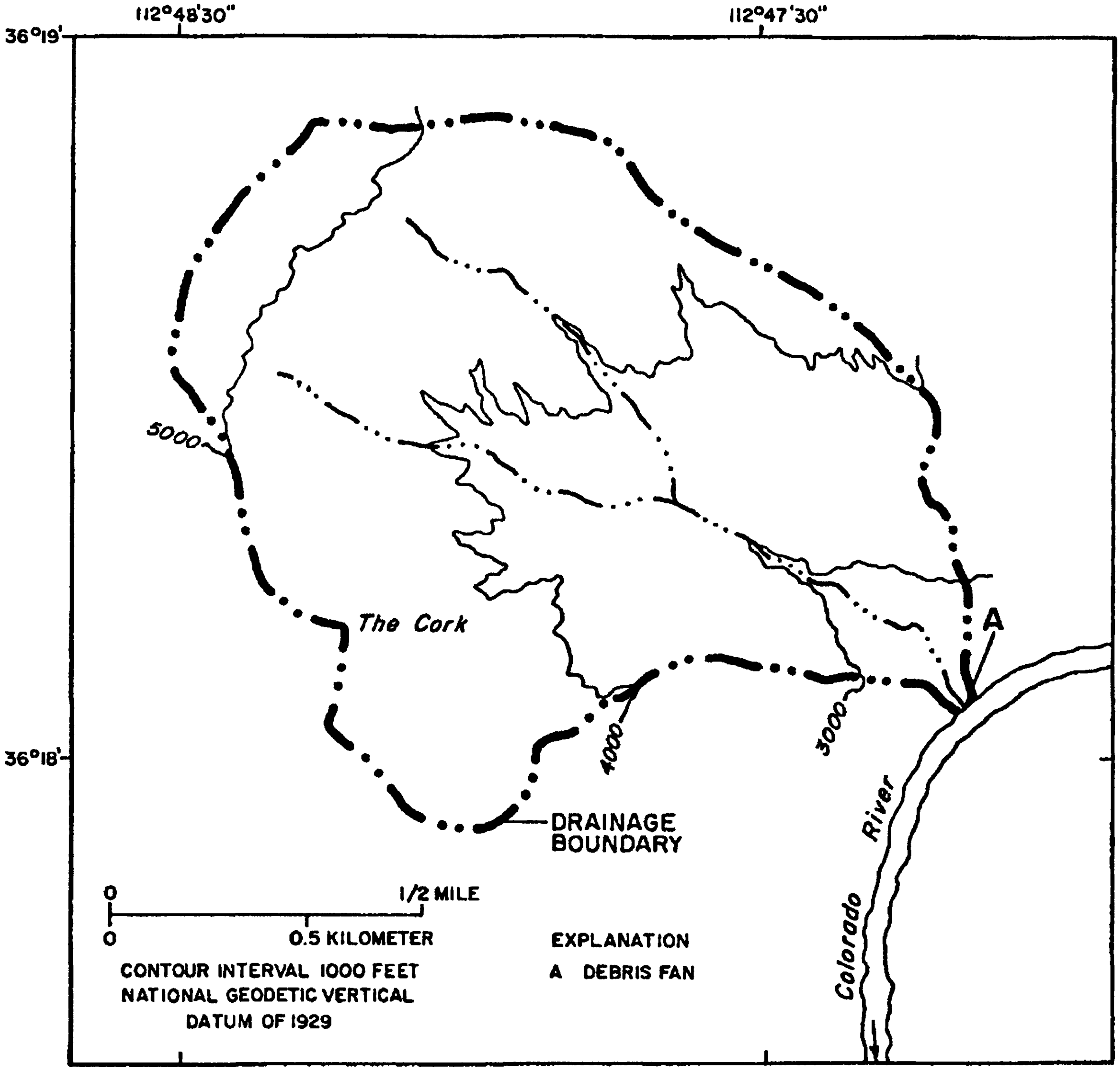
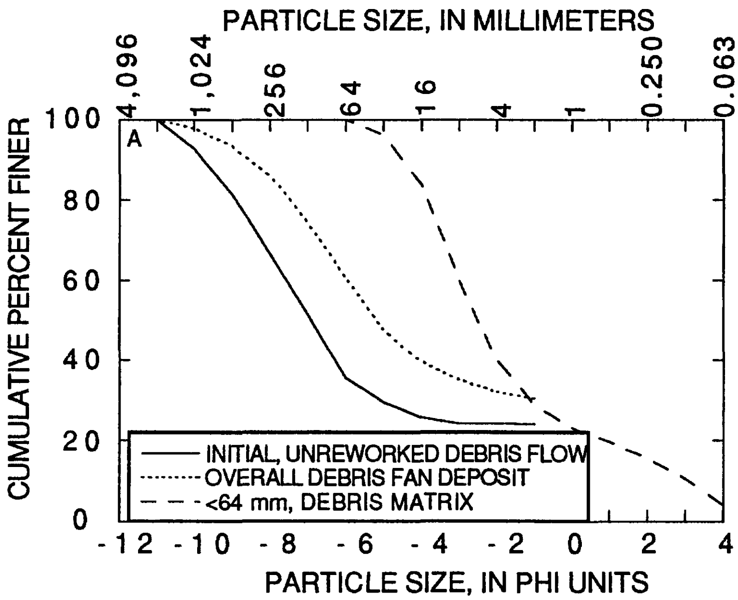


Figure 49. The drainage basin of an unnamed tributary of the Colorado River at river mile 157.6-R in Grand Canyon.



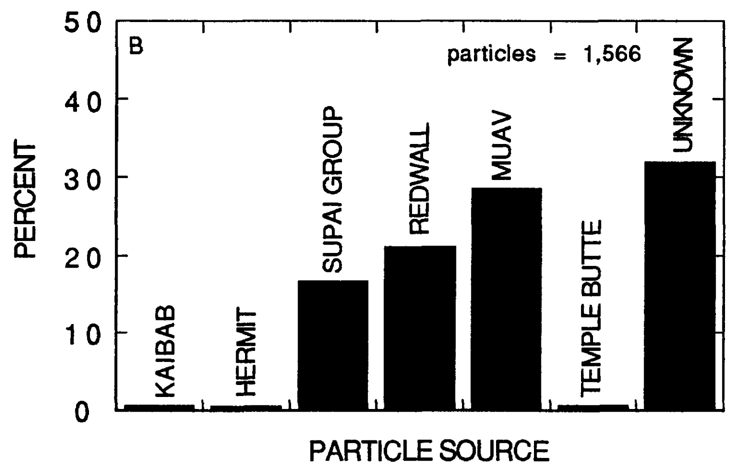
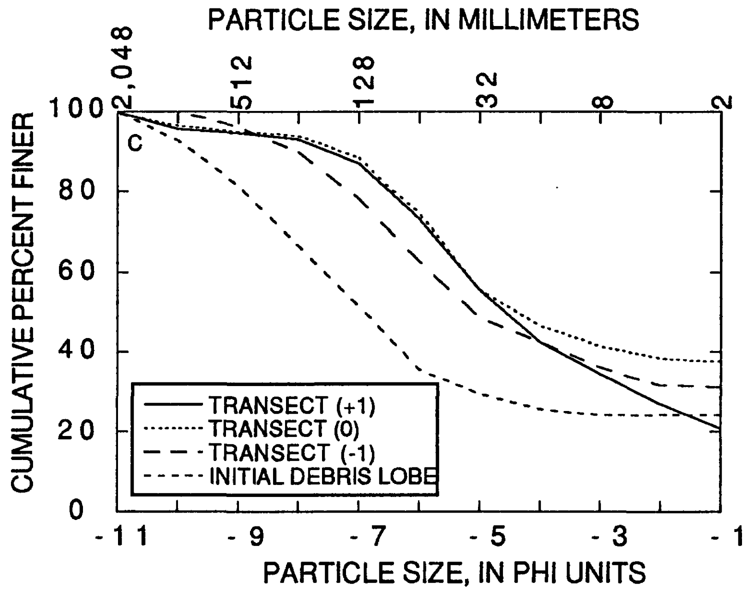


Figure 50. Particle-size and source distributions of sediment deposits associated with the debris flow of 1993 in an unnamed tributary at river mile 157.6-R. *A*, Particle-size distributions of the initial, undisturbed debris-flow lobe, the surface of the entire debris fan, and the < 64 mm fraction of the debris-flow matrix. *B*, Source distribution of particles on the undisturbed 1993 debris-flow deposit.



C, Particle-size distributions of the initial 1993 debris-flow lobe and three transects sampled across the entire surface of the 1993 debris-flow deposit.

Figure 50. Continued.

Unnamed Tributary at River Mile 160.8-R

A debris flow occurred in the unnamed tributary at river mile 160.8-R on or about August 20, 1993, during the same storm that affected the unnamed tributary at river mile 157.5-R. This small tributary drains 3.37 km^2 on the north side of the river (fig. 51). We were unable to determine peak discharge for this debris flow owing to the inaccessibility of the tributary. By surveying the deposit, we estimated that a minimum of 8,000 to 12,000 m^3 of debris was deposited in the Colorado River during the debris flow.

Large boulders ranging from 1 to 2 m in diameter (b-axis) were deposited in the river and on the existing debris fan (appendix 8). The resulting constriction of the river channel formed a new rapid where only a small riffle existed previously. The debris-flow sediment also partly buried a separation bar. The particle-size distribution (fig. 52A) for the tributary streamflow-reworked debris-fan deposit contained no sand by the time we sampled it in September 1993. Most of the largest boulders deposited on the fan and in the river were Muav and Redwall Limestone and Supai Group rocks (fig. 52B). The largest boulders ranged in weight from 2.6 to 26 Mg (appendix 8).

The frequency of debris flows in this unnamed tributary was determined by examining aerial photographs taken between 1965 and 1993. These photographs indicate that the 1993 debris flow was the first since 1965 and probably was the first since Glen Canyon Dam was closed in 1963. Twigs deposited on the 1993 debris fan deposit were analyzed for ^{14}C to test the accuracy of radiocarbon dating applied to recent debris flows. The ^{14}C activity of 116.2±1.5 PMC corresponds to a calendric date of either 1958 or 1993 (appendix 7).

Prospect Canyon (River Mile 179.4-L)

Prospect Canyon is a large tributary in western Grand Canyon that drains 257.22 km^2 of forests and grasslands. This tributary consists of a large upper-catchment area with a drainage called Prospect Creek and a small, steep lower basin called Prospect Canyon (fig. 53). The ephemeral stream channel of the upper and lower basins drains northward and joins the Colorado River at river mile 179.4-L (fig. 54). Lava Falls Rapid, considered the largest rapid on the Colorado River (Stevens, 1990), is formed by the large boulders deposited in the Colorado River from Prospect Canyon. On the basis of our reconnaissance of the upper reaches of the canyon, we concluded that debris flows are produced solely in Prospect Canyon.

The rocks exposed in Prospect Canyon consist of Paleozoic strata with Quaternary basalts produced in local vents. Prospect Creek is a large catchment draining a broad, low-gradient valley. This alluvial valley formed after Quaternary basalt flows filled the ancestral Prospect Canyon during the Pleistocene. Prospect Canyon contains large deposits of colluvium as a result of headword erosion into the basalt-filled drainage. Runoff generated in Prospect Creek flows over a steep, 500-m high talus slope of cinders and basalt-laden colluvium at the head of Prospect Canyon.

The Toroweap Fault, a major geologic structure of the region, trends south across the Colorado River and through Prospect Canyon. This post-Paleozoic fault is down-thrown to the west (Huntoon and others, 1986). The presence of the fault may increase sediment production in Prospect Canyon and may, in part, explain the atypically high frequency and magnitude of debris flows in this tributary. However, the most important geomorphic contributors to the relatively high frequency of debris flows are a headwardly-eroding cinder cone on the western rim of the lower basin and a steep scree slope at the head of Prospect Canyon. These two features provide enormous volumes of unconsolidated sediment for transport by debris flows. The size of the Prospect Canyon debris fan, which is 30-m high and one of the largest debris fans in Grand Canyon, strongly suggests that large debris flows have occurred frequently in this canyon. The channel of Prospect Canyon is incised 25 to 28 m into the debris fan and provides the depositional setting for recent debris flows.

Frequency

A total of 4 debris flows and 1 hyperconcentrated flow have occurred in Prospect Canyon since 1872. The debris flows and hyperconcentrated flow all occurred between 1939 and 1963 and are dated using 161 historical photographs that show the Prospect Canyon debris fan and Lava Falls Rapid (table 49). These photographs also indicate that no debris flows occurred between April 1872 and July 1938 or between October 1963 and 1994. Using photogrammetry, we estimated the areas and volumes of all five aggradational areas on the debris fan caused by recent debris flows from Prospect Canyon (table 50).

On the basis of the photographic record at this site, the debris flow occurred between July 29, 1938, and August 17, 1940. Using precipitation data from two nearby stations, the most likely date for the debris flow is either September 6 or 12, 1939. During the first three weeks of September, four dissipating tropical cyclones caused intense and prolonged precipitation in northern Arizona (Smith, 1986). The 1939 debris flow deposited a large debris-flow levee on the left side of Prospect Creek about 0.1 km upstream from the river and constricted the Colorado River by as much as 65 percent. Most of the 1939 debris-fan deposit was reworked during two Colorado River floods in 1941 (fig. 55A), one of which exceeded 3,200 m^3/s. The ten largest boulders deposited by the 1939 debris flow that remained behind on the debris fan after reworking were basalt boulders that ranged in weight from 3 to 29 Mg (appendix 8). The 1939 debris flow had a relatively high stage and significantly constricted the channel of Prospect Creek between newly deposited debris-flow levees (fig. 56B).

Debris flows also occurred in Prospect Canyon in 1954 and 1955 (table 49). Photographs taken in the summer of 1954 constrain the date for a debris flow between June 14 and August 29 (table 49). Although the 1954 debris flow had a major effect on Lava Falls Rapid, in terms of decreasing its severity (P.T. Reilly, oral commun., 1991), it was the smallest of the four historical debris flows in Prospect Creek (fig. 56B). No depositional evidence remains of this debris flow.

A larger debris flow occurred in Prospect Creek in 1955. The date of this debris flow is constrained by historic photographs taken on July 20 and in October 1955 (table 49). We analyzed an oblique aerial photograph taken by P.T. Reilly to determine the effect of this debris flow on the Colorado River (fig. 54). The 1955 debris flow reduced the cross-

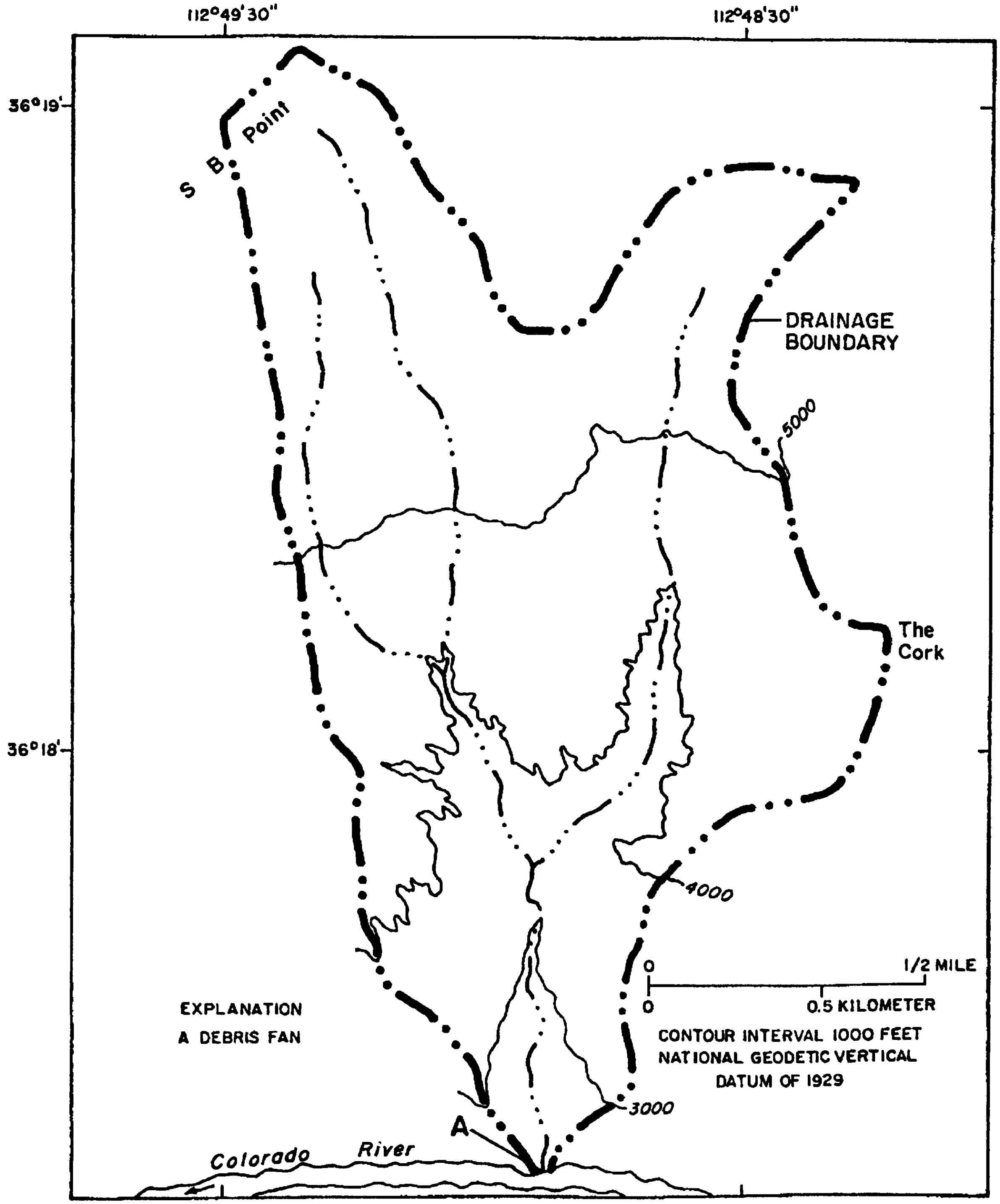


Figure 51. The drainage basin of an unnamed tributary of the Colorado River at river mile 160.8-R in Grand Canyon.

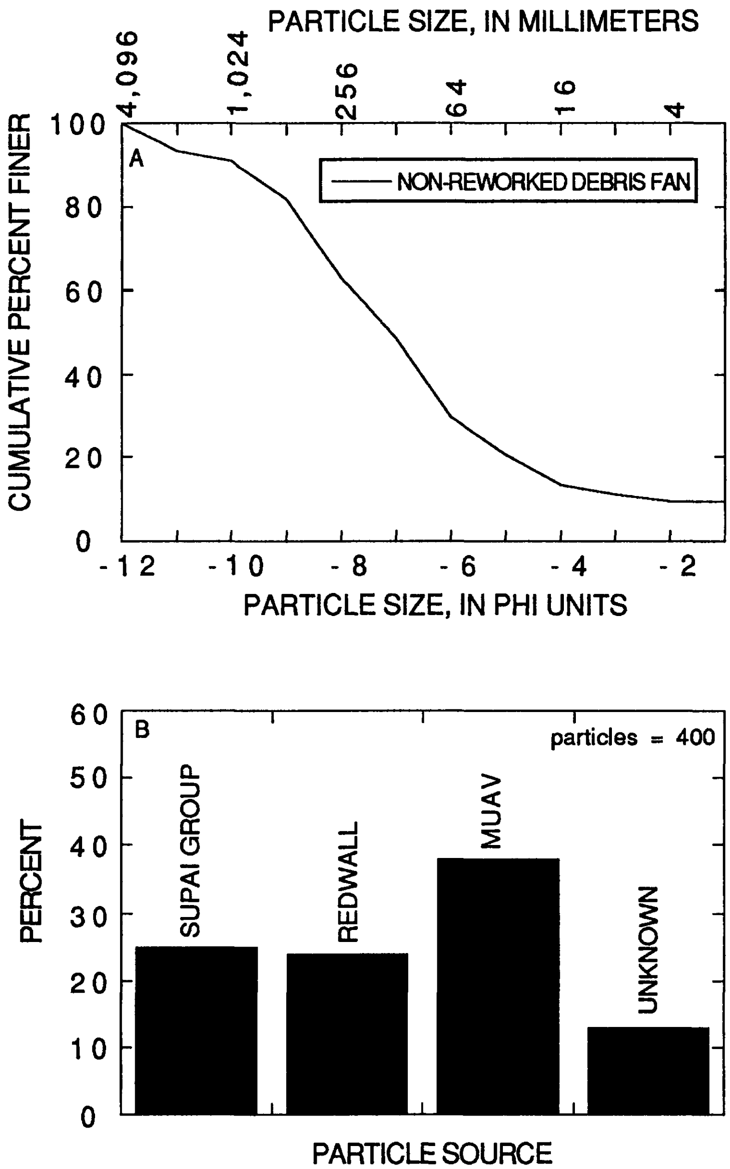


Figure 52. Particle-size and source distributions of sediment deposits associated with the debris flow of 1993 in an unnamed tributary at river mile 160.8-R. *A*, Particle-size distribution of the undisturbed 1993 debris-flow deposit. *B*, Source distribution of particles on the 1993 debris-flow deposit.

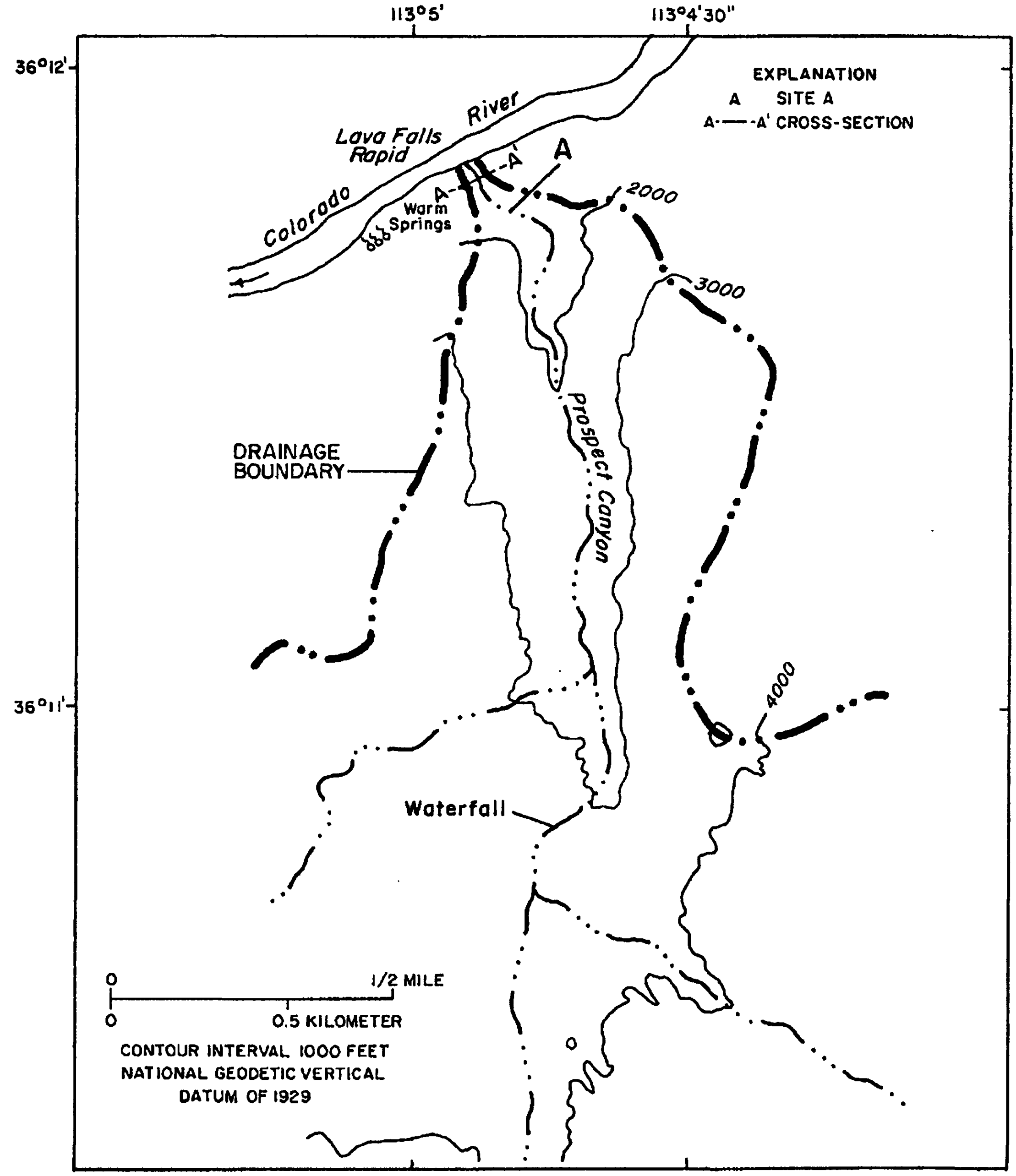


Figure 53. The lower 2 km of Prospect Canyon (river mile 179.4-L), a tributary of the Colorado River in Grand Canyon.

Figure 54. Oblique aerial view of Lava Falls Rapid (river mile 179.3) taken March 25, 1956 (P.T. Reilly, photograph L19-26). The debris flow of 1955 decreased the width of the Colorado River by two-thirds.

sectional area of Prospect Canyon near the top of Lava Falls Rapid by about 45 percent (table 50) and partly overtopped the 1939 debris levee (fig. 56C). Many large boulders were deposited in the rapid; some of these were reworked by Colorado River floods into a configuration that forms the current feature known commonly as the "Ledge Hole", a major navigational hazard in the rapid.

Aerial photographs taken by P.T. Reilly in 1956 (table 49) reveal that a flood, probably hyperconcentrated flow, occurred between April 16 and September 29, 1956. The newly deposited debris fan from the 1955 debris flow was partly eroded by the 1956 flood (fig. 54). All evidence of the 1954 debris fan, the 1956 hyperconcentrated-flow deposit, and most of the 1955 debris fan, were eroded by the 1957 flood in the Colorado River (fig. 55B).

The last debris flow in Prospect Canyon occurred in 1963 (table 49). Photographs taken on August 24 and September 25, 1963 show evidence of a sizeable debris fan and constriction of the Colorado River. A dissipating tropical cyclone (Tropical Storm Katherine) entered northern Arizona on September 17, 1963; this storm resulted in 75 to 150 mm of rainfall over a two day period (Smith, 1986). The timing of Tropical Storm Katherine coincides closely with the period of photographic coverage bracketing the debris flow and therefore is probably the storm that initiated this debris flow. The 1963 debris flow constricted the Colorado River by about 42 percent (table 50) and deposited debris-flow levees that are preserved as inset deposits along the base of the 1939 levees (figs. 56D and 56E). The 1963 debris flow occurred approximately 7 months after closure of Glen Canyon Dam. The first large releases from Glen Canyon Dam in June 1965 reworked most of the 1963 deposits (fig. 55C).

Several streamflow floods have recently occurred in Prospect Creek. During the 1966 storm that initiated debris flows in Crystal Creek and Lava Canyon, a streamflow flood deposited small boulders on the left side of Lava Falls Rapid, reportedly closing off a previously used run (John Cross Jr., written commun., 1994). During a period of widespread flooding in February 1993, a streamflow flood in Prospect Canyon deposited a small volume of cobbles on the debris fan.

Both ^{137}Cs and ^{14}C were used to determine the accuracy of radiometric techniques in dating recent debris flows in Prospect Creek. Sediment samples containing particles <2 mm in diameter were collected from each of the debris-flow levee deposits and at three levels in a deposit of Holocene age (table 51); in one case, a <63 m fraction was analyzed. As expected, the Holocene samples had detectable activities of ^{137}Cs in the surface and at 0.10 to 0.15 m depth, but no detectable activity at 0.5m depth.The 1939 debris flow had a low activity of ^{137}Cs, although one sample of the surface exposed to fallout had an activity above the detection limit. One sample of the 1955 deposits also had a significant, high activity of ^{137}Cs, as expected, but a second sample had no detectable ^{137}Cs (table 51). The activity of ^{137}Cs in the 1963 deposits was equivocal. Two samples had detectable, and high, activities, as expected, but four samples had no detectable activity (table 51). Two samples of sand-and-finer sediment from a 1993 flood deposit also had detectable ^{137}Cs, as expected. Five of 11 samples that should have contained significant activities of ^{137}Cs had no detectable activity, whereas pre-1952 deposits had no detectable 137Cs except on exposed surfaces. The ^{137}Cs analyses yielded results that indicate the technique does not reliably differentiate the age of pre-1952 versus post-1952 deposition of debris-flow sediments in Prospect Canyon.

Driftwood collected from the surfaces of the recent levees and an older levee (designated as surface F) was collected and radiocarbon dated to determine the association of organic material with the date of the debris flow that transported it (appendix 7; table 52). Driftwood collected from surface F yielded a radiocarbon age of 485±90 yrs BP, which corresponds to a calendric date range of AD 1330 to 1454. The young appearance of surface F, and lack of pedogenesis in the deposit, suggested the debris flow occurred in the last 1,000 years. Driftwood on top of the 1939 debris-flow levee yielded a radiocarbon age of 460±75 years BP, which corresponds to a calendric date range of AD1410 to 1473. Three samples of driftwood on the 1955 deposit provided radiocarbon ages of 635±80, 365±90, and 190±95 yrs BP; these correspond to calendric age ranges of AD 1279 to 1406, AD 1436 to 1644, and AD 1640 to 1955, respectively (appendix 7). Two samples of

Table 49. Historical photographs of Lava Falls Rapid (river mile 179.4) and the debris fan at the mouth of Prospect Canyon (river mile 179.4-L)

[The photographs listed in this table were obtained from private individuals and Grand Canyon National Park, Northern Arizona University Special Collections, University of Utah Special Collections, Utah State Historical Society, the Huntington Library, the National Archives, and the U.S. Geological Survey Photographic Library. For photographs taken before 1921, the discharge is estimated from known stage-discharge relations. In particular, see Kieffer (1988) for general stage-discharge relations for the rapid between 142 and 2,610 m3/s. For photographs taken between 1921 and 1963, discharge is estimated from daily discharge records of the previous day for the Colorado River near Grand Canyon. For unknown dates and after 1963, discharge is estimated from known stage-discharge relations. These estimates are perhaps accurate to ±30 m^3/s. (AV), vertical aerial photography; (AL), photograph is an oblique aerial taken from the left side of the river; (AR), photograph is an oblique aerial taken from the right side of the river; (RL), photograph was shot from river left; (RR), photograph was shot from river-right; (US), upstream view; (DS), downstream view; (AC), view across the river; (UC), view looking up the tributary channel or away from the river; (R), view shows a rapid; (DF), view shows debris fan(s); (--), no data; (n.m.), the photograph was analyzed but not matched; (n.a.), not applicable]

Year	Date	Photographer	Original number	Stake number	Side, direction	Subject	Discharge (m^3/s)
1872	Apr 16	Hillers	62	967	RR, DS	R, DF	283
	Apr 16	Hillers	896	2689	RR, AC	DF	na.
	Apr 19	Hillers	597	2744	RR, DS	DF	283
	Apr 19	Hillers	693	n.m.	RR, AC	R, DF	283
	Apr 19	Hillers	515	n.m.	RR, US	R, DF	283
	Apr 19	Hillers	602	2613	RR, US	R, DF	283
	Apr 19	Hillers	616	2598	RR, US	R	283
	Apr 19	Hillers	623	3005	RR, AC	R, DF	283
	Oct	Bell	243	2681	RR, AC	DF	na.
1890	Feb 27	Stanton	621	1510b	RL, DS	R, DF	226-396
1909	Nov 10	Cogswell	935	n.m.	RL, AC	R, DF	283
	Nov 10	Cogswell	936	n.m.	RL, US	R, DF	283
	Nov 10	Cogswell	937	n.m.	RL, US	R, DF	283
	Nov 10	Cogswell	938	n.m.	RL, US	R, DF	283
	Nov 10	Cogswell	940	1511	RL, US	R, DF	283
	Nov 10	Cogswell	941	n.m.	RL, DS	R, DF	283
	Nov 10	Cogswell	942	n.m.	RL, US	R, DF	283
	Nov 10	Cogswell	1161	2770	RL, US	R, DF	283
1911	Jan 1	Kolb	631	3052	RR, US	R, DF	28-85
	Jan 1	Kolb	632	2599	RR, DS	R, DF	28-85
1912	Jan 2	Kolb	4-4	2662	RL, US	R, DF	28-85
1923	Sep 18	LaRue	605	1732	RL, US	R, DF	255
	Sep 18	LaRue	606	2368	RL, US	R, DF	255
	Sep 18	LaRue	603	2769	RL, DS	R	2,970
1927	Aug 2	Eddy	92	1512	RL, AC	R, DF	510
	Aug 2	Eddy	93	2771	RL, US	R, DF	510
	Aug 2	Weatherhead	172.8	2663	RL, DS	R	510
1929	--	Scoyen	6616	967	RR, DS	R, DF	566
1930	Jul	Fraser	307 GDCN 179.1	967	RR, DS	R, DF	283-566
1934	July 31	Fahmi	3-254	2658b	RL, AC	R, DF	58
	July 31	Fahmi	3-255	2658c	RL, AC	R, DF	58
	July 31	Fahmi	3-258	2658a	RL, DS	R, DF	58
	July 31	Fahmi	3-260	2743	RL, US	R, DF	58
1937	Nov 16	Campbell	--	2045	RL, AC	R, DF	198

Table 49. Historical photographs of Lava Falls Rapid and the debris fan at the mouth of Prospect Canyon—Continued

Year	Date	Photographer	Original number	Stake number	Side, direction	Subject	Discharge (m^3/s)
	Nov 16	Maxon	275	n.m.	RL, US	R, DF	198
1938	--	Inglesby	[1]movie #7	n.m.	RR, AC	R, DF	>510
	Jul 29	Clover	2:14:14	2838	RL, US	R	357
1939	Jul	Gibson	[2]movie	n.m.	RL, AC	R, DF	218
1940	Aug 17	Goldwater	CR 24	2657	RL, AC	R, DF	71
	Aug 17	Goldwater	CR 57	2742	RL, DS	R, DF	71
	Aug 17	Goldwater	CR 34	2659	RL, UC	DF	71
1941	Jul 27	Heald	3:6:6	2741	RL, DS	R, DF	578
1942	Jul 26	Wilson	4:8:11	2660a	RL, AC	R, DF	459
	Jul 26	Wilson	4:6:8	2660b	RL, AC	R, DF	459
	Jul 26	Wilson	4:12:5	2834	RL, AC	R, DF	459
1947	Jul 22	Farquhar	477 GDCN 179.2.2	n.m.	RR, DS	R, DF	691
	Jul 27	Riffey	477 GDCN 179.444	1769	RL, AC	R, DF	524
	Jul 27	Marston	477 GDCN 179.2	1770	RL, AC	R, DF	524
	Jul 27	Marston	477 GDCN 179.12	1768	RL, AC	R, DF	524
	Jul 27	Nevills	5:12:1	2661	RL, AC	R, DF	524
1949	Jul 27	Anspach	497 GDCN 179.8	2004	RL, AC	R, DF	578
	Jul 27	Reilly	L6-35	2043	RL, DS	R, DF	578
1950	Jun 19	Belknap	48826	2772	RL, DS	R, DF	1,470
	Jun 19	Belknap	48833	n.m.	RR, AC	R, DF	1,470
	Jun 19	Belknap	48839	n.m.	RR, AC	R, DF	1,470
	Jun 19	Belknap	48841	803	RR, AC	R, DF	1,470
	Jul 25	Reilly	R01-11	2046	RL, US	R, DF	470
1951	Jul	Litton	--	967	RR, DS	R, DF	2,260
	Jul	Litton	--	969	RR, DS	R, DF	2,260
	Jul	Litton	--	2959	RR, DS	R, DF	2,260
	Sep	Eden	2082	969	RR, DS	R, DF	>283
	Sep	Eden	2085	967	RR, DS	R, DF	>283
	Sep	Eden	2087	967	RR, DS	R, DF	>283
1952	Jul	Nichols	--	2935	RL, DS	R, DF	1,130
	Jul	Nichols	--	2957	RL, DS	R, DF	1,130
	Jul	Nichols	--	2969	RL, AC	R, DF	1,130
	Jul	Litton	--	967	RR, DS	R, DF	1,130
	Jul	Litton	--	2968	RL, AC	R, DF	1,130
	Oct 22	Leding	2359	969	RR, DS	R, DF	164
	Oct 22	Leding	2360	969	RR, DS	R, DF	164
1953	Jul	Frost	--	2971a	RL, US	R, DF	708
	Jul	Frost	--	2971b	RL, DS	R	708
1954	Jun 14	Visbak	JV VI 5	2961	RR, DS	R, DF	360
	Jul	Nichols	--	2966	RR, DS	DF	>991
	Aug 29	Visbak	--	n.m.	RR, DS	R, DF	133
1955	Mar 19	Reilly	L11-13	n.m.	AR, DS	R, DF	538

Table 49. Historical photographs of Lava Falls Rapid and the debris fan at the mouth of Prospect Canyon—Continued

Year	Date	Photographer	Original number	Stake number	Side, direction	Subject	Discharge (m^3/s)
	Mar 19	Reilly	L11-14	n.m.	AL, AC	R, DF	538
	Mar 19	Reilly	L11-15	n.m.	AR, DS	R, DF	538
	Mar 19	Reilly	L11-16	n.m.	AR, AC	R, DF	538
	Mar 21	Reilly	L12-13	n.m.	AV		R, DF
	Mar 21	Reilly	L12-14	n.m.	AR, US	R, DF	396
	Mar 21	Reilly	L12-15	n.m.	AV		R, DF
	Apr 29	Beer	--	2972	RL, AC	R	430
	Apr 29	Beer	--	2934	RL, US	R, DF	430
	Apr 29	Beer	[3]movie	n.m.	RL, AC	R, DF	430
	Jul 20	Beckwith	--	n.m.	RL, AC	R, DF	209
	Oct	Hamilton	8352	969	RR, DS	DF	114
	Oct	Hamilton	8353	969	RR, DS	R, DF	114
	Oct	Hamilton	46-3-5605	969	RR, DS	R, DF	114
1956	Mar 25	Marston	563 GDCN 179.8	969	RR, DS	R, DF	181
	Mar 25	Reilly	L19-26	n.m.	AR, DS	R, DF	181
	Mar 25	Reilly	L19-27	n.m.	AL, AC	R, DF	181
	Mar 25	Reilly	L19-28	n.m.	AL, US	R, DF	181
	Mar 25	Reilly	L19-33	967	RR, DS	R, DF	181
	Mar 25	Reilly	L19-34	967	RR, DS	R, DF	181
	Mar 25	Reilly	L19-35	967	RR, DS	R, DF	181
	Apr 16	Reilly	L24-2	n.m.	AR, US	R, DF	297
	Apr 16	Reilly	L24-7	969	RR, DS	R, DF	297
	Apr 16	Reilly	G-875	969	RR, DS	R, DF	297
	Apr 16	Reilly	G-164	967	RR, DS	R, DF	297
	Sep 29	Reilly	L26-14	n.m.	AV		R, DF
	Sep 29	Reilly	L26-15	n.m.	AV		R, DF
	Sep 29	Reilly	L26-16	n.m.	AR, US	R, DF	79
1957	Apr 14	Reilly	L28-29	n.m.	AL, AC	R, DF	249
	Apr 14	Reilly	L28-30	n.m.	AL, AC	R, DF	249
	May 4	Reilly	L29-23	n.m.	AR, DS	R, DF	521
	May 4	Reilly	L29-24	n.m.	AL, DS	R, DF	521
	May 4	Reilly	L29-25	n.m.	AL, AC	R, DF	521
	May 4	Reilly	L29-26	n.m.	AL, AC	R, DF	521
	May 4	Reilly	L29-27	n.m.	AR, DS	R, DF	521
	May 4	Reilly	L29-28	n.m.	AR, AC	R, DF	521
	Jul 13	Nichols	--	2932	RL, DS	R, DF	1,982
	Jul 13	Beckwith	II-17	1586	RL, DS	R, DF	1,982
	Aug 29	Butchart	--	n.m.	RL, AC	R, DF	589
1958	Apr 20	Reilly	L37-33	n.m.	AL, AC	R, DF	708
	Apr 20	Reilly	L37-34	n.m.	AL, AC	R, DF	708
	Jun 1	Reilly	L40-8	969	RR, DS	R, DF	3,000
	Jun 1	Reilly	L40-10	969	RR, DS	R, DF	3,000

Table 49. Historical photographs of Lava Falls Rapid and the debris fan at the mouth of Prospect Canyon—Continued

Year	Date	Photographer	Original number	Stake number	Side, direction	Subject	Discharge (m^3/s)
	Jun 1	Reilly	L40-13	n.m.	AV		R, DF
	Jun 1	Reilly	L40-17	n.m.	AR, DS	R, DF	3,000
	Jun 1	Reilly	L40-20	n.m.	AR, DS	R, DF	3,000
	Jul 20	Stavely	--	2002	RL, DS	R, DF	218
	Oct 4	Reilly	L41-18	n.m.	AL, DS	R, DF	187
	Oct 4	Reilly	L41-19	n.m.	AL, DS	R, DF	187
	Oct 4	Reilly	L41-20	n.m.	AR, US	R, DF	187
	Oct 4	Reilly	G-407	n.m.	AR, US	R, DF	187
	Oct 4	Reilly	G-415	n.m.	AL, DS	R, DF	187
	Oct 4	Reilly	G-417	n.m.	AR, US	R, DF	187
1959	Aug 21	Dodge	8346	967	RR, DS	DF	224
1960	Jun 23	Marston	606 GDCN 179.2.19	1585	RL, DS	R, DF	1,140
	Jun 23	Marston	48832	1587b	RL, DS	R, DF	1,140
	Jun 23	Marston	606 GDCN 179.18.10	1588	RL, DS	R, DF	1,140
	Jun 23	Marston	606 GDCN 179.2.14	1587a	RL, DS	R, DF	1,140
	Oct 2	Reilly	L48-32	n.m.	AR, AC	R, DF	125
	Oct 2	Reilly	L48-33	n.m.	AL, AC	R, DF	125
	Oct 2	Reilly	L48-34	n.m.	AR, AC	R, DF	125
1961	Oct	Jones	46	2967	RL, AC	R, DF	57
1962	Jul 10	Reilly	L58-3	2003	RL, AC	R, DF	1,130
	Jul 10	Reilly	L58-4	2835	RL, DS	R, DF	1,130
	Nov 3	Reilly	L61-2	n.m.	AR, DS	R, DF	225
	Nov 3	Reilly	L61-4	n.m.	AL, AC	R, DF	225
	Nov 3	Reilly	L61-5	n.m.	AL, US	R, DF	225
	Nov 4	Reilly	R74-8	n.m.	AL, AC	R, DF	225
1963	May	Wieland	24	969	LR, DS	R, DF	37
	Aug 22	Belknap	48822	n.m.	AL, US	R, DF	57
	Aug 22	Belknap	48823	n.m.	AL, US	R, DF	57
	Aug 24	Belknap	48858	2746	RR, AC	R, DF	57
	Aug 24	Belknap	48865	2746	RR, AC	R, DF	57
	Aug 24	Belknap	48824	969	RR, DS	R, DF	57
	Aug 25	Belknap	48866	803	RR, AC	R, DF	57
	Sep 25	--	63-9-25 GDCN 179-25	1589	RR, DS	R, DF	35
	Sep 25	--	63-9-25 GDCN 179-28	2005	RR, US	R, DF	35
1964	Apr 6	Visbak	34	n.m.	AV		R, DF
	Apr 6	Visbak	36	n.m.	AR, DS	R, DF	405
	May 12	Reilly	L70-32	2044	RL, AC	R, DF	348
	May 20	Reilly	L71-26	n.m.	AL, US	R, DF	37
	May 20	Reilly	L71-28	n.m.	AR, DS	R, DF	37
	May 20	Reilly	L71-29	n.m.	AR, US	R, DF	37
	May 20	Reilly	L71-30	n.m.	AR, US	R, DF	37
	May 20	Reilly	L71-32	n.m.	AL, US	R, DF	37

Table 49. Historical photographs of Lava Falls Rapid and the debris fan at the mouth of Prospect Canyon—Continued

Year	Date	Photographer	Original number	Stake number	Side, direction	Subject	Discharge (m^3/s)
	May 20	Reilly	L71-33	n.m.	AL, AC	R, DF	37
	May 20	Reilly	L71-34	n.m.	AL, AC	R, DF	37
	May 20	Reilly	L71-36	n.m.	AR, US	R, DF	37
1965	Feb 21	Visbak	16	1592	RR, DS	R, DF	198
	Feb 21	Visbak	24	3050	RR, US	R, DF	198
	Feb 21	Visbak	14	967	RR, DS	R, DF	198
	Feb 22	Visbak	36	n.m.	RR, DS	R, DF	198
	May 18	WRD	--	n.m.	AV		R, DF
	May 21	Harris	2	3010	RL, DS	R, DF	792
	May 21	Harris	3	2836	RL, AC	R, DF	792
1966	May 19	Hertzog	6525NA	969	RR, DS	R, DF	340
	Jul	Belknap	83(157)	n.m.	RR, DS	R, DF	198
1967	Apr 30	Harris	P557-400-896	2739	RL, AC	R, DF	283
	Aug	Luepke	--	n.m.	RL, DS	R, DF	--
	Aug	Luepke	--	n.m.	RL, DS	R, DF	--
1968	Sep 26	Stephens	3515	n.m.	RR, US	R, DF	283
	Sep 26	Stephens	3693	n.m.	RR, AC	R, DF	283
	Sep 26	Stephens	3597	2744	RR, DS	DF	283
1969	Jul	Harris	4	2740b	RL, AC	R	566-849
	Jul	Harris	1	2740a	RL, AC	R	566-849
	Sep 14	Marston	69-9-14 GDCN 179-5	n.m.	RL, DS	R, DF	
1970	Oct	Mooz	16	n.m.	RL, US	R, DF	141-368
1972	--	Litton	--	2677	RR, AC	R, DF	283-424
	--	Litton	--	2962	RR, US	R, DF	283-424
	--	Litton	--	2963	RR, US	R, DF	283-424
1973	Jun 19	USGS	516 WRD	n.m.	AV		R, DF
	Jun 19	USGS	517 WRD	n.m.	AV		R, DF
	Jun 19	USGS	518 WRD	n.m.	AV		R, DF
1976	Sep 26	Turner	803	803	RR, AC	R, DF	99
1977	--	Brown	--	2837	RR, US	R, DF	<85
	--	Brown	--	2907	RR, US	R, DF	<85
	--	Brown	--	n.m.	RR, US	R, DF	<85
1979	Jun 10	Turner	967	967	RR, DS	R, DF	227
	Jun 10	Turner	48824	969	RR, DS	R, DF	227
1983	Oct 31	Turner	803	803	RR, AC	R, DF	765

[1]The movie, titled "Hiking to Lava Falls," was shot by Dr. Inglesby in 1938 (Utah Historical Society). The movie shows panning shots of the rapids and close-ups of the waves.

[2]The movie was shot by Bill Gibson on the Harris-Loper river trip of July 1939.

[3]The movie was shot by John Daggett and Bill Beer in April 1955.

[4]These are matches of the Hillers' photographs of the same number; see Stephens and Shoemaker (1987).

Table 50. Debris fans deposited at Lava Falls Rapid (river mile 179.3) between 1939 and 1963

[(HF), hyperconcentrated flow; (DF), debris flow; Maximum area, determined by projecting non-eroded fan deposits across depositional areas. Measurements were made with calibrated and rectified aerial photographs using the Map and Image Processing System (MIPS) software; Minimum area, measurements of non-eroded deposits using the calibrated on-line planimeter within MIPS software (use of trade names does not imply endorsement by the U.S. Geological Survey); Maximum thickness, field surveys of non-eroded debris flow deposits; Minimum thickness, depth of debris flow deposits that were required to cover the largest pre-existing boulders at mouth of Prospect Creek; Constriction, constricted river channel width divided by the average river channel width immediately upstream of the rapid times 100, estimated at an approximate discharge of 142 cubic meters per second; Reduction in area, is the ratio of the cross-sectional area at the constriction after the debris flow, divided by the cross-sectional area at the constriction before the debris flow times 100; estimated at a discharge of 142 m3/s; (n.d.), no data; (n.a.), not applicable]

Year of flood (type)	Maximum debris fan area (m^2)	Minimum debris fan area (m^2)	Average debris fan area (m^2)	Maximum debris fan thickness (m)	Minimum debris fan thickness (m)	Average debris fan thickness (m)	Maximum debris fan volume (m^3)	Minimum debris fan volume (m^3)	Average debris fan volume (m^3)	River constriction ratio (%)	Reduction in cross-sectional area (%)
1939 (DF)	12,500	9,300	11,000	5.0	2.0	3.5	62,500	18,600	38,200	n.d.	n.d.
1954 (DF)	4,200	2,700	3,500	2.0	1.2	1.6	8,400	3,200	5,500	n.a.	n.a.
1955 (DF)	7,300	6,300	6,800	2.9	1.2	2.1	21,000	7,600	14,000	30	45
1956 (HF)	2,400	2,400	2,400	1.8	1.2	1.5	4,300	2,900	3,600	n.a.	n.a.
1963 (DF)	7,300	5,100	6,200	2.6	1.2	1.9	19,000	6,100	11,800	45	42

driftwood from the 1963 deposits provided post-bomb radiocarbon ages of 153.8±1.5 and 141.1±1.1 PMC, which correspond to calendric date ranges of AD 1963 or 1969 and AD 1959, 1961, or 1981, respectively. Finally, driftwood deposited by a flood in 1993 provided a post-bomb radiocarbon age of 127.7±1.3 PMC, which corresponds to a calendric date of AD 1962 or 1974. The radiocarbon analyses indicate that organic materials may only rarely be flushed from Prospect Creek. Both the 1939 and 1955 debris flows transported wood that was significantly older than the known date of the transporting debris flow.

Discharge Estimates

We estimated peak discharges for the 1939, 1955, and 1963 debris flows at a single cross section in a right-hand bend about 50 m upstream from the Colorado River (cross section A-A, fig. 53). This discharge estimate site has no bedrock control in the channel, the high-water evidence is poorly preserved, and the channel geometry for the 1939 and 1955 events was reconstructed from aerial photography. Therefore, we consider these peak discharges to be order-of-magnitude estimates. Comparison of the debris-flow levees deposited on the inside of the channel bend indicated superelevation for the debris flows of 1939 and 1963 and runup for the debris flow of 1955. We estimated a peak discharge of about 1,000 m^3/s for the debris flow of 1939 (table 53), which indicates this debris flow peak discharge was likely the largest in Grand Canyon during the last 122 years. The 1955 and 1963 debris flows, which travelled through a greatly constricted channel of Prospect Canyon as a result of deposition by the 1939 debris flow, had substantially lower peak discharges on the order of 260 to 340 m^3/s (table 53).

Sediment Characteristics

Particle-size distributions were measured for the levees deposited by the 1939 and 1963 debris

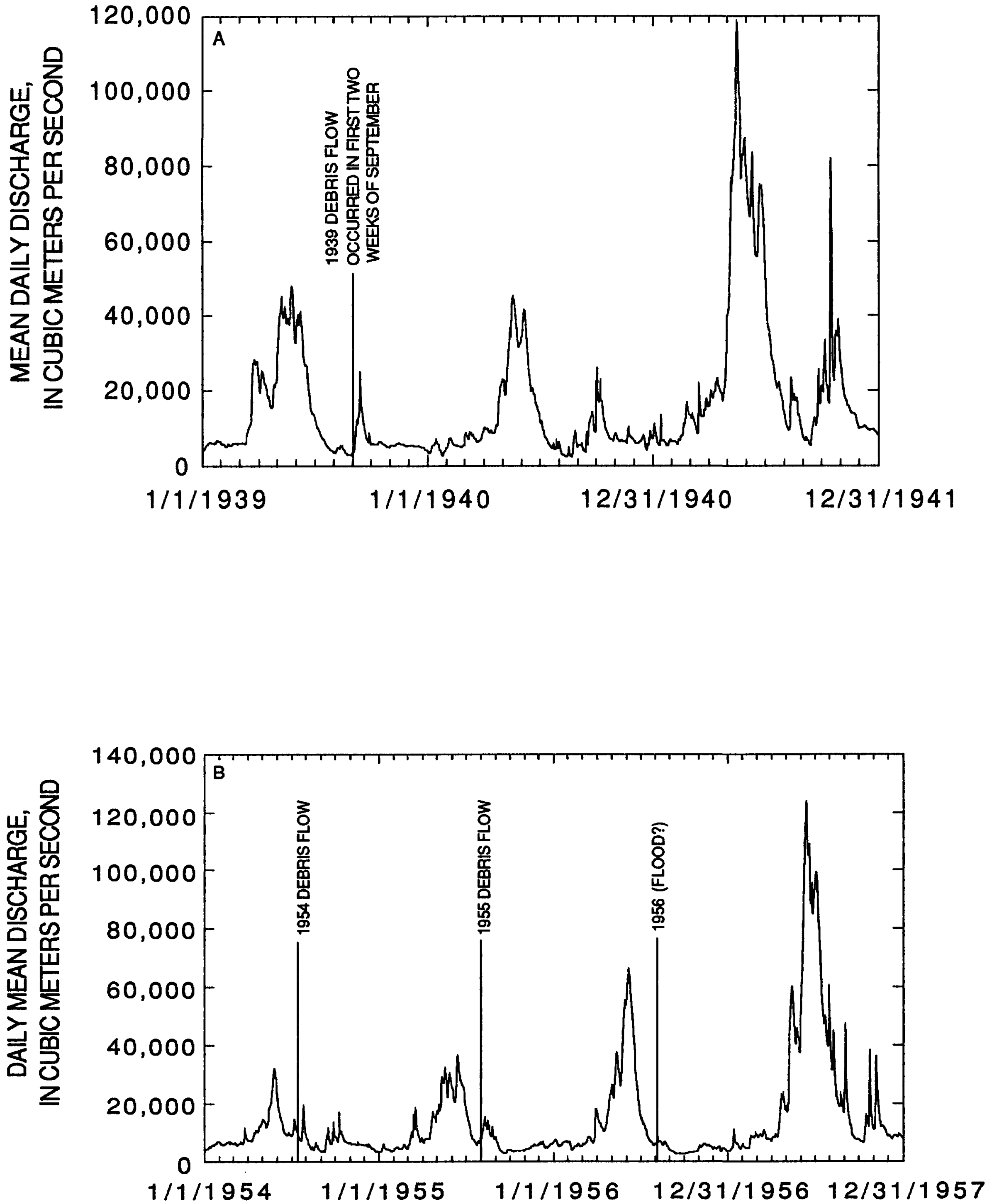
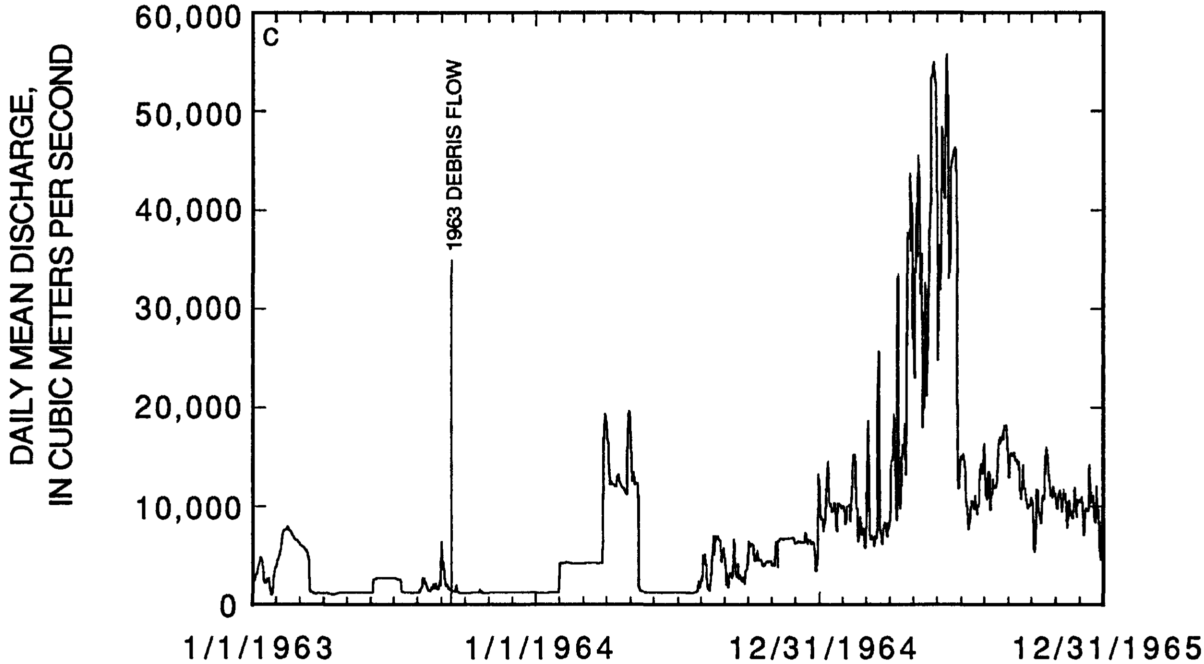


Figure 55. Hydrographs of the Colorado River during periods of reworking of the aggraded debris fans at Lava Falls Rapid (river mile 179.3). All hydrographs were measured at the gaging station named "the Colorado River near Grand Canyon, Arizona," at river mile 87. *A*, Hydrograph of 1939 to 1942. *B*, Hydrograph of 1954 to 1958.



C, Hydrograph of 1963 to 1966.

Figure 55. Continued.

flows, the reworked debris-fan deposit on the left side of the rapid, and the 1993 hyperconcentrated-flow deposit. The 1963 debris-flow levee contained about 11 percent sand-and-finer sediment (fig. 57A). The particle-size distribution (>2 mm) of the 1939 debris flow is similar to that of the 1963 deposit (fig. 57A). Both of these particle-size distributions contrast greatly when compared to the reworked debris fan on the left side of the rapid, which we interpreted as the remnant of the 4 debris flows (fig. 57A). Most of the reworking occurred between 1939 and 1965 (fig. 55). In contrast to the 1963 debris flow, the 1993 hyperconcentrated-flow deposit contained about 28 percent sand-and-finer sediment (fig. 57A).

A comparison of source distributions for the undisturbed 1963 debris-flow levee and the reworked debris fan indicates that whereas most of the sediment in the 1963 debris flow consisted of Redwall Limestone, most of the large boulders that have aggraded the debris fan between 1939 and 1963 were of Quaternary basalt (fig. 57B). Only about 5 percent of the boulders found on the left side of the rapid are Redwall Limestone. This provides another example of how certain lithologies may dominate debris flows but may not be important in the formation and stability of rapids. The <16 mm fraction of the 1963 debris flow was reconstituted to yield a weight-percent water content of between 11 and 17 percent.

Unnamed Tributary at River Mile 207.8-L

A debris flow that occurred in an unnamed tributary at river mile 207.8-L in September 1991 caused minor aggradation of an existing debris fan. The tributary drains 3.09 km^2 on the south side of the Colorado River (fig. 58). This tributary is underlain exclusively by Paleozoic strata, primarily Redwall and Muav Limestone and Bright Angel Shale. The tributary channel is steep and large quantities of colluvium have accumulated on Muav Limestone and Bright Angel Shale beneath cliffs of Redwall Limestone. The Granite Park Fault trends southeast through the upper reaches of the drainage (Huntoon and

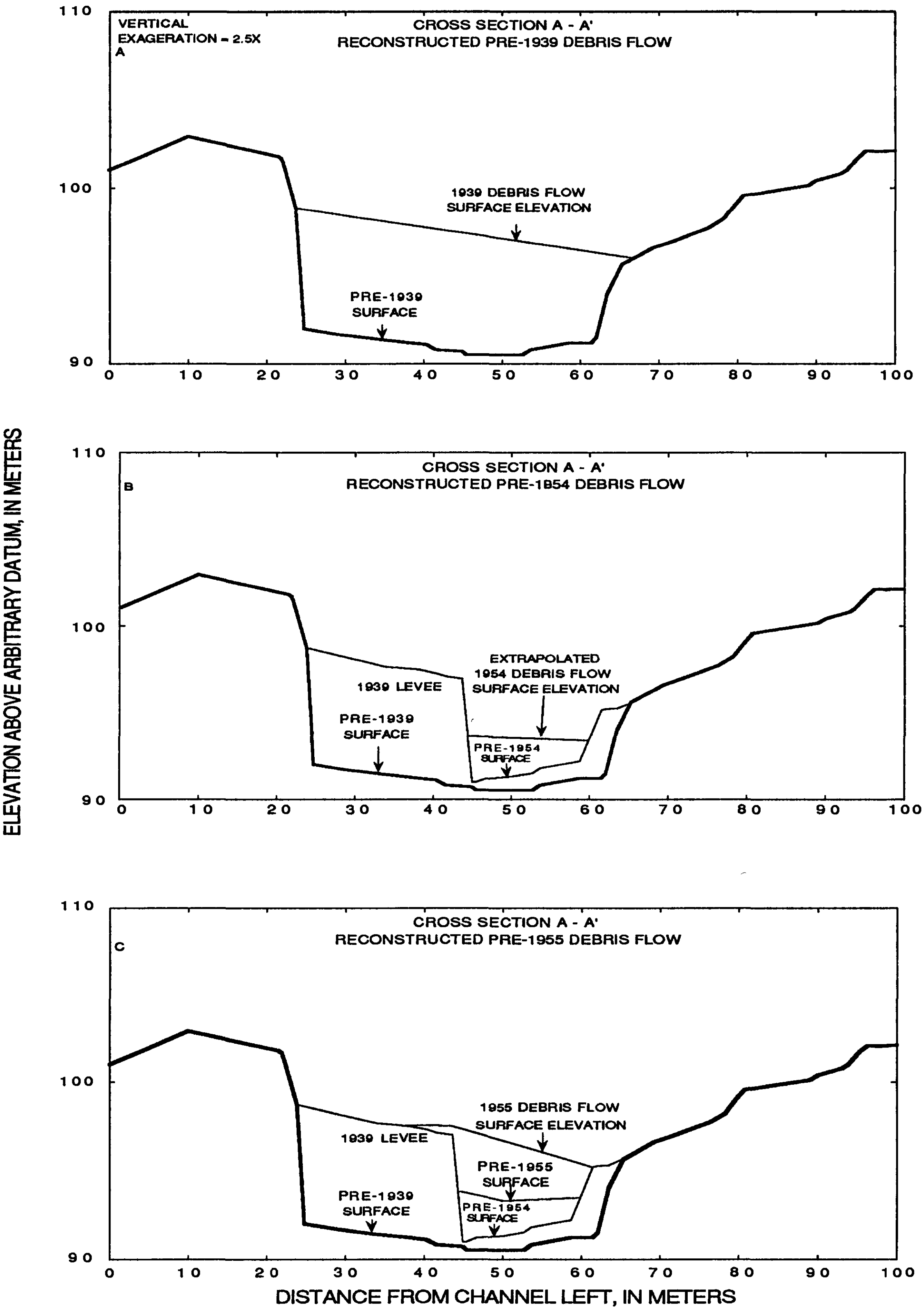


Figure 56. Cross-sectional diagrams showing the evolution of the channel morphology of Prospect Canyon (river mile 179.4-L) caused by four debris flows and one hyperconcentrated flow that occurred in 1939, 1954, 1955, 1956, and 1963.

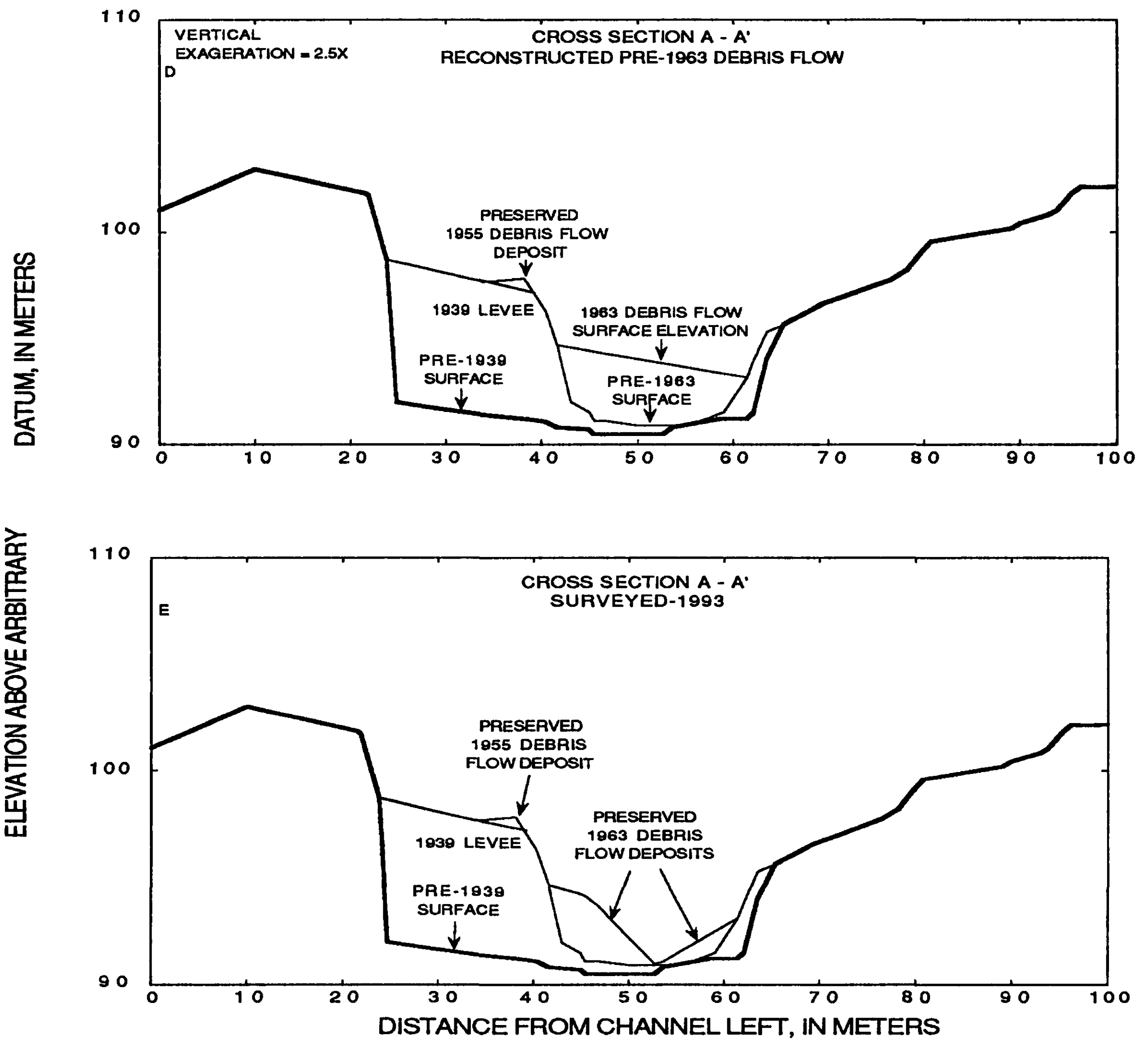


Figure 56. Continued.

others, 1986). This large fault is down-thrown to the southwest; it is the dominant geologic structure in western Grand Canyon.

Sediment Characteristics

Particle-size distributions were determined for the tributary-reworked surface of the 1991 debris-fan deposits at site C. An 8.2-kg sample of debris-flow matrix was collected from a levee in the main channel at site B, and a 4.5-kg sample of hyperconcentrated-flow sediment was collected at site A. The <64 mm fraction of the debris-flow sample contained 18 percent sand-and-finer sediment, whereas the hyperconcentrated-flow sample contained 90 percent sand-and-finer sediment (fig. 59A). An activity of 0.2±0.1 pCi/g of ^{137}Cs was measured in one sample of debris-flow matrix; two additional samples yielded activities of 0.29±0.02 and 0.31±0.02 pCi/g. A source distribution of the reworked debris fan indicates that most of the coarse sediment in the 1991 debris flow was Muav and Redwall Limestones (fig. 59B). The <16 mm fraction of the debris-flow sample had a weight-percent water content of 13 to 16 percent.

Discharge Estimates

Two indirect estimates of peak discharge were made for the 1991 debris flow in the unnamed

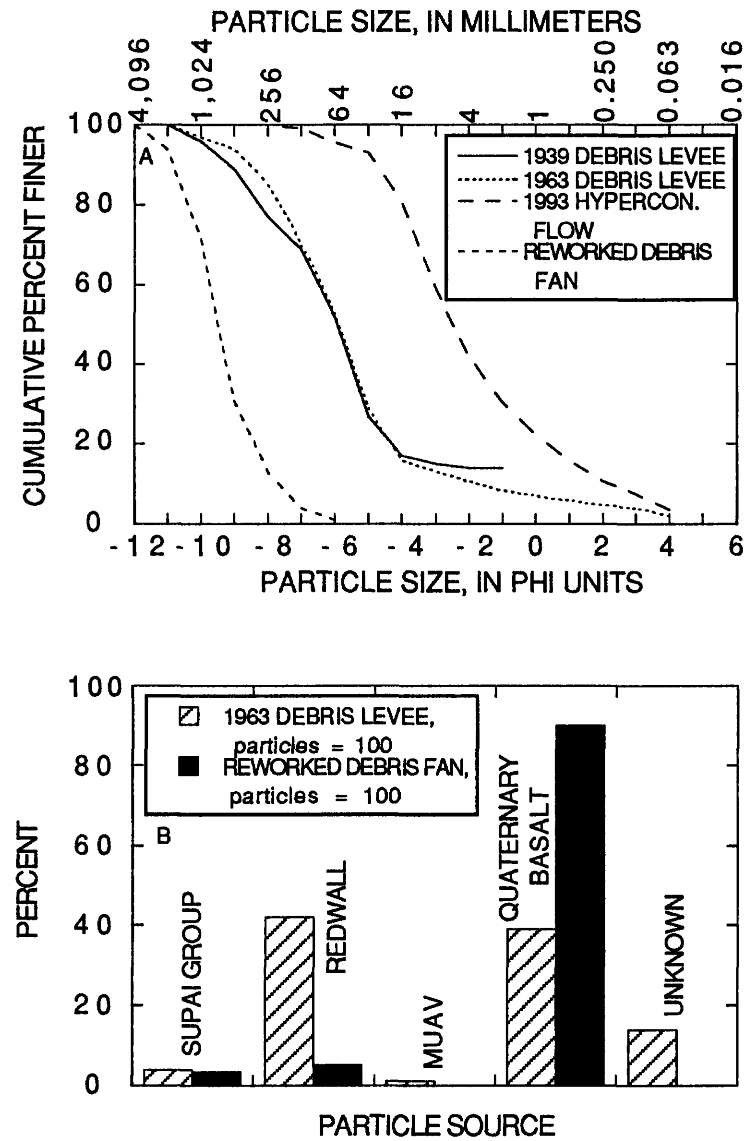


Figure 57. Particle-size and source distributions of various sediment deposits associated with recent debris flows between 1939 and 1963 that occurred at Prospect Canyon (river mile 179.4-L). *A*, Particle-size distributions of debris-flow levees deposited in 1939 and 1963, a 1993 hyperconcentrated-flow deposit, and the reworked distal edge of the 1939 debris-flow deposit. *B*, Source distributions of particles on the 1963 debris-flow levee, and the reworked distal edge of the 1939 debris-flow deposit.

Table 51. List of ^{137}Cs activities of sediment collected from historic debris-flow deposits near the mouth of Prospect Canyon (river mile 179.4-L)

Deposit Date	Type of sediment	Activity of ^{137}Cs (pCi/g)	Expected result
1939	<2 mm	0.08±0.01	no detection
	<2 mm	0.0±0.1	no detection
1955	<2 mm	1.02±0.05	detection; sizeable activity
1963	<0.063 mm	0.2±0.1	detection; sizeable activity
	<2 mm	2.43±0.11	detection; sizeable activity
	<2 mm	0.0±0.1	detection; sizeable activity
	<2 mm	0.0±0.1	detection; sizeable activity
	<2 mm	0.0±0.1	detection; sizeable activity
1993	<2 mm	0.09±0.01	detection

tributary at river mile 207.8-L. The first estimate was made at site A, where evidence of superelevated debris flow was preserved in a left-hand bend in the channel. Using this evidence, we estimated a peak discharge of 26 m^3/s (table 54).

Site B, just downstream from site A, contained evidence of runup preserved on a bedrock wall in a 90-degree channel bend for a debris flow that originated in a small, steep side canyon of the main channel. The debris flow in the side canyon scoured the channel to the underlying Muav Limestone; most of the debris-flow activity began in this part of the drainage. Most of the sediment entrained by the debris flow came from steep slopes of colluvium that were eroded during intense precipitation. The runup at site B consisted of large boulders deposited on top of a bedrock outcrop at the junction of the tributary and main channels. Peak discharge for the debris flow in this side canyon was 190 m^3/s (table 55).

Table 52. List of radiocarbon dates of organic material collected from historic debris-flow deposits at the mouth of Prospect Canyon (river mile 179.4-L)

[Debris surface, indicated by year of debris flow, if known exactly; otherwise the surface is designated by letter. BP, years before present (AD 1950). PMC, percent of modern carbon]

Debris surface	Type of organic material	Radiocarbon date	Calendric date (AD)
Surface F	driftwood	485±90 yrs BP	AD 1330 to 1454
1939 levee	driftwood	460±75 yrs BP	AD 1410 to 1473
1955 levee	driftwood	365±90 yrs BP	AD 1436 to 1644
	driftwood	190±95 yrs BP	AD 1640 to 1955
	driftwood	635±80 yrs BP	AD 1279 to 1406
1963 levee	driftwood	153.8±1.5 PMC	AD 1963 or 1969
	driftwood	141.1±1.1 PMC	AD 1962 or 1974
1993 gravel	driftwood	127.7±1.3 PMC	AD 1959, 1961, or 1981

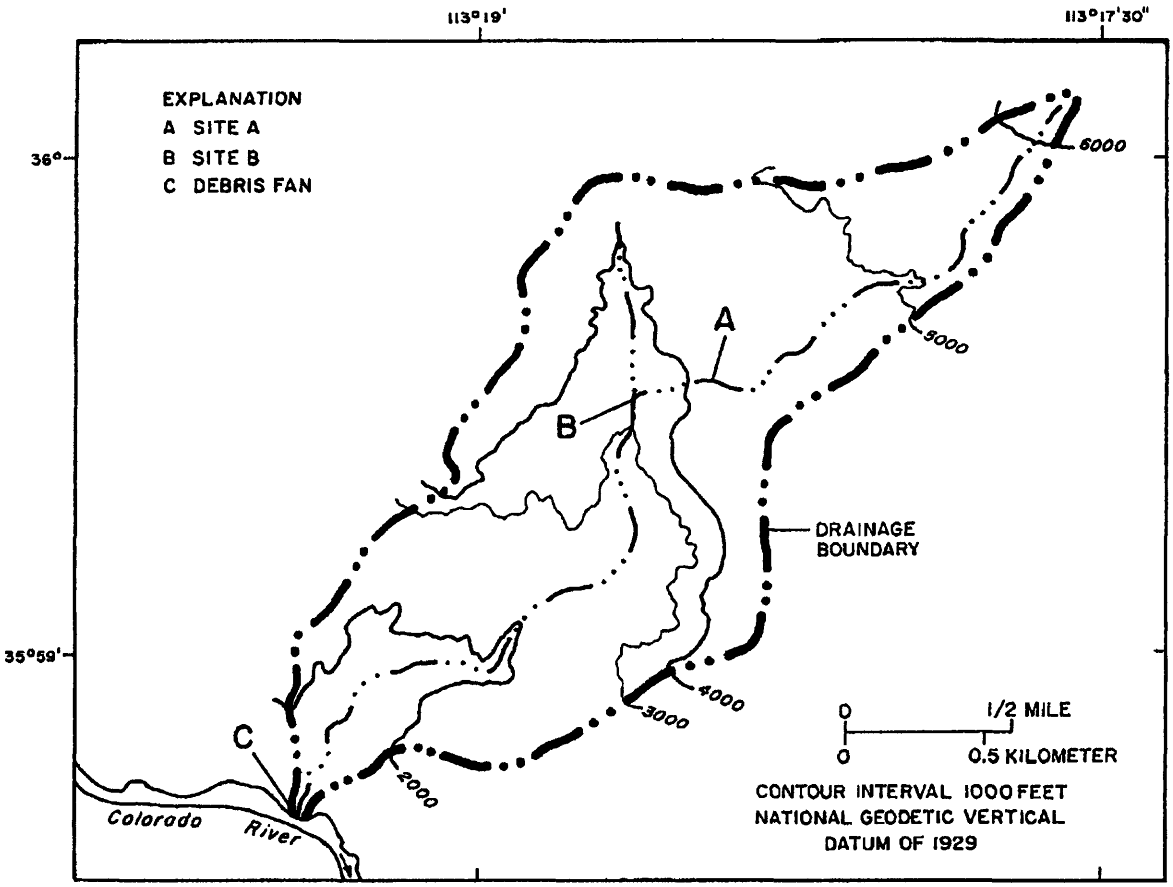


Figure 58. The drainage basin of an unnamed tributary of the Colorado River at river mile 207.8-L in Grand Canyon.

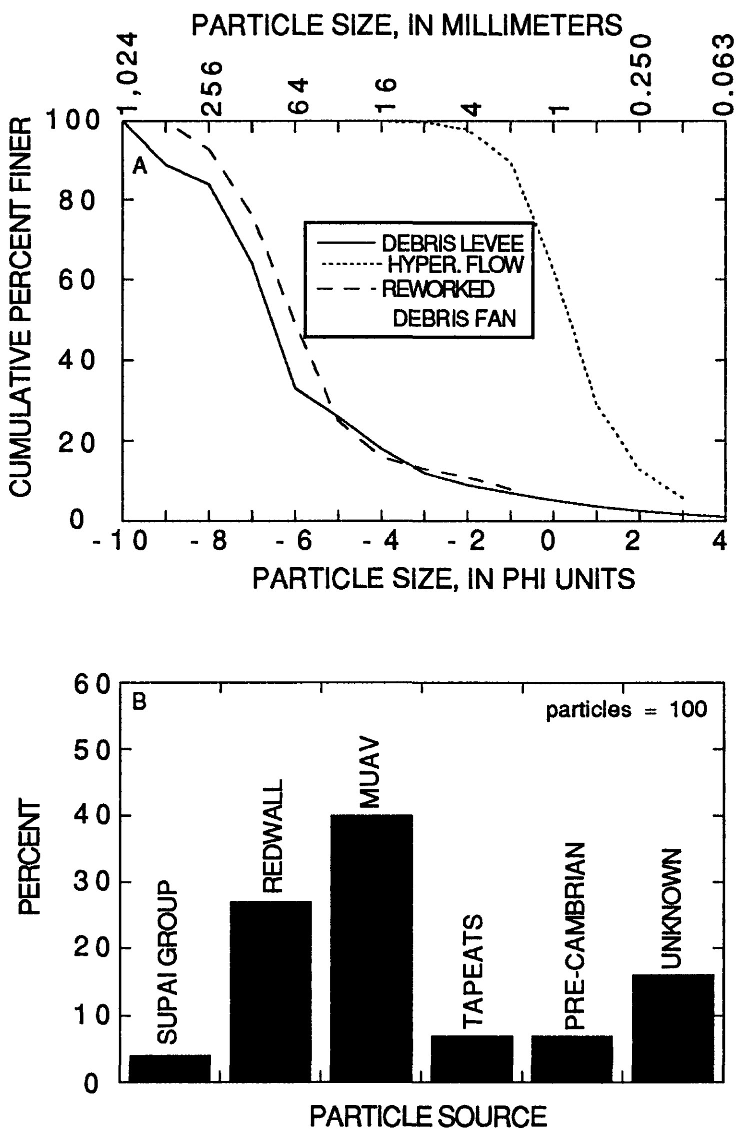


Figure 59. Particle-size and source distributions of various deposits associated with the debris flow of 1991 in an unnamed tributary of the Colorado River at river mile 207.8-L. *A*, Particle-size distributions of an undisturbed 1991 debris-flow levee, a 1991 hyperconcentrated-flow deposit, and the reworked distal edge of the 1991 debris fan. *B*, Source distribution of particles on the undisturbed 1991 debris-flow deposit.

Volume of the 1991 Debris-Flow Fan Deposit

The volume of the 1991 debris fan (400 m^3) was estimated using a surveyed area of 400 m^2 for the fan deposit and a thickness of 1 m. The volume of sand-and-finer sediment contained in the debris fan was about 70 m^3, based on the particle-size distribution of the debris-fan surface. On the basis of aerial photographs, the 1991 debris flow was the first to occur in the unnamed tributary at river mile 207.8-L since 1965.

209-Mile Canyon (River Mile 208.6-R)

209-Mile Canyon (fig. 1) drains 95.46 km^2 on the north side of the Colorado River. Interbedded debris-flow deposits and sands from the Colorado River were examined in the mouth of this tributary. We found a piece of wood identified as Arizona walnut (*Juglans microcarpa*) embedded in the most recent debris-flow deposit. The nearest source of Arizona walnut is probably 5 to 10 km upstream in 209-Mile Canyon, which indicates the wood was transported in the debris flow. A radiocarbon date of 285±60 yrs BP was obtained on this wood sample. This date indicates that the most recent debris flow in 209-Mile Canyon occurred between AD 1513 to 1658.

UnnamedTributary at River Mile 222.6-L

The unnamed tributary at river mile 222.6-L drains 0.58 km^2 on the south side of the Colorado River in western Grand Canyon (fig. 1). Evidence of debris-flow activity in the drainage basin

Table 53. Indirect peak-discharge estimates for the debris flows of 1939, 1955, and 1963 in Prospect Canyon (river mile 179.4-L), measured at cross section A-A'

[Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Type of estimate procedure used: superelevation in a right-hand bend
Outside high-water mark: continuous line of boulders
Inside high-water mark: continuous scourline and boulders
Visually estimated percentage of channel controlled by bedrock: 0% (alluvial channel)

Superelevation and runup data

Channel slope (S) = 0.093

1939
Radius of curvature (R_c) = 52 m
Elevation difference (ΔHs) = 3.0 m
Mean velocity (V_s) = 6.2 m/s
Channel top width (W) = 40 m

1955
Elevation difference (ΔH_r) = 0.7 m
Mean velocity (V_r) = 3.7 m/s

1963
Radius of curvature (R_c) = 48 m
Elevation difference (ΔH_s) = 1.5 m
Mean velocity (V_s) = 6.0 m/s
Channel top width (W) = 20 m

Cross-section data

Cross-section name	Area, in square meters	Discharge, in cubic meters per second	Site rating
1939	[1]169	1,000	Poor
1955	[1]71	260	Poor
1963	[1]57	340	Poor

[1]Cross sectional area at ΔH_s or ΔH_r

includes debris-flow levees deposited near the confluence with the Colorado River. The tributary is underlain by both Paleozoic and Proterozoic strata (fig. 3) and is traversed by the southwest-trending Hurricane Fault (Huntoon and others, 1986).

The frequency of debris flows in this drainage basin was determined using a combination of repeat photography and aerial photography. An 1890 photograph, replicated in 1991, documents the occurrence of one debris flow (fig. 60). The aggraded debris fan appears in a 1965 aerial photograph, and analyses of two samples of debris-flow matrix yielded no detectable activity of ^{137}Cs. Therefore, the debris flow occurred between 1890 and 1952. Analysis of aerial photography indicates that the debris flow had occurred by 1965. No aerial photographs from 1935 are available.

Replication of the 1890 photograph revealed that the separation bar downstream from the debris fan at mile 222.6 increased in size after 1890 (fig. 60). The enlarged sand bar also appears in a 1965 aerial photograph. The changes in this sand bar are probably directly related to the altered geometry of the aggraded debris fan.

Unnamed Tributary at River Mile 224.5-L

The unnamed tributary at river mile 224.5-L drains 0.45 km^2 on the south side of the Colorado River in western Grand Canyon (fig. 61). The tributary is underlain by Paleozoic and Precambrian rocks and is cut by the southwest-trending Hurricane and Three Springs Faults, which are parallel along the east side of the Colorado River in this reach (Huntoon and others, 1986).

The frequency of debris flows in this drainage is based on repeat and aerial photography and analysis of ^{137}Cs. The 1890 view, replicated in February 1991, revealed that a boulder levee was deposited on the debris fan after 1890 (fig. 62); none of the boulders visible in the 1890 view could be identified in 1991. Two samples of sediment from the debris-flow levee had no detectable activity of ^{137}Cs. Therefore, the debris flow occurred between 1890 and 1952. The debris flows at river mile 222.6-L and 224.5-L may have occurred during the same storm, but the precise relation between debris-flow activity in the two tributaries cannot be determined. Comparison of 1935, 1965, and 1973 aerial photographs reveals no significant changes in the debris fan. Therefore, the debris flow in the unnamed tributary at river mile 224.5-L occurred between 1890 and 1935 and is the only debris flow in this tributary during the last century.

A particle-size distribution was determined for 1890 to 1935 debris flow. Point-count data collected from the surface of the debris-flow levee and sieve data from a 23-kg sample were combined. The <64 mm fraction of sediment contained 32 percent sand-and-finer sediment and 62 percent gravel (fig. 63A). The <16 mm fraction was reconstituted, yielding a weight-percent water content of 16 to 18 percent. A source distribution shows that the debris flow consisted mostly of Redwall Limestone along with lesser amounts of Muav Limestone (fig. 63B).

Diamond Creek (River Mile 225.8-L)

Diamond Creek (fig. 1) drains 716.74 km^2, most of which is covered by forests and grasslands on the south side of the Colorado River. Debris flows in Diamond Creek are an important hazard because it is used as an access route to the Colorado River by tourists and thousands of commercial river runners annually. A debris flow that occurred in July 1984 has been previously described (Carothers and Brown, 1991, p. 46-47; Ghiglieri, 1992, p. 270-276; Webb, in press). The debris flow destroyed several vehicles including a 2-ton truck used by commercial river runners and deposited a large amount of sediment on the debris fan.

We were unable to determine either a peak discharge or depositional volume for the July 1984 debris flow in Diamond Creek. However, anecdotal accounts of the flood, recounted by commercial river guides who witnessed the debris flow, reveal much about the process of debris flow (Webb, in press). The initial pulse of debris contained abundant wood (including trees) along with boulders and poorly-sorted sediment (Dennis Silva, oral commun., 1993). Recessional muddy streamflow continued for several hours after the initial surge.

According to others, Diamond Creek experienced several flash floods during the summer

Figure 60. Replicate photographs of the debris fan of an unnamed tributary at river mile 222.6-L in Grand Canyon. *A,* The original view, looking downstream, was taken on March 1, 1890 (Robert Brewster Stanton, number 660, National Archives).

B, The replicate view, taken on February 26, 1991 (Raymond M. Turner, U.S. Geological Survey, stake 1521b), shows a prominent debris-flow terrace that covers the foreground of the 1890 view. This debris flow occurred on an unknown date sometime between 1890 and 1965. The large separation bar that has been deposited downstream from the aggraded debris fan is probably an effect of the aggraded debris fan.

Figure 60. Continued.

Table 54. Indirect peak-discharge estimate for the September 1991 debris flow in an unnamed tributary at river mile 207.8-L, site A

[Thalweg distance, was measured for individual cross sections relative to the cross section at which ΔH_s max occurred. Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Type of estimate procedure used: superelevation in a left-hand bend
Outside high-water mark: continuous line of boulders
Inside high-water mark: continuous scourline with damaged plant remains
Visually estimated percentage of channel controlled by bedrock: 25 percent

Superelevation data

Radius of curvature (R_c) = 18 m
Elevation difference (ΔH_s) = 0.7 m
Mean velocity (V_s) = 2.4 m/s

Channel top width (W) = 22 m
Channel slope (S) = 0.093

Cross-section data

Cross-section location	Thalweg distance, in meters	Area, in square meters	Hydraulic radius, in meters	Hydraulic depth, in meters	Flow-elevation difference, in meters	Top width, in meters
Downstream	10	11	0.1	0.5	0.3	21

$Q_s = 26\ m^3/s$

Site rating for estimating discharge: Poor

Table 55. Indirect peak-discharge estimate for the September 1991 debris flow in an unnamed tributary at river mile 207.8-L, site B

[Thalweg distance, was measured for individual cross sections relative to the cross section at which ΔH_s max occurred. Flow-elevation difference, is the measure of how much the flow elevations differed between channel-right and channel-left margins at any given cross section]

Evidence of peak discharge

Type of estimate procedure used: runup of debris flow onto bedrock outcrop
Channel left high-water mark: continuous scourline and damaged plant remains.
Channel right high-water mark: discontinuous debris levee and damaged plant remains
Runup evidence: boulders deposited on top of bedrock spur
Visually estimated percentage of channel controlled by bedrock: 75 percent

Runup data

Elevation difference = 4.1 m
Mean Velocity (V_r) = 9.0 m/s

Channel slope (S) = 0.093

Cross-section data

Cross-section location	Thalweg distance, in meters	Area, in square meters	Hydraulic radius, in meters	Hydraulic depth, in meters	Flow-elevation difference, in meters	Top width, in meters
Upstream	24	21	0.1	1.6	0.8	14

$Q_r = 190\ m^3/s$

Site rating for estimating discharge: Good

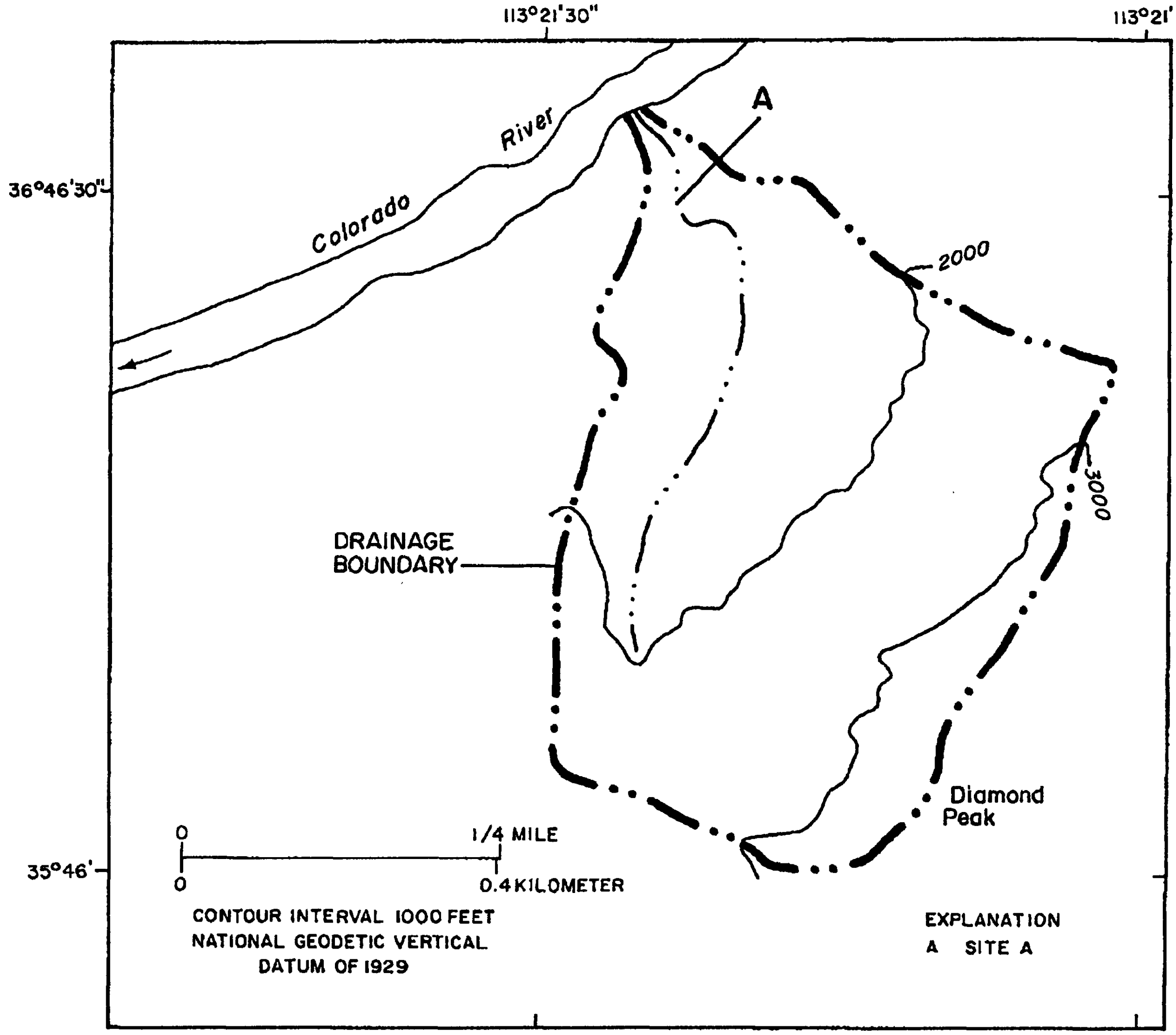


Figure 61. The drainage basin of unnamed tributary of the Colorado River at river mile 224.5-L in Grand Canyon.

of 1984 (Larry Stevens, oral commun., 1994) which severely limited vehicle access to the Colorado River. Another debris flow was witnessed during August 1984, based on an eyewitness account (George Billingsley, oral commun., 1994). According to Billingsley, the August debris flow was initiated during an extremely intense monsoon thunderstorm over the Diamond Creek drainage basin, and originated within Blue Mountain Canyon; it debouched from the top of the Redwall Limestone as he and others watched it from a helicopter. The free-falling debris flow caused extensive scour at the base of the cliff, but it is unknown whether the flood traveled all the way to the Colorado as a debris flow, or later transformed into watery streamflow. We were unable to determine peak discharge or other attributes of the August 1984 debris flow.

We used repeat photography to determine debris-flow frequency in Diamond Creek (table 56). Photographs taken in 1883 by Ben Wittick provide a long time frame for our analysis (table 56). One of the 1883 photographs shows a debris fan deposited by a pre-1883 debris flow in Diamond Creek (fig. 64). We estimated that this deposit constricted the channel of the Colorado River by approximately 40 to 50 percent. This debris fan was probably significantly reworked by an 8,500 m^3/s flood that occurred in the Colorado River in 1884. No further evidence of debris flow is apparent between 1883 and 1923, when several photographs were taken at Diamond Creek (table 56). The pre-1883 debris fan was completely removed by 1923. The debris fan of Diamond Creek and the channel upstream from the confluence apparently did not change significantly between 1923 and the early 1980s. Replicates of other 1883 photographs made in Diamond Creek and Peach Springs Wash (a major tributary in the drainage) show post-1883 debris-flow levees that were deposited in the last 111 years. However, these levees appeared to be older than the 1984 debris flow. We therefore conclude that at least one other debris flow must have occurred in the drainage between 1883 and 1984.

The 1923 photos of the channel of Diamond Creek near the confluence of Peach Springs Wash lacked the dense riparian vegetation now present. This indicates that relatively frequent streamflows and (or) debris flows occurred before 1923, which is in accord with other findings that the frequency of floods in the region was higher around the turn of the century (Webb and others, 1991). Such large floods may have obliterated evidence of historic debris flows downstream from the confluence of Diamond Creek and Peach Springs Wash.

The 1984 debris flow was probably the largest to occur since before 1883 in Diamond Creek. On the basis of the two debris flows which we documented from historic photographs and the 1984 debris flow which was witnessed, we estimate a frequency of approximately one debris flow every 35 years. This is in accord with estimates of debris-flow frequency made elsewhere in western Grand Canyon. A replicate of an 1883 photograph of the bottom of Diamond Creek Rapid (appendix 6) reveals a new, mid-channel debris bar (fig. 65). On the basis of aerial photographs taken in 1935 and 1989 this debris bar was probably the result of reworking of the 1984 debris fan. The newly formed debris bar below Diamond Creek Rapid is one of the only two new debris bars we observed in the Colorado River (the other is at mile 62.5).

DISCUSSION AND SUMMARY OF DATA

Debris flow is an important sediment-transport process in 529 tributaries of the Colorado River between Lees Ferry and Diamond Creek (river miles 0 to 225) in Grand Canyon, Arizona. An episodic type of flash flood, debris flows transport and deposit sediment ranging in size from clay to boulders into the Colorado River and are one source of sand downstream from Glen Canyon Dam. The frequency, magnitude, and particle-size distributions of historic debris flows are important data for developing a sediment budget in Grand Canyon. Debris flows also create and maintain the debris fans and rapids that control the hydraulics of the Colorado River; most of the contributing drainages are small tributaries of low stream order. In addition, debris fans constrict the river's channel, creating areas of flow expansion downstream from stable debris fans. These expansions form recirculating eddies, or flow separation zones, that facilitate the deposition and

Table 56. Historical photographs showing Diamond Creek Rapid (river mile 225.8) and the debris fan at the mouth of Diamond Creek (river mile 225.8-L)

[For photographs taken before 1921, the discharge is estimated from known stage-discharge relations at Diamond Creek Rapid. For photographs taken between 1921 and 1963, discharge is estimated from daily discharge records of the Colorado River near Grand Canyon. After 1963, discharge is estimated from known stage-discharge relations at Diamond Creek Rapid. These estimates are perhaps accurate to ±1,000 ft^3/s. (AV), vertical aerial photography; (AL), photograph is an oblique aerial taken from the left side of the river; (AR), photograph is an oblique aerial taken from the right side of the river; (RL), photograph was shot from river-left; (RR), photograph was shot from river-right; (US), upstream view; (DS), downstream view; (AC), view across the river; (UC), view looking up the tributary channel or away from the river; (R), view shows a rapid; (DF), view shows debris fan(s); (SB), view shows sand bar(s); (n.d.), no data; (n.m.), the photograph was analyzed, but not matched]

Year	Date	Photographer	Original number	Stake number	Side	Direction	Subject	Discharge (ft^3/s)
1883	April 2	Wittick	15496	n.m.	RL	US	R,DF	n.d.
	April 2	Wittick	15493	n.m.	RL	US	SB	n.d.
	April 2	Wittick	15466	2839	RL	AC	R,DF	n.d.
	April 2	Wittick	15467	n.m.	RL	US	R,DF	n.d.
	April 2	Wittick	15490	2782	RL	AC	R	n.d.
	April 2	Wittick	15500	2783	RL	DS	R	n.d.
1890	Mar 11	Stanton	664	2615	RL	UC	DF	n.d.
	Mar 11	Stanton	665	2665a	RL	US	DF,SB	n.d.
	Mar 11	Stanton	666	2665b	RL	DS	DF	n.d.
1900	n.d.	James	n.d.	n.m.	RL	US	DF	n.d.
1902	n.d.	Darton	910	723a	RL	DS	DF,SB	n.d.
	n.d.	Darton	911	723b	RL	US	R,DF,SB	n.d.
1909	Nov 12	Cogswell	1245	n.m.	RL	DS	R,DF	n.d.
1923	Sep 22	LaRue	675	805	RL	US	R,DF,SB	n.d.
	Oct 6	LaRue	677	2671	RL	UC	DF	n.d.
	Oct 6	LaRue	678	2670	RL	UC	DF	n.d.
	Oct 6	LaRue	684	2668	RL	UC	SB	n.d.
	Oct 6	LaRue	685	2669	RL	UC	DF,SB	n.d.
1935	Nov	Maxon	176	n.m.	AV	AV	R,DF,SB	~6,000
1976	Sep 29	Turner	805	805	RL	US	R,DF,SB	n.d.
1983	Nov 2	Turner	805	805	RL	US	R,DF,SB	n.d.
1984	n.d.	GCES	n.d.	n.m.	AV	AV	R,DF,SB	~5,000

storage of fine sediment along the river in sand bars, also called beaches.

Most of the debris flows that reached the Colorado River in the last century occurred in Marble Canyon and eastern Grand Canyon (fig. 66). Western Grand Canyon had comparatively fewer debris flows during the last century; the notable exception is Prospect Canyon, where 4 debris flows occurred between 1939 and 1963. Numerous factors influence the probability that tributaries will produce debris flows. Variability of regional and local climate, particularly in the warm season (between June and October), affects the probability of high-intensity precipitation, one of two causes of debris-flow initiation. Furthermore, drainages of western Grand Canyon are generally drier than those in the vicinity of the Kaibab Plateau; therefore, the frequency of debris flows should be lower in western Grand Canyon. However, the clustering of debris flows (fig. 66) may be, in part, a consequence of our short period of record for debris flows in Grand Canyon. Other factors that may influence the magnitude and frequency of debris flows are the shape and area of drainage basins; total relief; the dominant aspect, or orientation, of the drainage; and local orographic effects that increase the intensity and duration of precipitation. Local and regional geologic structure,

Figure 62. Replicate photographs showing the debris fan of an unnamed tributary of the Colorado River at river mile 224.5-L in Grand Canyon. *A*, The original view, looking upstream, was taken on March 1, 1890 (Robert Brewster Stanton, number 661, National Archives).

B, The replicate view, taken on February 26, 1991 (Dave Edwards, U.S. Geological Survey, stake 1522b), shows a levee at left-center that was deposited between 1890 and 1965. The deposition resulted from superelevation of a debris flow around a short bend in the channel through the debris fan.

Figure 62. Continued.

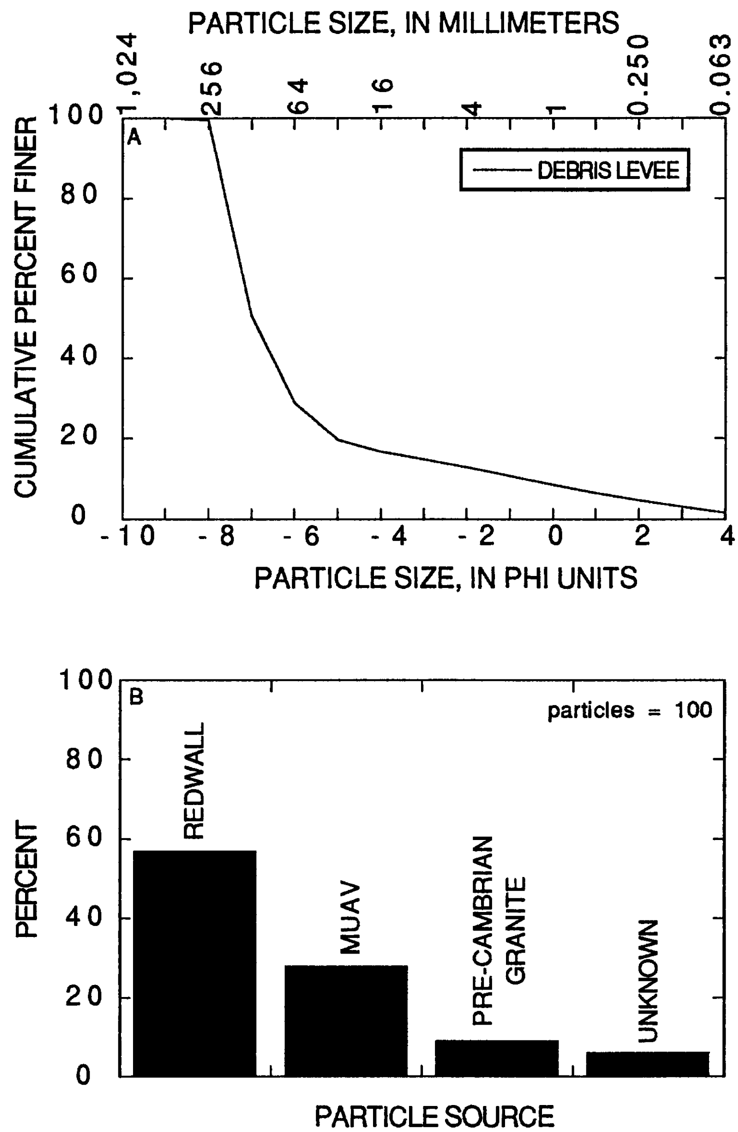


Figure 63. Particle-size and source distributions of a sediment deposit associated with a debris flow that occurred between 1890 and 1965 in an unnamed tributary of the Colorado River at river mile 224.5-L. *A*, Particle-size distribution of a debris-flow levee deposited by the debris flow that occurred between 1890 and 1965. *B*, Source distribution of an undisturbed debris-flow levee deposited by the debris flow that occurred between 1890 and 1965.

such as large faults and folds, increase the abundance and distribution of source sediment, such as colluvium.

Debris flows are initiated by bedrock and colluvial slope failures that occur during intense rainfall. The intensity of rainfall required to initiate debris flows in Grand Canyon is unknown, but sparse data suggest that a sustained intensity of over 20 mm/hr and a total rainfall of 25 to 50 mm may be required. Three different types of storms have initiated debris flows in Grand Canyon. Convective thunderstorms occur mainly in summer, frontal storms occur mainly in winter, and dissipating tropical cyclones occur during the summer or fall months. The peak discharges of debris flows are related to the triggering storm type (fig. 67). In general, convective thunderstorms cause most debris flows in Grand Canyon, although most have low to moderate peak discharges. In contrast, dissipating tropical cyclones and frontal storms generally initiate moderate to large debris flows. Few data exist for debris flows triggered by tropical cyclones and frontal storms owing to their infrequency.

We have documented three types of debris-flow initiation mechanisms in Grand Canyon (fig. 68). These mechanisms are: 1) slope failures that occur in exposures of weathered bedrock, typically Hermit Shale and Supai Group Formations; 2) failures in colluvial wedges caused by water cascading over cliffs (the fire-hose effect); and 3) classic hillslope failures in colluvium caused by intense precipitation. In addition, combinations of these three types of failures may also occur, and often complicate interpretations of debris-flow initiation scenarios. Multiple source areas combined with extreme topographic relief often result in complex scenarios of debris-flow initiation in Grand Canyon. The most common initiation mechanism in Grand Canyon is the fire-hose effect, occurring mainly on slopes termed colluvial wedges below cliffs of Redwall Limestone (fig. 68). With the exception of debris flows in Prospect Canyon, where fire-hose effects are uniquely related to the basins geology, the largest debris flows generally have been caused by combinations of failures in colluvium and weathered bedrock.

Typically, as is the case with most highly-sediment laden floods, debris flows in Grand Canyon are very-poorly sorted with particles ranging in size from clay to boulders. The most common clay minerals in debris flows are micas and kaolinite (table 9); kaolinite is a single-layer, non-swelling clay. Smectites, a group of multilayer clays that includes montmorillonite, have been detected in only one Grand Canyon debris flow (18-Mile Wash). Kaolinite has properties that may facilitate the initiation of debris flows (Pierson and Costa, 1987). The presence of kaolinite in Grand Canyon strata, as opposed to smectites, may be a major reason why debris flows occur in Grand Canyon.

Previous research yielded a general estimate of 20 to 30 years for the average recurrence interval of debris flows in Grand Canyon (Webb and others, 1989). Estimation of the frequency of debris flows is difficult because of the physical nature of debris flow, the isolated nature of the study area, and the lack of low-level aerial photography before 1935 and between 1935 and 1965. Interpretation of 1,107 historical photographs spanning 120 years, supplemented with oblique and vertical aerial photography taken after 1935, indicates that the recurrence of debris flows ranges from one debris flow every 10 to 15 years in certain tributaries, to less than 1 debris flow per century in other drainages. On average, debris flows may recur approximately every 30 to 50 years for any given tributary. Tributaries in eastern Grand Canyon appear to have a higher frequency of debris flows than those in western Grand Canyon, at least during the 20th century.

Debris flows appear to cluster in time within tributaries having a high debris-flow activity. In Prospect Canyon, four debris flows and one hyperconcentrated flow occurred between 1939 and 1963[1]; no debris flows occurred in 1872 to 1939 or 1963 to 1993. In 75-Mile Canyon, no debris flows reached the Colorado River between 1935 and 1987, but two debris flows occurred between 1987 and 1990. This clustering suggests that initially debris flows destabilize the hillslopes and channels in the tributary, which then yield a higher frequency of debris flows until sediment sources are stabilized or exhausted.

We used ^{137}Cs activity in fine-grained sediments and radiocarbon analysis to date debris

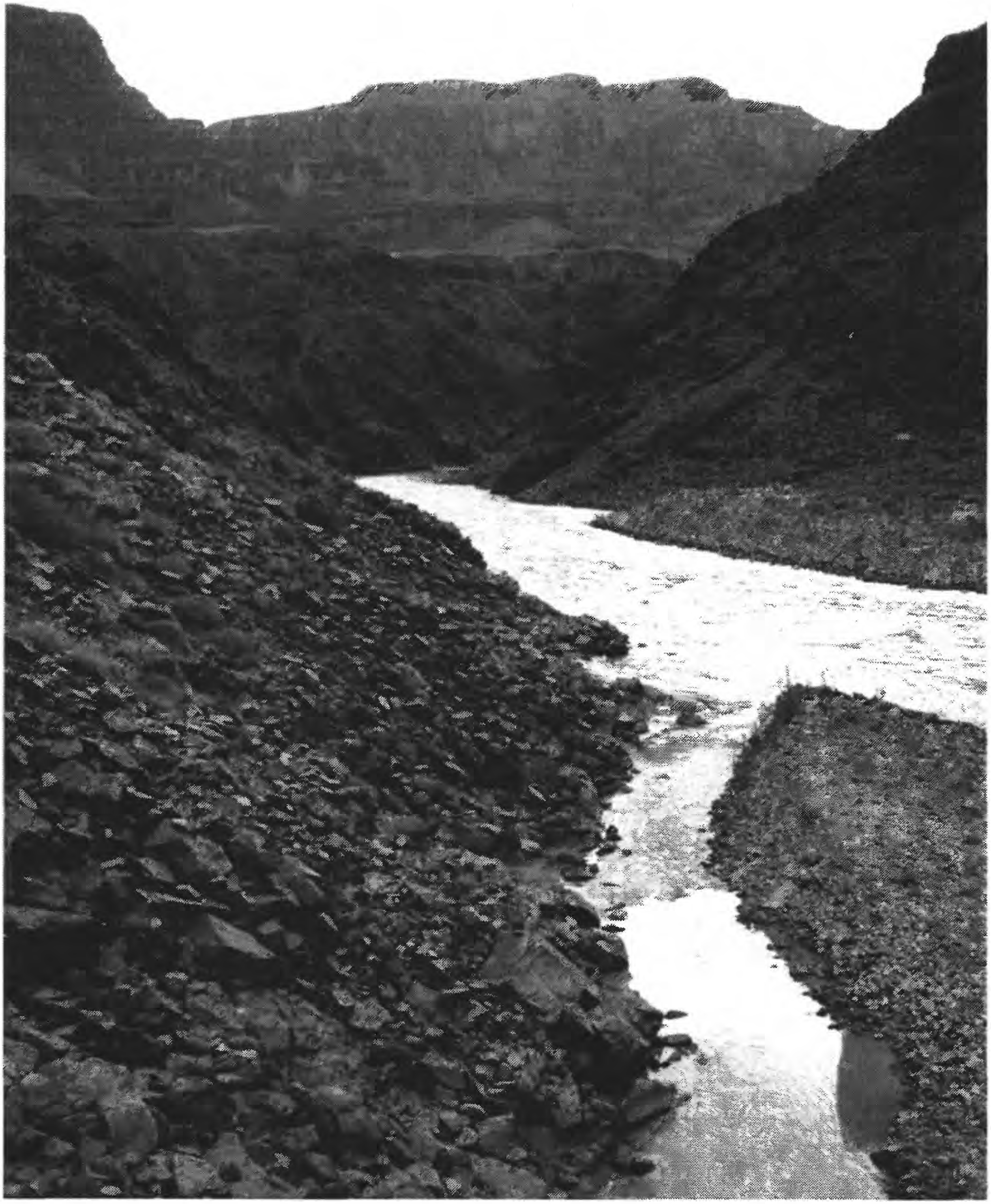
1. After preparation of this manuscript, a fifth debris flow was identified that occurred in December 1966.

Figure 64. Replicate photographs showing the head of Diamond Creek Rapid near the confluence of Diamond Creek (river mile 225.8-L), a tributary of the Colorado in Grand Canyon. A, The original view, looking upstream toward the confluence of Diamond Creek, was taken in April 1883 (Ben Wittick, 15467, Museum of New Mexico). The prominent debris fan constricting the river channel at the head of the rapid is indicative of a recent debris flow..

B, The replicate view, taken on March 16, 1994 (T.S. Melis, stake 2776a,), shows that the debris fan shown in the 1883 photograph has been completely removed. The debris fan was probably eroded during the discharge of 8,500 m3/s on the Colorado River in the summer of 1884 or later.

Figure 64. Continued.

Figure 65. Replicate photographs of the Colorado River near the bottom of Diamond Creek Rapid (river mile 226.0). *A*, The original view, looking downstream, was taken in the spring of 1884 (Ben Wittick, 15468, Museum of New Mexico). The channel appears to be open and without a debris bar.



B, The replicate view, taken on March 16, 1994 (T.S. Melis, stake 2777), documents the presence of a new debris bar at the bottom of Diamond Creek Rapid. This debris bar was formed by reworking and deposition of cobbles and boulders eroded from the 1984 debris fan at the mouth of Diamond Creek.

Figure 65. Continued.

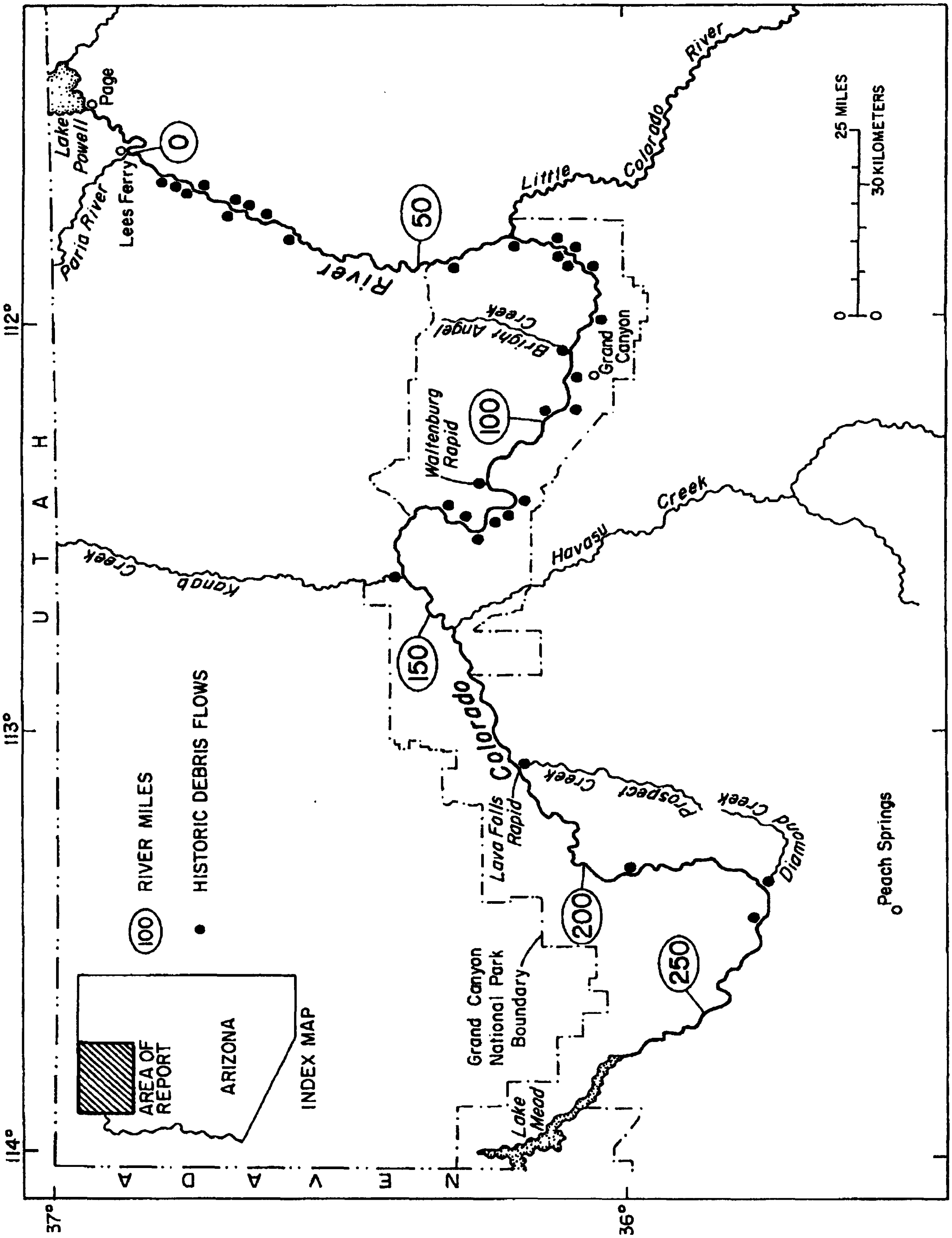


Figure 66. Locations of major debris flows that have occurred during the last century in Grand Canyon.

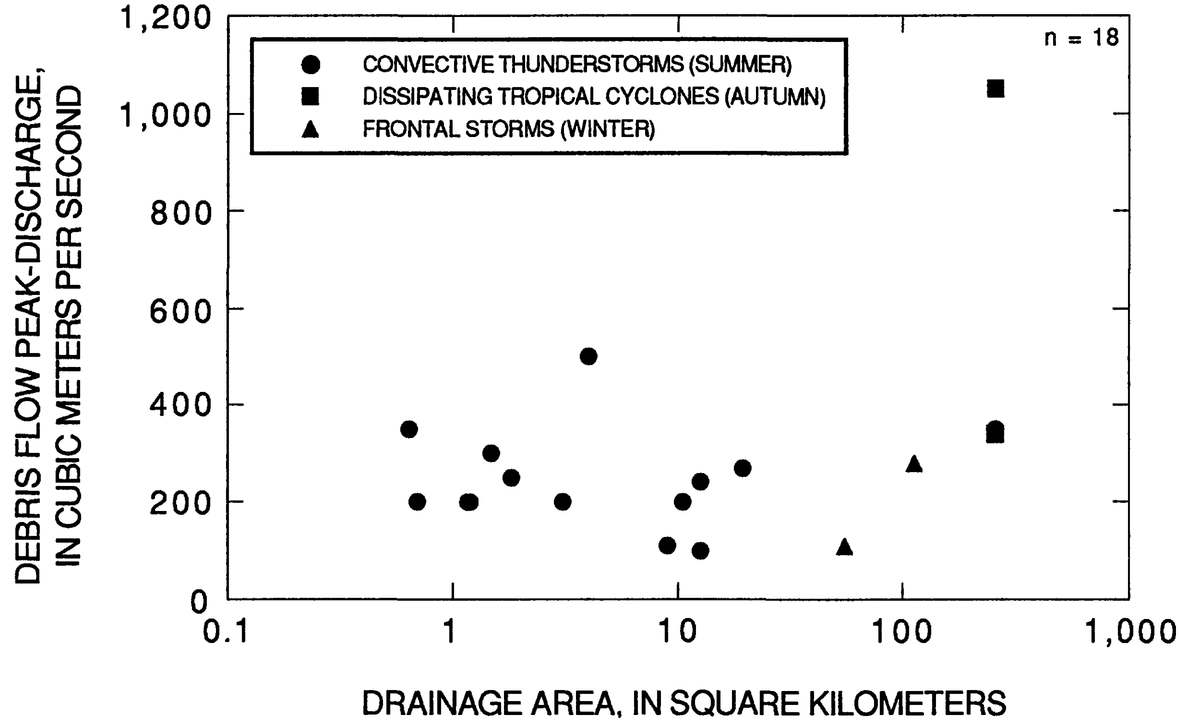


Figure 67. Comparison of peak discharges of debris flows and the total drainage area of the tributary for debris flows caused by different types of storms in Grand Canyon between 1939 and 1994.

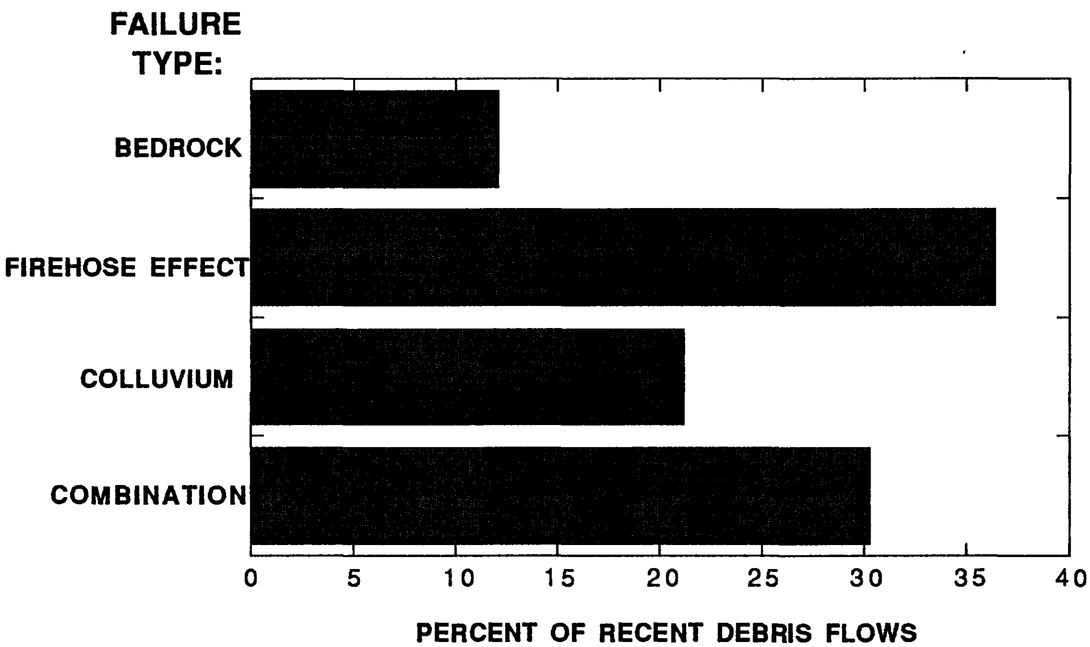


Figure 68. The percentage of each type of failure that has initiated debris flows in Grand Canyon between 1939 and 1994.

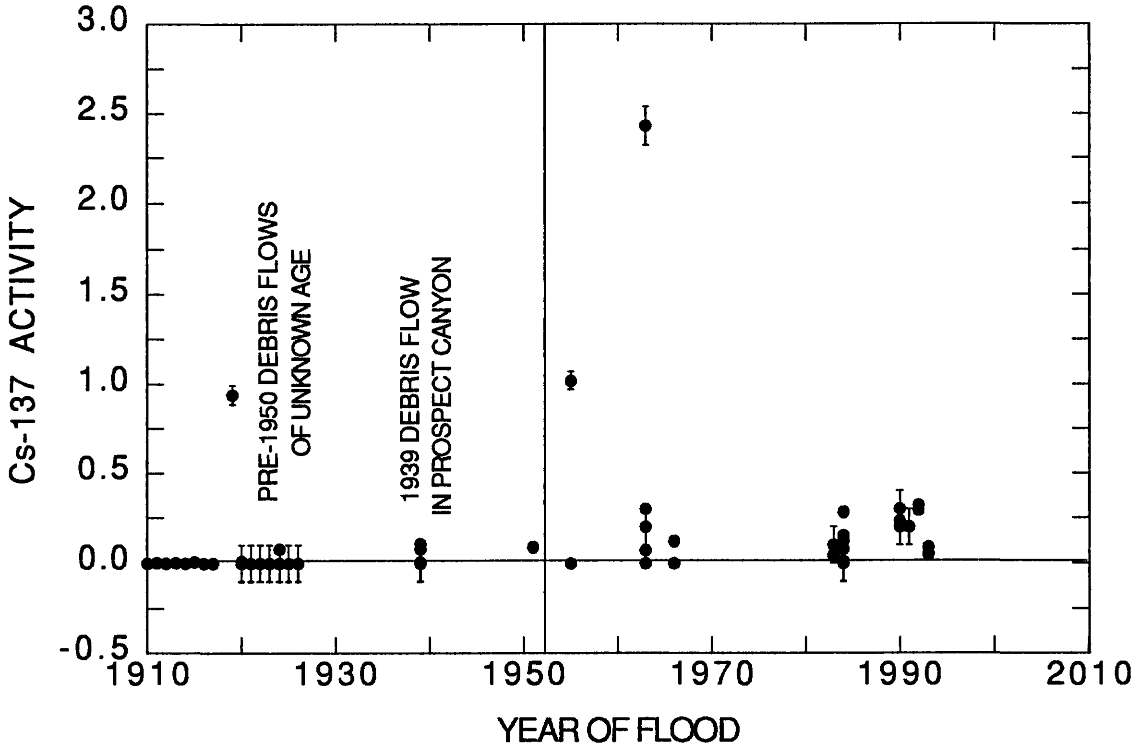


Figure 69. The activities of ^{137}Cs in debris-flow deposits in Grand Canyon of known or constrained ages.

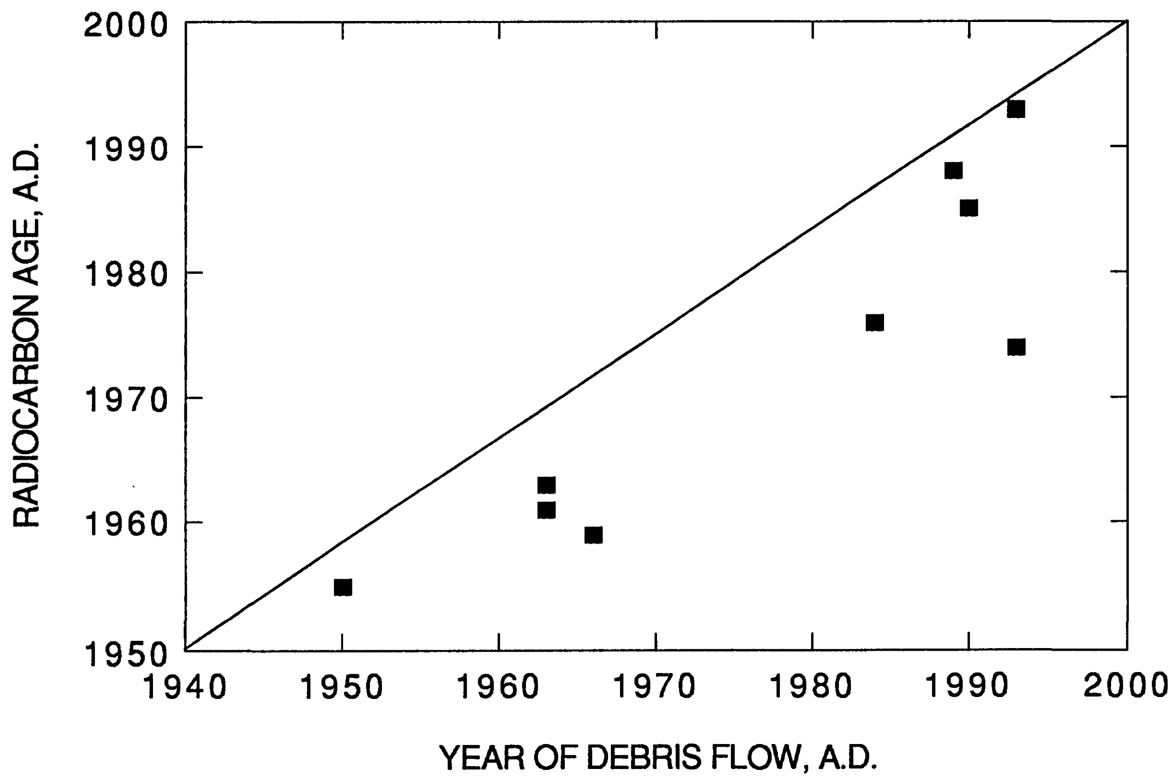


Figure 70. Radiocarbon ages of organic materials collected from debris-flow deposits of known age in Grand Canyon.

Table 57. Relation of peak-discharge estimates of debris flows made using cross-sectional areas measured at the point of maximum superelevation to estimates made using average cross-sectional areas measured upstream and (or) downstream

[Location, includes only sites where both the superelevated, upstream, and (or) downstream cross-sectional areas were measured; mean velocities; determined from superelevation evidence, as reported in tables in this report; peak discharge, refers to the cross-sectional area at the superelevation multiplied by the mean velocity; average area, equals the mean of all cross-sectional areas except the superelevated cross section; mean peak-discharge, equals the velocity estimated at the point of superelevation multiplied by the average of cross-sectional areas measured up and (or) downstream of the superelevated cross section]

Location of the flood	Mean velocity, in meters per second	Area at or near superelevation, in square meters	Peak discharge, in cubic meters per second	Mean of upstream and (or) downstream cross-sectional areas, in square meters	Mean peak-discharge, in cubic meters per second
62.6-R Site A	3.8	42	160	30	110
62.6-R Site B	5.1	146	740	53	270
62.6-R Site D	6.5	54	350	51	330
62.6-R Site E	5.3	81	430	77	400
68.5-L Site A	4.5	110	490	61	270
70.9-L Site A	9.4	21	200	30	280
71.2-R Site A	3.9	111	430	130	500
72.1-R Site B	6.1	16	98	6	37
72.1-R Site C	5.7	86	490	41	230
75.5-L Site A	3.6	25	90	16	58
75.5-L Site F	4.3	20	90	14	60
75.5-L Site A	6.1	116	710	43	260
75.5-L Site H	4.8	31	150	20	100

Table 57. Relation of peak-discharge estimates of debris flows made using cross-sectional areas measured at the point of maximum superelevation to estimates made using average cross-sectional areas measured upstream and (or) downstream—Continued

Location of the flood	Mean velocity, in meters per second	Area at or near superelevation, in square meters	Peak discharge, in cubic meters per second	Mean of upstream and (or) downstream cross-sectional areas, in square meters	Mean peak-discharge, in cubic meters per second
75.5-L Site I	6.5	30	190	39	250
122.7-L Site A	6.1	80	490	60	370
126.9-L Site A	5.2	27	140	35	180
127.6-L Site A	6.4	180	1,100	65	420
127.6-L Site B	6.9	81	560	48	330

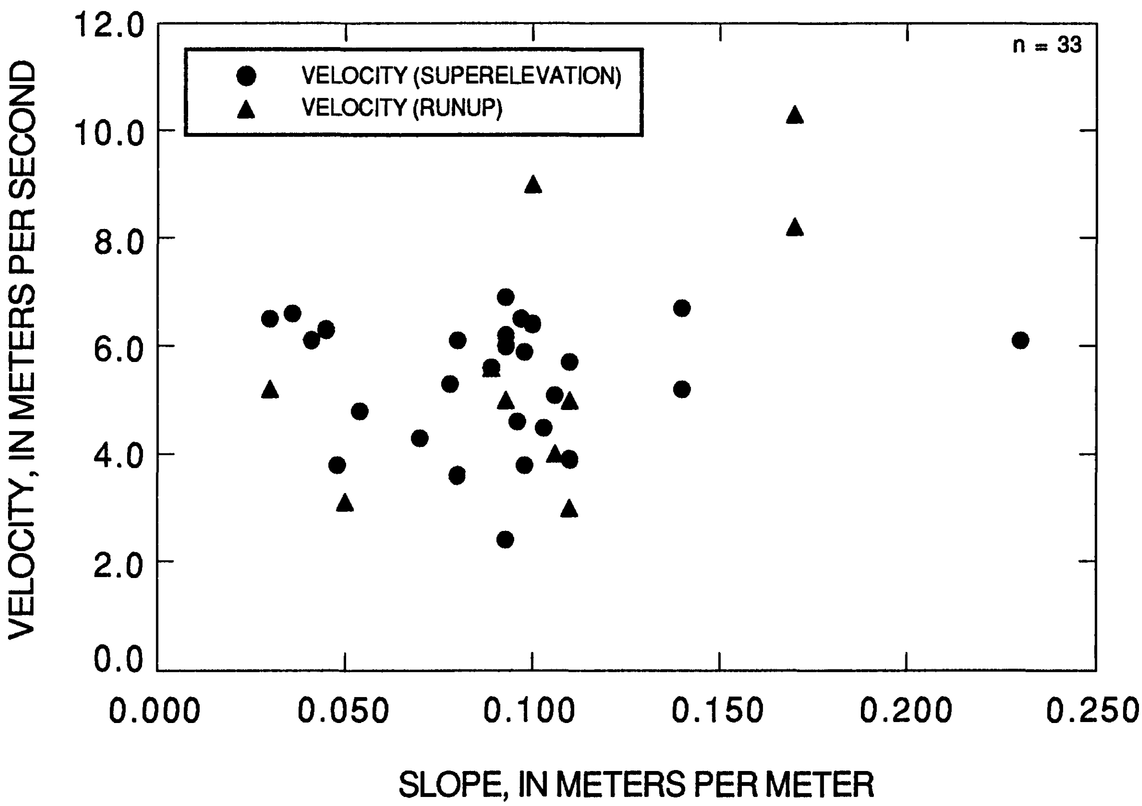


Figure 71. Peak velocity of debris flows as a function of channel slope calculated using superelevation and runup evidence for recent debris flows in Grand Canyon.

Table 58. Estimated volumes of debris-flow sediment recently deposited at debris fans in Grand Canyon
[Areas and volumes of debris fan deposits estimated above the approximate stage of 142 m3/s in the Colorado River. Depth of debris determined from excavated test pits; sand volumes, estimated from particle-size distributions; peak discharge, estimated from superelevation and (or) runup evidence]

Location and year of historic debris flow	Area of debris-fan deposit, in square meters	Estimated depth of debris-fan deposit, in meters	Total volume of debris fan, in cubic meters	Sand volume, in cubic meters	Peak-discharge, in cubic meters per second
62.6R (1990)	700	1.7	1,200	160	300
68.5L (1993)	3,000	2.0	5,900	1,200	300
70.9L (1993)	13,100	0.3	3,900	1,600	200
71.2R (1984)	4,800	1.5	7,200	3,400	500
72.1R (1984)	3,000	1.5	4,500	2,000	100 to 200
75.5L (1990)	10,000	1.2	12,000	1,300	100 to 300
93.5L (1984)	14,600	11.5	16,800	12,400	1110
98.2R (1966)	225,000	23.0	275,000	1,211,000	1300
127.3L (1989)	1,600	5.3	8,500	1,700	300
127.6L (1989)	2,500	2.0	5,000	700	200-400
157.8R (1993)	3,400	4.0	10,000 to 13,000	2,500 to 5,000	Unknown
160.8R (1993)	4,100	3.0	8,000 to 12,000	2,000 to 3,000	Unknown
207.8L (1991)	400	1.0	400	100	200

[1]Data from Webb and others, 1989.

[2]Estimated, based on the reworked size of the debris-fan deposit as it existed in 1992, and typical relations between river-reworked debris fans and non-reworked debris-flow deposits.

flows. To estimate the accuracy of our techniques, we applied both methods to debris flows of known age to determine the association of the datable material with the year of the debris flow. Analysis of ^{137}Cs activity in fine-grained sediments appears to equivocally distinguish debris flows into the age ranges of pre- and post-1952 (fig. 69). With the exception of sediments deposited during debris flows in Prospect Creek, pre-1952 debris flows had

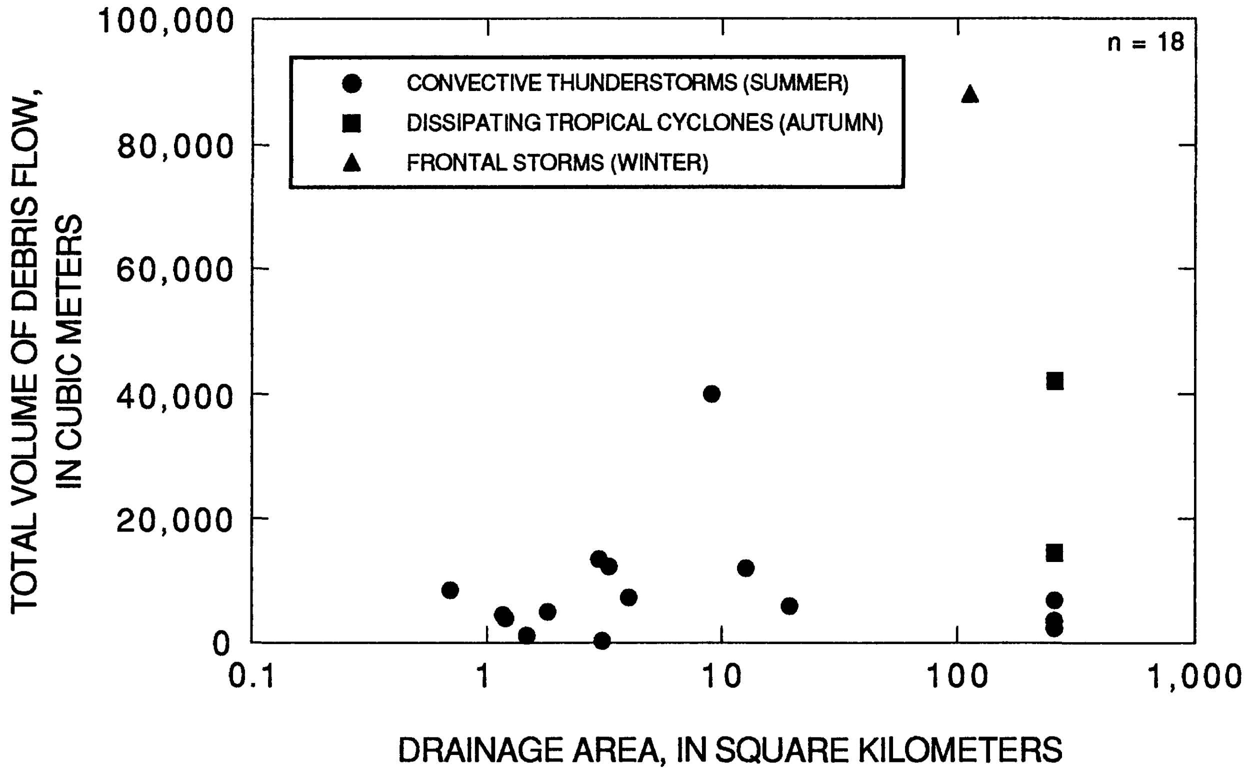


Figure 72. The relation of total volume of debris-flow deposits on debris fans to the total drainage area of the tributary for debris flows initiated by different storm types in Grand Canyon between 1939 and 1994.

no detectable activity of ^{137}Cs in the interior of the deposit (depths > 0.20 m). In contrast, most debris flows that occurred after 1952 had detectable activities (fig. 69). Debris flows initiated in weathered bedrock failures, such as the Crystal Creek debris flow of 1966, may not have detectable ^{137}Cs activities because the human-made isotope was not in the bedrock source material. However, debris flows initiated in fine-grained sediments by fire-hose effects can be classified as pre- or post-1952 using ^{137}Cs.

Radiocarbon analysis was used to test the relation between organic debris and the transporting debris flow. For Prospect Canyon, the age of driftwood was not closely related to the date of the debris flow for three events (table 52). In several cases, driftwood was 500 years older than the flood. A better correlation was obtained using post-bomb ^{14}C analysis of debris flows that occurred after 1950 (fig. 70). In two cases, the radiocarbon dates agree with the year of the associated debris flow; in several cases, the dates were within one year of the transporting flow. In other cases, the organic material was killed many years before the debris flow. The residence time of organic material in tributaries of the Colorado River is on the order of decades to hundreds of years, depending on the type of material (wood as opposed to fine-grained organics).

Peak discharges were estimated in 18 drainages for debris flows that occurred between 1939 and 1994 in Grand Canyon. Typically, discharges of recent debris flows ranged from about 100 to 300 m^3/s (fig. 67). The largest in the last century in Grand Canyon, which occurred in Prospect Creek (river mile 179.4-L), had a peak discharge of about 1,000 m^3/s. Estimates for peak discharges made at superelevation sites can vary significantly depending on where cross-sectional areas were measured within reaches (table 57). This finding is similar to that of Webb and others (1989) and emphasizes the importance of careful selection of cross sections for estimating peak discharges. However, the extent that estimates of velocity made using superelevation or runup evidence accurately

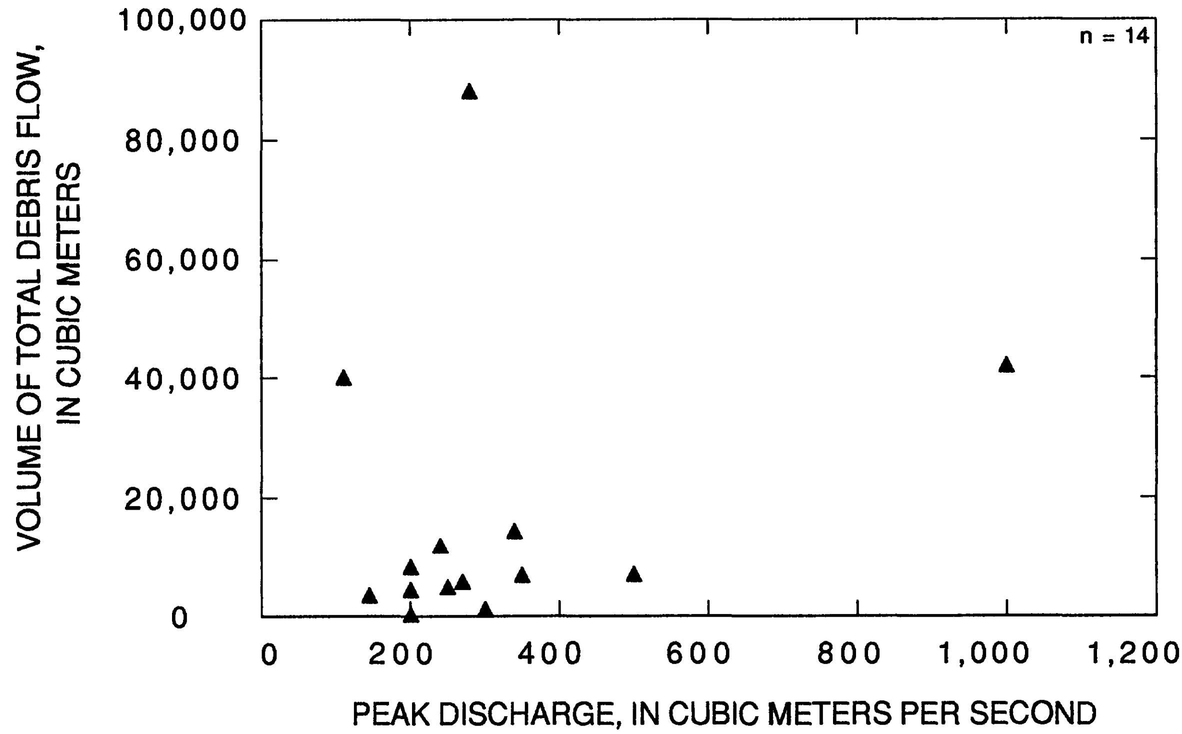


Figure 73. The relation of volume of sediment deposited on debris fans to the peak discharge of the debris flow for recent events in Grand Canyon between 1939 and 1994.

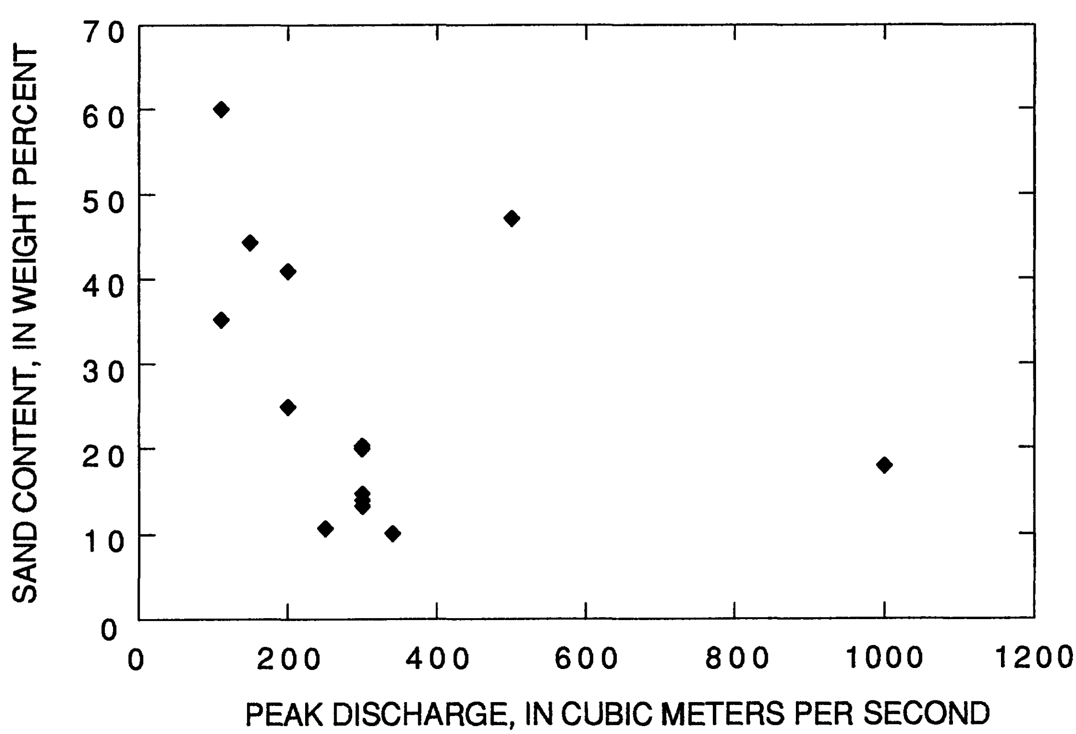


Figure 74. The relation of peak discharge to weight percent sand content for debris flows in Grand Canyon between 1939 and 1994.

Table 59. Percent sand content of some recent debris-flow deposits in Grand Canyon

Tributary	Year of occurrence	Sand content (percent)
"18-Mile Wash" (18.0-L)	1987	15
Unnamed tributary at mile 19.9-L	1987	46
Unnamed tributary at mile 62.5-R	1990	13
"Crash Canyon" (mile 62.6-R)	1990	13
Unnamed tributary at mile 63.3-R	1990	20 to 25
Lava Canyon (65.5-R)	1966	30 to 35
Tanner Canyon (68.5-L)	1993	25 to 35
Cardenas Creek (70.9-L)	1993	13 to 41
Unnamed tributary at mile 71.2-R	1984	47
Unnamed tributary at mile 72.1-R	1984	45
75-Mile Creek (75.5-L)	1987	22
75-Mile Creek (75.5-L)	1990	4
Monument Creek (93.5-L)	1984	[1]30 to 40
Crystal Creek (98.2-R)	1966	[1]10 to 15
Unnamed tributary at mile 126.9-L	1989	3
Unnamed tributary at mile 127.3-L	1989	27
"127.6-Mile Canyon" (mile 127.6-L)	1989	15
Unnamed tributary at mile 157.6-R	1993	25 to 35
Unnamed tributary at mile 160.8-R	1993	25
Prospect Canyon (179.4-L)	1963	7
Unnamed tributary at mile 207.8-L	1991	6
Unnamed tributary at mile 224.5-L	1890-1935	11

[1]Data from Webb and others, 1989.

reflect the mechanics of flowing debris is an unresolved problem. Debris-flow velocity is not clearly related to channel slope at either superelevation or runup sites (fig. 71).

Debris flows deliver significant volumes of sediment to the Colorado River (table 58). The total volume of sediment delivered to the river channel appears to be related to drainage area and storm type (fig. 72). Historic debris flows initiated during winter frontal storms and autumn dissipating tropical cyclones deposited larger volumes of material on debris fans than did debris flows initiated by summer convective thunderstorms. However, the total volume of sediment-transported to the river is poorly related to the peak discharge of debris flows (fig. 73).

Extended periods of recessional flow, lasting up to several hours, typically erode fresh looking debris-flow deposits and obscure evidence of the debris-flow process. Reworking by recessional flow greatly complicates studies of debris flow processes. Large debris flows that occurred before closure of Glen Canyon Dam deposited large volumes of debris in the river, but most of that sediment finer than boulders was removed from debris fans by river floods. This ongoing interaction between tributaries and the river results in accumulations of boulders that form rapids. Since 1963, reworking has been limited by dam releases. Hence, comparatively small debris flows now have a greater impact on the channel of the Colorado River; post-dam debris flows are progressively constricting the rivers channel at many locations and aggrading rapids with sediment finer than boulders. As a result, debris-flow deposits that bury or erode sand bars cannot be eroded from debris fans. In order to redeposit sand bars in their former locations, higher dam releases are required to inundate and (or) rework aggraded debris fans.

Debris flows in Grand Canyon transport very poorly sorted sediment. The deposits generally contain between 15 and 30 percent sand, but the variability of sand content is large among sites (table 59). The sand content of debris flows is poorly related to the peak discharge (fig. 74). Reconstitution of debris-flow samples indicates that most debris flows have a water content of 10- to 25 percent by weight. Owing to the infrequency of debris flows, sand input to the river from these floods is comparatively small relative to the input from periodic floods in the Paria and Little Colorado Rivers. Debris flows commonly transport large boulders weighing 100- to 300 Mg to the Colorado River. Several recent debris flows have created new rapids and (or) have enlarged existing ones (table 2; and appendix 1). These boulders constrict the river and increase the volume of channel-stored sediment in low velocity pools above rapids; aggraded debris fans increase the damming effect at rapids and decrease the flow velocities immediately upstream from the rapid.

Debris flows can directly and indirectly affect the stability of sand bars deposited in recirculation zones. Debris flows also directly affect sand bars (primarily separation bars) through burial and (or) erosion. Such effects have been observed in relation to several debris flows, including the debris flow of July 1987 in "18-Mile Wash" (river mile 18.0-L), the debris flow of September 1989 in "127.6-Mile Canyon"; the debris flow of September 1990 at "Crash Canyon" (river mile 62.6-R); and the debris flows of August 1993 at river miles 157.6-R and 160.8-R. Flow patterns in recirculation zones can change as a result of increased constriction, as demonstrated by the effects of the debris flow of September 1989 at "127.6-Mile Canyon". These changes may change the form of (or eliminate) reattachment bars. In addition, debris flows control geomorphic characteristics of the river corridor, influencing the preferred habitat of certain endangered fish species, such as the Humpback Chub (*Gila cyphus*) (Dr. Richard Valdez, oral commun., Bio/West Inc., 1994; use of trade names does not imply endorsement by the U.S. Geological Survey).

Operation of Glen Canyon Dam between 1963 and 1994 has greatly diminished the competence of the Colorado River to rework debris-fan deposits and redeposit sand bars on debris fans that have been buried or eroded. This is clearly demonstrated by the sharp contrasts in particle-size data presented in this report for reworked, partially-reworked, and undisturbed debris fans deposited in the pre- and post-dam eras. Future debris flows and streamflow floods will continue to erode sand bars, reducing this resource along the river corridor.

REFERENCES CITED

Apmann, R.P., 1973, Estimating discharge from superelevation in bends: Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers, HY1, p. 65–79.

Beverage, J.P., and Culbertson, J.K., 1964, Hyperconcentrations of suspended sediment: American Society of Civil Engineers, Journal of the Hydraulics Division, v. 90, p. 117–126.

Blackwelder, E., 1928, Mudflow as a geologic agent in semiarid mountains: Geological Society of America Bulletin, v. 39, p. 465–494.

Blakey, R.C., 1990, Supai Group and Hermit Formation, *in* Beus, S.S., and Morales, M., editors, Grand Canyon geology: New York, Oxford University Press, p. 147–182.

Blaustein, J., 1977, The hidden canyon, a river journey: New York, Penguin Books, 135 p.

Brunsden, D., and Prior, D.B., editors, 1984, Hillslope processes: New York, John Wiley and Sons, 620 p.

Bull, W.B., 1991, Geomorphic responses to climate change: New York, Oxford University Press, 326 p.

Carmony, N.B., and Brown, D.E., 1987, The log of the Panthon: Boulder, Colorado, Pruett Publishing, 109 p.

Carothers, S.W., and Brown, B.T., 1991, The Colorado River through Grand Canyon: Tucson, University of Arizona Press, 235 p.

Cooley, M.E., Aldridge, B.N., and Euler, R.C., 1977, Effects of the catastrophic flood of December, 1966, North Rim area, eastern Grand Canyon, Arizona: U.S. Geological Survey Professional Paper 980, 43 p.

Costa, J.E., 1984, Physical geomorphology of debris flows, *in* Costa, J.E., and Fleisher, P.J., editors, Developments and applications of geomorphology: Berlin, Springer-Verlag Publishing, p. 268–317.

Costa, J.E., and Jarrett, R.D., 1981, Debris flows in small mountain stream channels of Colorado and their hydrologic implications: Bulletin of the Association of Engineering Geologists, v. 18, p. 309–322.

Dalrymple, T., and Benson, M.A., 1967, Measurement of peak discharge by the slope-area method: Techniques of Water-Resources Investigations of the U.S. Geological Survey, Book 3, Chapter A2, 12 p.

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

Dolan, R., Howard, A., and Gallenson, A., 1974, Mans impact on the Colorado River in the Grand Canyon: American Scientist, v. 62, p. 392–401.

Eddy, C., 1929, Down the worlds most dangerous river: New York, F.A. Stokes Company, 293 p.

Ely, L.L., Webb, R.H., and Enzel, Y., 1992, Accuracy of post-bomb ^{137}Cs and ^{14}C in dating fluvial deposits: Quaternary Research, v. 38, p. 196–204.

Enos, P., 1977, Flow regimes in debris flow: Sedimentology, v. 24, p. 133–142.

Folk, R.L., 1974, Petrology of sedimentary rocks: Austin, Texas, Hemphill Publishing, 182 p.

Ford, T.D., Huntoon, P.W., Billingsley, G.H., and Breed, W.J., 1974, Rock movement and mass wastage in the Grand Canyon, *in* Geology of the Grand Canyon: Flagstaff, Museum of Northern Arizona, Grand Canyon Natural History Association Publication, p. 116–128.

Ghiglieri, M.P., 1992, Canyon: Tucson, University of Arizona Press, p. 311.

Glancy, P.A., and Harmsen, L., 1975, A hydrologic assessment of the September 14, 1974, flood in Eldorado Canyon, Nevada: U.S. Geological Survey Professional Paper 930, 28 p.

Graf, J.B., Webb, R.H., and Hereford, R., 1991, Relation of sediment load and floodplain formation to climatic variability, Paria River drainage basin, Utah and Arizona: Geological Society of America Bulletin, v. 103, p. 1405–1415.

Graf, W.L., 1979, Rapids in canyon rivers: Journal of Geology, v. 87, p. 533–551.

Hamblin, W.K., and Rigby, J.K., 1968, Guidebook to the Colorado River, Part 1, Lees Ferry to Phantom Ranch in Grand Canyon National Park: Provo, Utah, Brigham Young University Geology Studies, v. 15, part 5, 84 p.

Hastings, J.R., and Turner, R.M., 1965, The changing mile: An ecological study of vegetation change with time in the lower mile of an arid and semiarid region: Tucson, University of Arizona Press, 317 p.

Hereford, R., and Webb, R.H., 1992, Historic variation of warm-season rainfall, southern Colorado Plateau, southwestern U.S.A: Climatic Change, v. 22, p. 239–256.

Hereford, R., 1993, Map showing surficial geology and geomorphology of the Palisades Creek archaeologic area, Grand Canyon National Park, Arizona: U.S. Geological Survey Open–File report 93-553, 20 p. and one map, scale 1:4,600.

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

Howard, A., and Dolan, R., 1981, Geomorphology of the Colorado River in Grand Canyon: Journal of Geology, v. 89, p. 269–297.

Hungr, O., Morgan, G.C., and Kellerhals, R., 1984, Quantitative analysis of debris torrent hazards for design of remedial measures: Canadian Geotechnical Journal, v. 21, p. 663–677.

Huntoon, P.W., Billingsley, G.H., Breed, W.J., Sears, W.J., Ford, T.D., Clark, M.D., Babcock, S., and Brown, E.H., 1986, Geologic map of the eastern part of the Grand Canyon National Park, Arizona: Grand Canyon Natural History Association Map, scale 1:62,500, 1 sheet.

Jensen, S.K., and Domingue, J.O., 1988, Extracting topographic structure from digital elevation data for geographic information system analysis: Photogrammetric Engineering and Remote Sensing, v. 54, p. 1593–1600.

Johnson, A.M., and Rodine, J.R., 1984, Debris flow, *in* Brunsden, D., and Prior, D.B., editors, Slope instability: New York, John Wiley and Sons, p. 257–361.

Kellerhals, R., and Bray, D.I., 1971, Sampling procedures for coarse fluvial sediments: American Society of Civil Engineers, Journal of the Hydraulics Division, v. 97, p. 1165–1180.

Kieffer, S.W., 1985, The 1983 hydraulic jump in Crystal Rapid: Implications for river-running and geomorphic evolution in the Grand Canyon: Journal of Geology, v. 93, p. 385–406.

Kolb, E.L., 1914, Through the Grand Canyon from Wyoming to Mexico (1989 reprint): Tucson, Arizona, University of Arizona Press, 344 p.

Laenen, A., Scott, K.M., Costa, J.E., and Orzol, L.L., 1987, Hydrologic hazards along Squaw Creek from a hypothetical failure of a glacial moraine impounding Carver Lake near Sisters, Oregon: U.S. Geological Survey Open-File Report 87-41, 48 p.

Langbein, W.B., and Leopold, L.B., 1964, Quasi-equilibrium states in channel morphology: American Journal of Science, v. 262, p. 782–794.

Leopold, L.B., 1969, The rapids and pools: Grand Canyon, *in* The Colorado River Region and John Wesley Powell: U.S. Geological Survey Professional Paper 669, p. 131–145.

Laursen, E.M., Ince, S., and Pollack, J., 1976, On sediment transport through Grand Canyon: Third Federal Interagency Sedimentation Conference Proceedings, p. 4-76 to 4–87.

Major, J.J., and Pierson, T.C., 1992, Debris flow rheology: experimental analysis of fine-grained slurries: Water Resources Research, v. 28, no. 3, p. 841–858.

Melis, T.S., and Webb, R.H., 1993, Debris flows in Grand Canyon National Park, Arizona: Magnitude, frequency, and effects on the Colorado River, *in* Shen, Hsieh Wen, Su, S.T., and Wen, Feng, editors, Hydraulic engineering 93, Volume 2: New York, American Society of Civil Engineering, p. 1290–1295.

O'Connor, J.E., Ely, L.L., Wohl, E.E., Stevens, L.E., Melis, T.S., Kale, V.S., and Baker, V.R., 1994, A 4,500-year record of large floods on the Colorado River in the Grand Canyon, Arizona: Journal of Geology, v. 102, p. 1–9.

Pearson, G.W., Pilcher, J.R., Baille, M.G., Corbett, D.M., and Qua, F., 1986, High-precision ^{14}C measurement of Irish oaks to show the natural ^{14}C variations from AD 1840-5210 BC: Radiocarbon, v. 28, p. 911–934.

Pierson, T.C., 1980, Erosion and deposition by debris flows at Mt. Thomas, North Canterbury, New Zealand: Earth Surface Processes, v. 5, p. 227-247.

Pierson, T.C., 1985, Effects of slurry composition on debris flow dynamics, Rudd Canyon, Utah, *in* Bowles, D.S., ed., Proceedings of the Specialty Conference on delineation of landslide, flash flood, and debris flow hazards in Utah: Logan, Utah State University, p. 132–152.

Pierson, T.C., 1985, Initiation and flow behavior of the 1980 Pine Creek and Muddy River lahars, Mount St. Helens, Washington: Geological Society of America Bulletin, v. 96, p. 1056–1069.

Pierson, T.C., and Scott, K.M., 1985, Downstream dilution of a lahar: Transition from debris flow to hyperconcentrated streamflow: Water Resources Research, v. 21, p. 1511–1524.

Pierson, T.C., and Costa, J.E., 1987, A rheologic classification of subaerial sediment-water flows, *in* Costa, J.E., and Wieczorek, G.F., editors, Debris flows / avalanches: Process, recognition, and mitigation: Reviews in Engineering Geology, v. VII, p. 1–12.

Pierson, T.C., Janda, R.J., Thouret, J., and Borrero, C.A., 1990, Perturbation and melting of snow and ice by the 13 November 1985 eruption of Nevado del Ruiz, Columbia, and consequent mobilization, flow and deposition of lahars: Journal of Volcanology and Geothermal Research, 41 (1990), p. 17–66.

Powell, J.W., 1875, Exploration of the Colorado River and its canyons: New York, Dover Publications, 400 p.

Rodine, J.D., and Johnson, A.R., 1976, The ability of debris, heavily freighted with coarse clastic materials, to flow on gentle slopes: Sedimentology, v. 23, p. 213–234.

Roeske, R.H., 1978, Methods for estimating the magnitude and frequency of floods in Arizona: Phoenix, Arizona Department of Transportation Report for Research Project Arizona HPR-1-15 (121), 82 p.

Rubin, D.M., Schmidt, J.C., and Moore, J.N., 1990, Origin, structure, and evolution of a reattachment bar, Colorado River, Grand Canyon, Arizona: Journal of Sedimentary Petrology, v. 60, p. 982–991.

Schick, A.P., 1988, Hydrologic aspects of floods in extreme arid environments, *in* Baker, V.R., Kochel, R.C., and Patton, P.C., editors, Flood geomorphology: New York, John Wiley and Sons, p. 189–203.

Schmidt, J.C., 1990, Recirculating flow and sedimentation in the Colorado River in Grand Canyon, Arizona: Journal of Geology, v. 98, p. 709–724.

Schmidt, J.C., and Graf, J.B., 1990, Aggradation and degradation of alluvial sand deposits, 1965 to 1986, Colorado River, Grand Canyon National Park, Arizona: U.S. Geological Survey Professional Paper 1493, 74 p.

Schmidt, J.C., Rubin, D.M., and Ikeda, H., 1993, Flume simulation of recirculating flow and sedimentation: Water Resources Research, v. 29, p. 2925–2939.

Scott, K.M., 1988, Origins, behavior, and sedimentology of lahars and lahar-runout flows in the Toutle-Cowlitz River system: U.S. Geological Survey Professional Paper 1447–A, 74 p.

Sharp, R.P., and Nobles, L.H., 1953, Mudflows of 1941 at Wrightwood, southern California: Geological Society of America Bulletin, v. 64, p. 547–560.

Smith, W., 1986, The effects of eastern North Pacific tropical cyclones on the southwestern United States: Salt Lake City, Utah, National Oceanic and Atmospheric Administration, Technical Memorandum NWS-WR–197, 229 p.

Steiger, L., 1993, My God, its Waltenberg!: Flagstaff, The News, Grand Canyon River Guides Newsletter, v. 6, p. 22–26.

Stephens, H.G., and Shoemaker, E.M., 1987, In the footsteps of John Wesley Powell: Boulder, Colorado, Johnson Books, 286 p.

Stevens, L.E., 1989, Mechanisms of riparian plant community organization and succession in the Grand Canyon, Arizona: Flagstaff, Northern Arizona University, unpublished Ph.D dissertation, 115 p.

Stevens, L., 1990, The Colorado River in Grand Canyon, A guide: Flagstaff, Arizona, Red Lake Books, 107 p.

Strahler, A.N., 1952, Hypsometric (area-altitude) analysis of erosional topography: Bulletin of the Geological Society of America, v. 63, p. 1117–1142.

Stuiver, Minze, and Becker, B., 1986, High-precision decadal calibration of the radiocarbon time scale, AD 1950-2500 BC: Radiocarbon, v. 28, p. 863–910.

Stuiver, Minze, and Reimer, P.J., 1986, A computer program for radiocarbon age calibration: Radiocarbon, v. 28, p. 1022–1030.

Thomas, B.E., and Lindskov, K.L., 1983, Methods for estimating peak discharge and flood boundaries of streams in Utah: U.S. Geological Survey Water-Resources Investigations Report 83–4129, 77 p.

Turner, R.M., and Karpiscak, M.M., 1980, Recent vegetation changes along the Colorado River between Glen Canyon Dam and Lake Mead, Arizona: U.S. Geological Survey Professional Paper 1132, 125 p.

United States Department of the Interior, 1989, Glen Canyon Environmental Studies, final report: Springfield, Virginia, National Technical Information Service Report NTIS No. PB88–183348/AS, 84 p. + Appendices.

Webb, R.H., 1987, Occurrence and geomorphic effects of streamflow and debris flow floods in northern Arizona and southern Utah, *in* Mayer, L., and Nash, D., editors, Catastrophic flooding: Boston, Allen and Unwin, p. 247–265.

Webb, R.H., in press, A century of environmental change in Grand Canyon: Tucson, University of Arizona Press.

Webb, R.H., Pringle, P.T., Reneau, S.L., and Rink, G.R., 1988, Monument Creek debris flow, 1984: Implications for formation of rapids on the Colorado River in Grand Canyon National Park: Geology, v. 16, p. 50–54.

Webb, R.H., Pringle, P.T., and Rink, G.R., 1989, Debris flows in tributaries of the Colorado River in Grand Canyon National Park, Arizona: U.S. Geological Survey Professional Paper 1492, 39 p.

Webb, R.H., Smith, S.S., and McCord, V.A.S., 1991, Historic channel change of Kanab Creek, southern Utah and northern Arizona: Grand Canyon, Arizona, Grand Canyon Natural History Association Monograph Number 9, 91 p.

Wegner, D.L., 1991, A brief history of the Glen Canyon Environmental Studies, *in* Colorado River ecology and dam management: Washington, D.C., National Academy Press, p. 226–238.

Wolman, M.G., 1954, A method of sampling coarse-river-bed material: Transactions of the American Geophysical Union, v. 35, no. 6, p. 951–956.

Appendix 1. Locations of recent, observed streamflow floods and debris flows in Grand Canyon (modified from Webb and others, 1989)

[These changes in the geomorphology of the river are reported from river-runners, in historical accounts (e.g., Cooley and others, 1977), or from aerial photographs taken between 1935 and 1994. No data from repeat photography or stratigraphic analysis is included here. Type of change, type of changes and (or) process that caused the change(s). Confidence, a confidence rating of (1) indicates a change or event occurred; a rating of (2) indicates that though a change or event probably occurred, the evidence is not strong; a rating of (3) indicates little confidence in the reported change; (-), indicates that the tributary is unnamed]

River mile	Side	Tributary name	Type of change	Year	Confidence
5.7	R	Seven Mile Draw	Debris-flow deposits	1987	1
7.0	L	E-area	Rockfall deposits	1970	1
7.9	R	Badger Canyon	River or tributary-channel changes	[2]1973-84	1
11.2	R	Soap Creek	River or tributary-channel changes	[2]1973-84	1
11.2	R	Soap Creek	Streamflow flood	1987	1
11.8	L	Salt Water Wash	River or tributary-channel changes	[2]1935-65	2
11.8	L	Salt Water Wash	River or tributary-channel changes	[2]1973-84	2
16.8	R	House Rock Wash	Debris-flow deposits	[2]1966-73	2
17.4	L	"Redneck Rapid"	Rockfall deposits	[2]1973-74	1
18.0	L	"18 Mile Wash"	Debris-flow deposits	1987	1
19.1	L	Unnamed tributary	Debris-flow deposits	1987	1
19.9	L	Unnamed tributary	Debris-flow deposits	1987	1
24.0	L	Unnamed tributary	Debris-flow deposits	1989	1
24.2	L	Unnamed tributary	Debris-flow deposits	1989	1
24.4	L	Sheep Spring Wash	Debris-flow deposits	1989	1
24.7	L	Unnamed tributary	Streamflow flood	1989	1
26.7	L	Unnamed tributary	Debris flow	1974	1
26.8	R	Unnamed chute	[1]Rockfall deposits	1975	1
30.2	L	Unnamed tributary	Hyperconcentrated-flow deposits	1989	1
30.2	L	Unnamed tributary	Hyperconcentrated-flow deposits	1990	1
30.2	R	Unnamed tributary	Debris-flow deposits	1989	1
30.5	R	Unnamed tributary	Debris-flow deposits	1989	1
31.6	R	South Canyon	River or tributary-channel changes	[2]1965-73	2
35.6	L	Unnamed tributary	Debris fan changes	[2]1973-84	1
37.4	L	Tatahatso Wash	Rockfall deposits	1977	1
37.4	L	Tatahatso Wash	River or tributary-channel changes	[2]1973-84	2
41.0	R	Buck Farm Canyon	Debris-flow deposits	1981-83	1
41.3	R	"Bert's Canyon"	River or tributary-channel changes	[2]1973-84	2
43.2	L	Tatahoysa Wash	Debris-flow deposits	1983	1
43.7	L	Unnamed tributary	Debris-flow deposits	1983	1
44.1	L	E-area	Debris fan changes	1983	1
44.6	L	Unnamed tributary	Debris fan changes	1983	1
44.8	L	Unnamed tributary	Debris fan changes	1983	1
52.2	R	Nankoweap Canyon	Channel change	[2]1935-65	1
52.2	R	Nankoweap Canyon	Streamflow flood-channel change	1966	1
52.2	R	Nankoweap Canyon	River or tributary-channel changes	[2]1973-84	1
52.2	R	Nankoweap Canyon	Flood	1995	1

Appendix 1. Locations of recent, observed streamflow floods and debris flows in Grand Canyon (modified from Webb and others, 1989)—Continued

River mile	Side	Tributary name	Type of change	Year	Confidence
62.2	R	Unnamed tributary	Debris-flow deposits	1990	1
62.5	R	Unnamed tributary	Debris-flow deposits	1990	1
62.6	R	"Crash Canyon"	Debris-flow deposits	1990	1
63.0	L	Unnamed tributary	Debris-flow deposits	1990	1
63.3	R	Unnamed tributary	Debris-flow deposits	1990	1
64.5	L	Unnamed tributary	Debris-flow deposits	1990	1
65.3	L	Unnamed tributary	Hyperconcentrated-flow deposits	1990	1
65.5	L	Palisades Creek	[1]Debris-flow deposits	[2]1965-73	1
65.5	L	Palisades Creek	River or tributary-channel changes	[2]1973-84	1
65.5	L	Palisades Creek	Debris-flow deposits	1987	1
65.5	L	Palisades Creek	Hyperconcentrated-flow deposits	1990	1
65.5	R	Lava Canyon	Debris-flow deposits	1966	1
65.5	R	Lava Canyon	Debris-flow deposits	[2]1973-84	1
65.5	R	Lava Canyon	Flood deposits	1995	1
66.3	R	Unnamed tributary	Debris fan changes	[2]1965-84	1
66.3	L	Unnamed tributary	River or tributary-channel changes	[2]1965-73	1
66.8	L	Espejo Creek	Debris fan changes	[2]1973-84	1
67.2	L	Comanche Creek	Debris fan changes	[2]1973-84	1
67.8	L	Unnamed tributary	Debris fan changes	[2]1973-84	1
68.0	L	Unnamed tributary	Debris fan changes	[2]1973-84	1
68.5	L	Tanner Canyon	Debris-flow deposits	1993	1
69.6	R	Basalt Canyon	[1]Streamflow flood	1983	1
70.0	R	E-area	Debris fan changes	[2]1973-84	1
70.2	R	E-area	Debris fan changes	[2]1965-84	1
70.3	R	Unnamed tributary	Debris fan changes	[2]1965-84	1
70.4	L	E-area	Debris fan changes	[2]1973-84	1
70.5	L	E-area	Debris fan changes	[2]1973-84	1
70.7	L	Unnamed tributary	Debris fan changes	[2]1973-84	1
70.9	L	Cardenas Creek	Debris-flow deposits	1984	1
70.9	L	Cardenas Creek	Debris-flow deposits	1993	1
70.9	R	Unnamed tributary	Debris fan changes	[2]1973-84	2
71.1	R	E-area	Debris fan changes	[2]1965-84	1
71.2	R	Unnamed tributary	Debris-flow deposits	1984	1
71.8	R	E-area	Debris fan changes	[2]1973-84	1
72.1	R	Unnamed tributary	Debris-flow deposits	1984	1
72.6	R	Unkar Creek	Streamflow flood	1966	1
72.6	R	Unkar Creek	River or tributary-channel changes	[2]1973-84	1
73.3	L	Unnamed tributary	River or tributary-channel changes	[2]1965-84	2
73.5	L	E-area	Debris fan changes	[2]1973-84	1
73.7	R	E-area	Debris fan changes	[2]1973-84	1
73.9	R	Unnamed tributary	Debris fan changes	[2]1973-84	1
74.5	R	Unnamed tributary	Debris fan changes	[2]1965-84	2
75.0	L	Escalante Creek	Debris fan changes	[2]1973-84	1

Appendix 1. Locations of recent, observed streamflow floods and debris flows in Grand Canyon (modified from Webb and others, 1989)—Continued

River mile	Side	Tributary name	Type of change	Year	Confidence
75.5	L	75-Mile Creek	Debris-flow deposits	1987	1
75.5	L	75-Mile Creek	Debris-flow deposits	1990	1
76.0	L	Papago Creek	Streamflow flood	1987	1
76.7	L	Red Canyon	River or tributary-channel changes	[2]1973-84	2
78.7	L	Hance Creek	Debris-flow deposits	1983	1
84.1	R	Clear Creek	Streamflow flood	1966	1
87.8	R	Bright Angel Creek	Large streamflow flood	1966	1
87.8	R	Bright Angel Creek	[1]Debris-flow deposits	1966	1
87.8	R	Bright Angel Creek	River or tributary-channel changes	[2]1973-84	1
87.8	R	Bright Angel Creek	Flood and(or) debris flow	1995	1
88.9	L	Pipe Creek	River or tributary-channel changes	[2]1973-84	2
91.5	R	Trinity Creek	Streamflow flood or debris flow	1985	1
92.2	L	E-area	River or tributary-channel changes	[2]1973-84	2
92.7	L	Salt Creek	River or tributary-channel changes	[2]1973-84	2
93.5	L	Monument Creek	[1]Debris-flow deposits	1984	1
93.5	L	Monument Creek	Flood	1995	1
95.0	L	Hermit Creek	Streamflow flood	1992	1
96.7	L	Boucher Creek	River or tributary-channel changes	[2]1973-84	2
96.9	L	E-area	River or tributary-channel changes	[2]1973-84	3
98.2	R	Crystal Creek	[1]Debris-flow deposits, and later river-reworking of 1966 deposits	1966 and [2]1973-86	1 1
98.2	R	Crystal Creek	Debris flow and flood	1995	1
99.3	R	Tuna Creek	Streamflow flood	1966	1
100.6	L	Agate Canyon	River or tributary-channel changes	[2]1973-84	1
102.0	L	Turquoise Canyon	River or tributary-channel changes	[2]1973-84	2
107.6	L	Bass Canyon	Streamflow flood	1989	1
108.6	R	Shinumo Creek	River or tributary-channel changes	[2]1973-84	2
108.6	R	Shinumo Creek	Streamflow flood	1989	1
108.6	R	Shinumo Creek	Flood	1995	1
115.5	R	Unnamed tributary	River or tributary-channel changes	1985	1
116.5	L	Royal Arch Creek	Debris-flow deposits	1985	1
119.0	R	119 Mile Creek	River or tributary-channel changes	[2]1973-84	1
121.7	L	Unnamed tributary	River or tributary-channel changes	[2]1973-84	1
122.3	L	Unnamed tributary	River or tributary-channel changes	[2]1973-84	1
122.7	L	Forster Canyon	[1]River or tributary-channel changes	[2]1973-84	1
122.7	L	Forster Canyon	[1]Debris-flow deposits	1991	1
123.6	L	Unnamed tributary	New debris fan	1989	1
125.0	L	Fossil Canyon	[1]Debris flow and streamflow flood	1989	1
126.9	L	Unnamed tributary	Debris-flow deposits	1989	1
127.2	R	Unnamed tributary	Hyperconcentrated-flow deposits	1989	1
127.3	L	Unnamed tributary	Debris-flow deposits	1989	1
127.5	R	Unnamed tributary	Hyperconcentrated-flow deposits	1989	1
127.6	L	"127.6 Mile Canyon"	[1]Debris-flow deposits	1989	1

Appendix 1. Locations of recent, observed streamflow floods and debris flows in Grand Canyon (modified from Webb and others, 1989)—Continued

River mile	Side	Tributary name	Type of change	Year	Confidence
127.9	R	Unnamed tributary	Debris-flow deposits	1989	1
128.5	R	128-Mile Creek	River or tributary-channel changes	[2]1973-84	1
129.0	L	Specter Chasm	River or tributary-channel changes	[2]1973-84	1
129.0	L	Specter Chasm	[1]Debris-flow deposits	1989	1
130.5	R	Bedrock Canyon	[1]Debris-flow deposits	1989	1
131.9	R	Stone Creek	River or tributary-channel changes	[2]1973-84	2
132.0	L	E-area	[1]New debris fan	[2]1872-68	1
133.8	R	Tapeats Creek	[1]Debris-flow deposits	1961	1
133.8	R	Tapeats Creek	Streamflow flood	1975	1
133.8	R	Tapeats Creek	Streamflow flood	1984	1
136.2	R	Deer Creek	Debris-flow deposits	1985	1
136.2	R	Deer Creek	Streamflow flood	1988	1
137.2	R	E-area	Debris-flow deposits	[2]1973-84	1
143.5	R	Kanab Creek	[1]Large streamflow flood	1883	1
143.5	R	Kanab Creek	[1]Large streamflow flood	1909	1
143.5	R	Kanab Creek	River or tributary-channel changes	[2]1973-84	1
143.5	R	Kanab Creek	Streamflow flood	1988	1
143.5	R	Kanab Creek	Streamflow flood	1991	1
147.9	L	Matkatamiba Canyon	Streamflow flood	1989	1
156.8	L	Havasu Creek	[1]Streamflow flood	1911	1
156.8	L	Havasu Creek	[1]Streamflow flood	1918	1
156.8	R	Havasu Creek	Streamflow flood	1920	1
156.8	L	Havasu Creek	[1]Streamflow flood	1990	1
156.8	L	Havasu Creek	Streamflow flood	1993	1
157.6	R	Unnamed tributary	Debris-flow deposits	1993	1
160.8	R	Unnamed tributary	Debris-flow deposits	1993	1
166.4	L	National Canyon	River or tributary-channel changes	1984	1
168.0	R	Fern Glen Canyon	River or tributary-channel changes	[2]1973-84	2
174.4	R	Cove Canyon	River or tributary-channel changes	[2]1973-84	1
176.4	R	Saddle Horse Canyon	River or tributary-channel changes	[2]1973-84	1
178.1	L	E-area	Debris-flow deposits	[2]1973-84	1
179.4	L	Prospect Canyon	Debris flows, hyperconcentrated flow, and streamflow floods	1939, 54, 55, 56, 63, 66,93,95	1
181.3	R	E-area	Debris-flow deposits	1973	1
198.5	R	Parashant Wash	Streamflow flood	1993	1
198.5	R	Parashant Wash	Streamflow flood	1995	1
202.4	R	Unnamed tributary	Debris-flow deposits	[2]1973-84	2
202.5	R	Unnamed tributary	Debris-flow deposits	[2]1973-84	1
204.0	R	Unnamed tributary	Debris-flow deposits	[2]1973-84	3
204.2	L	Unnamed tributary	River or tributary-channel changes	[2]1973-84	2
205.5	L	205-Mile Canyon	[1]River or tributary-channel changes	1983	1
207.8	L	Unnamed tributary	River or tributary-channel changes	[2]1973-84	3
207.8	L	Unnamed tributary	Debris-flow deposits	1991	1

Appendix 1. Locations of recent, observed streamflow floods and debris flows in Grand Canyon (modified from Webb and others, 1989)—Continued

River mile	Side	Tributary name	Type of change	Year	Confidence
208.6	L	Unnamed tributary	Debris-flow deposits	1991	1
208.6	R	209-mile	Flood	1995	1
208.6	L	Granite Park Canyon	Flood	1995	1
209.0	R	E-area	Rockfall deposits	[2]1978-79	1
211.5	R	Fall Canyon	River or tributary-channel changes	[2]1973-84	1
220.0	R	220 Mile Canyon	River or tributary-channel changes	1984	1
225.8	L	Diamond Creek	Debris flow and later floods	1984-1986	1
225.8	L	Diamond Creek	Flood	1995	1

[1]A major change occurred at the site owing to a debris flow or astreamflow flood; determinations of geomorphic change are somewhat subjective.

[2]Exact year of the flood is uncertain.

Appendix 2. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon that produce debris flows

[Tributary name, is taken from U.S. Geological Survey 7.5-minute quadrangle maps; informal names are given in quotations. Digitaized drainage area, was measured from 1:24,000 scale quadrangle maps. Rapid name, is usually taken from Stevens (1990); rapids not included are Nixon Rock (99.9), Kanab (143.5), Havasu (156.8), and Lower Lava Falls (179.7); informal rapid names are given in quotations. Rapid rating, is given for the rapid at a discharge of approximately 283 m3/s. Water-surface fall, is converted to metric units from U.S. Geological Survey data collected in 1923 and adjusted to a discharge of approximately 283 m3/s. 7.5-minute quadrangle name, U.S. Geological Survey 7.5-minute quadrangle map on which tributary juncture with Colorado River occurs. (UR), indicates an unnamed riffle. (-), indicates no data, that tributary is unnamed, or that no riffle or rapid exist at the site]

River Mile	Side	Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
START OF REACH 1, MILE 0.0							
2.2	L	-	2.53	-	-	-	Lee's Ferry
2.2	R	-	7.71	-	-	-	Lee's Ferry
2.8	R	Cathedral Wash	17.27	UR	-	-	Lee's Ferry
3.4	L	-	5.26	-	-	-	Navajo Bridge
3.5	L	-	0.61	-	-	-	Navajo Bridge
3.9	L	-	4.29	-	-	-	Navajo Bridge
4.5	L	-	5.87	-	-	-	Navajo Bridge
5.1	L	"5- Mile Wash"	4.64	-	-	-	Navajo Bridge
5.7	R	Seven Mile Draw	18.65	UR	-	-	Navajo Bridge
7.9	L	Jackass Creek	52.24	Badger Creek	6	5	Navajo Bridge
7.9	R	Badger Canyon	47.01	Badger Creek	6	5	Navajo Bridge
8.6	R	-	2.09	UR	-	-	Navajo Bridge
10.0	L	-	1.90	-	-	-	Bitter Springs
10.2	L	-	1.37	-	-	-	Bitter Springs
11.2	R	Soap Creek	90.26	Soap Creek	5	6	Bitter Springs
11.8	L	Salt Water Wash	9.60	UR	-	-	Bitter Springs
START OF REACH 2, MILE 11.3							
12.1	L	-	9.81	UR	-	-	Bitter Springs
12.3	R	-	1.36	-	-	-	Bitter Springs
12.8	R	-	7.99	13-Mile	1	-	Bitter Springs
13.0	L	-	1.13	-	-	-	Bitter Springs
13.0	R	-	1.19	-	-	-	Bitter Springs
13.6	L	-	2.58	-	-	-	Bitter Springs
14.3	L	Tanner Wash	182.55	Sheer Wall	2	3	Bitter Springs
15.1	L	-	7.40	-	-	-	Bitter Springs
15.3	L	-	2.52	-	-	-	Bitter Springs
16.3	L	Hanaa Ninadzidzahi	28.84	UR	-	-	Bitter Springs
16.8	R	House Rock Wash	770.52	House Rock	7	3	Bitter Springs
17.4	L	-	3.75	Redneck	3	-	Bitter Springs
18.0	L	"18- Mile Wash"	5.06	UR	-	-	Bitter Springs

Appendix 2. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon that produce debris flows—Continued

River Mile	Side	Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
18.1	L	-	3.83	UR	-	-	Bitter Springs
19.0	R	"19- Mile Canyon"	1.12	-	-	-	Emmett Wash
19.1	L	-	1.42	-	-	-	Emmett Wash
19.3	R	-	2.48	-	-	-	Emmett Wash
19.9	L	-	3.78	-	-	-	Emmett Wash
20.5	R	North Canyon	407.72	North Canyon	5	4	North Canyon Point
21.1	L	-	0.04	21-Mile	5	2	Emmett Wash
21.1	R	-	0.39	21-Mile	5	2	Emmett Wash
21.4	L	-	13.96	UR	-	-	North Canyon Point
21.5	L	"22- Mile Wash"	1.59	UR	-	-	North Canyon Point
21.8	R	-	0.27	-	-	-	North Canyon Point
22.2	L	-	3.05	-	-	-	North Canyon Point
START OF REACH 3, MILE 22.6							
22.9	L	-	7.87	-	-	-	North Canyon Point
23.2	R	-	0.12	-	-	-	North Canyon Point
23.3	L	-	0.27	Indian Dick	5	-	North Canyon Point
23.4	R	-	0.15	Indian Dick	5	-	North Canyon Point
23.5	L	-	0.82	23.5-Mile	4	-	North Canyon Point
24.0	L	-	1.71	-	-	-	North Canyon Point
24.2	L	-	0.22	24-Mile	6	-	North Canyon Point
24.2	R	-	0.35	24-Mile	6	-	North Canyon Point
24.4	L	Sheep Spring Wash	26.12	24.5-Mile	5	3	North Canyon Point
24.7	L	-	1.16	25-Mile	5	3	North Canyon Point
25.0	L	-	2.01	UR	-	-	North Canyon Point
25.3	L	-	0.74	Cave Springs	5	2	North Canyon Point
25.3	R	-	1.24	Cave Springs	5	2	North Canyon Point
25.4	L	-	0.07	-	-	-	North Canyon Point
25.4	R	-	0.11	-	-	-	North Canyon Point
26.6	L	Tiger Wash	51.89	Tiger Wash	4	2	North Canyon Point
26.6	R	-	3.42	Tiger Wash	4	2	North Canyon Point
26.8	R	-	0.02	MNA	1	-	North Canyon Point
27.2	L	-	1.24	-	-	-	North Canyon Point
28.2	L	To Hajisho	20.22	UR	-	-	North Canyon Point
29.2	L	Shinumo Wash	186.55	29-Mile	2	2	North Canyon Point
30.2	L	-	6.03	UR	-	-	North Canyon Point
30.2	R	-	0.29	-	-	-	North Canyon Point
30.5	R	-	0.95	-	-	-	North Canyon Point
31.0	R	-	3.08	-	-	-	North Canyon Point
31.6	R	South Canyon	193.12	UR	-	-	North Canyon Point
31.8	R	-	0.49	-	-	-	North Canyon Point

Appendix 2. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon that produce debris flows—Continued

River Mile	Side	Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
32.0	R	-	1.19	UR	-	-	Tatahatso Point
32.6	L	-	0.14	-	-	-	Tatahatso Point
32.8	L	-	1.01	-	-	-	Tatahatso Point
34.2	R	-	0.94	-	-	-	Tatahatso Point
34.7	L	Nautiloid Canyon	10.59	UR	-	-	Tatahatso Point
34.9	L	-	0.09	-	-	-	Tatahatso Point
35.2	L	-	0.70	-	-	-	Tatahatso Point
35.6	L	-	0.78	-	-	-	Tatahatso Point
START OF REACH 4, MILE 35.9							
36.0	L	-	2.01	36-Mile	3	-	Tatahatso Point
36.7	R	-	20.50	-	-	-	Tatahatso Point
37.4	L	Tatahatso Wash	202.60	UR	-	-	Tatahatso Point
37.6	L	-	0.95	-	-	-	Tatahatso Point
37.7	L	-	1.49	UR	-	-	Tatahatso Point
38.6	R	-	0.79	-	-	-	Tatahatso Point
39.0	R	"Redbud Alcove"	1.41	UR	-	-	Tatahatso Point
41.0	R	Buck Farm Canyon	31.15	UR	-	-	Buffalo Ranch
41.3	R	"Bert's Canyon"	1.81	UR	-	-	Buffalo Ranch
42.9	L	-	1.33	UR	-	-	Buffalo Ranch
43.0	L	-	0.65	-	-	-	Buffalo Ranch
43.1	L	-	0.26	-	-	-	Buffalo Ranch
43.2	L	Tatahoysa Wash	50.77	President	4	1	Tatahatso Point
43.7	L	-	6.10		-	-	Tatahatso Point
44.6	L	-	2.66	UR	-	-	Tatahatso Point
44.8	L	-	1.26	-	-	-	Tatahatso Point
45.8	L	-	0.61	-	-	-	Tatahatso Point
46.7	R	-	1.46	-	-	-	Tatahatso Point
46.8	R	-	1.30	-	-	-	Tatahatso Point
47.0	R	Saddle Canyon	29.30	-	-	-	Point Imperial
47.4	L	-	0.71	-	-	-	Nankoweap Mesa
47.4	R	-	0.49	-	-	-	Nankoweap Mesa
47.8	L	-	0.28	-	-	-	Nankoweap Mesa
47.8	R	-	0.77	-	-	-	Nankoweap Mesa
48.5	R	-	1.31	UR	-	-	Nankoweap Mesa
49.4	R	-	4.36	UR	-	-	Nankoweap Mesa
49.6	L	-	2.22	UR	-	-	Nankoweap Mesa
49.8	R	-	3.39	-	-	-	Nankoweap Mesa
49.9	L	-	0.15	-	-	-	Nankoweap Mesa
50.0	L	-	0.12	-	-	-	Nankoweap Mesa
50.1	L	-	0.13	-	-	-	Nankoweap Mesa

Appendix 2. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon that produce debris flows—Continued

River Mile	Side	Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
50.3	L	-	0.26	-	-	-	Nankoweap Mesa
50.4	L	-	0.43	-	-	-	Nankoweap Mesa
50.8	L	-	0.36	-	-	-	Nankoweap Mesa
51.2	L	-	0.37	-	-	-	Nankoweap Mesa
51.7	R	Little Nankoweap Creek	10.59	-	-	-	Nankoweap Mesa
52.2	R	Nankoweap Canyon	84.58	Nankoweap	3	8	Nankoweap Mesa
52.5	L	-	3.49	Nankoweap	3	8	Nankoweap Mesa
53.1	R	-	1.23	UR	-	-	Nankoweap Mesa
53.5	R	-	0.26	-	-	-	Nankoweap Mesa
53.8	R	-	0.75	-	-	-	Nankoweap Mesa
54.0	R	-	0.39	-	-	-	Nankoweap Mesa
54.5	R	-	1.66	-	-	-	Nankoweap Mesa
55.0	L	-	0.60	-	-	-	Nankoweap Mesa
55.4	R	-	0.70	-	-	-	Nankoweap Mesa
56.0	R	Kwagunt Creek	39.25	Kwagunt	6	2	Nankoweap Mesa
56.3	L	-	4.58	UR	-	-	Nankoweap Mesa
56.6	R	-	0.12	-	-	-	Nankoweap Mesa
56.8	R	-	0.10	-	-	-	Nankoweap Mesa
56.9	L	-	0.93	-	-	-	Nankoweap Mesa
57.3	L	-	0.61	-	-	-	Nankoweap Mesa
57.5	R	Malgosa Canyon	6.98	UR	-	-	Cape Solitude
57.7	L	-	0.39	-	-	-	Cape Solitude
57.8	R	-	0.14	-	-	-	Cape Solitude
58.0	R	Awatubi Canyon	5.54	-	-	-	Cape Solitude
58.5	L	-	0.74	-	-	-	Cape Solitude
58.8	R	-	1.19	-	-	-	Cape Solitude
59.4	R	-	0.15	-	-	-	Cape Solitude
59.6	L	-	9.49	60-Mile	4	-	Cape Solitude
59.6	R	60- Mile Canyon	9.69	60-Mile	4	-	Cape Solitude
59.7	L	-	0.39	-	-	-	Cape Solitude
60.2	R	-	0.40	-	-	-	Cape Solitude
60.3	L	-	1.42	-	-	-	Cape Solitude
60.5	L	-	0.40	-	-	-	Cape Solitude
60.6	R	-	0.94	-	-	-	Cape Solitude
61.1	R	-	0.66	-	-	-	Cape Solitude
START OF REACH 5, MILE 61.5							
61.7	R	-	0.66	-	-	-	Cape Solitude
61.9	L	-	0.24	-	-	-	Cape Solitude
62.0	R	-	0.09	-	-	-	Cape Solitude
62.1	L	-	0.21	-	-	-	Cape Solitude

Appendix 2. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon that produce debris flows—Continued

River Mile	Side	Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
62.2	R	-	0.37	-	-	-	Cape Solitude
62.5	R	-	0.67	UR	-	-	Cape Solitude
62.6	L	-	0.19	-	-	-	Cape Solitude
62.6	R	"Crash Canyon"	1.79	-	-	-	Cape Solitude
63.0	L	-	0.64	-	-	-	Cape Solitude
63.3	L	-	0.26	-	-	-	Cape Solitude
63.3	R	-	0.66	UR	-	-	Cape Solitude
63.5	L	-	0.40	-	-	-	Cape Solitude
63.5	R	-	0.05	-	-	-	Cape Solitude
63.8	L	-	0.37	-	-	-	Cape Solitude
63.8	R	-	0.31	-	-	-	Cape Solitude
64.0	L	-	0.61	-	-	-	Cape Solitude
64.5	L	-	0.33	-	-	-	Cape Solitude
64.6	R	Carbon Creek	11.40	-	-	-	Cape Solitude
65.3	L	-	0.60	-	-	-	Cape Solitude
65.5	L	Palisades Creek	4.06	Lava Canyon	4	1	Cape Solitude
65.5	R	Lava Canyon	54.71	Lava Canyon	4	1	Cape Solitude
66.3	L	-	1.15	-	-	-	Desert View
66.3	R	-	1.47	-	-	-	Desert View
66.8	L	Espejo Creek	1.73	-	-	-	Desert View
67.2	L	Comanche Creek	5.40	UR	-	-	Desert View
67.6	R	-	1.22	-	-	-	Desert View
67.8	L	-	0.28	-	-	-	Desert View
68.0	L	-	0.63	-	-	-	Desert View
68.5	L	Tanner Canyon	19.25	Tanner	4	6	Desert View
68.8	R	-	0.15	-	-	-	Desert View
69.6	R	Basalt Canyon	14.06	UR	-	-	Desert View
70.0	L	-	4.74	-	-	-	Desert View
70.3	R	-	0.88	-	-	-	Desert View
70.7	L	-	0.65	-	-	-	Desert View
70.9	L	Cardenas Creek	3.87	UR	-	-	Desert View
70.9	R	-	2.45	-	-	-	Desert View
71.2	R	-	1.11	-	-	-	Desert View
72.1	R	-	1.16	-	-	-	Cape Royal
72.6	R	Unkar Creek	37.26	Unkar	6	8	Desert View
73.3	L	-	1.32	UR	-	-	Desert View
73.9	R	-	3.56	-	-	-	Cape Royal
74.5	R	-	0.39	-	-	-	Cape Royal
75.0	L	Escalante Creek	4.76	UR	-	-	Cape Royal
75.0	R	-	1.11	UR	-	-	Cape Royal
75.5	L	75- Mile Creek	11.47	Nevills	6	5	Cape Royal
75.5	R	-	0.44	Nevills	6	5	Cape Royal

Appendix 2. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon that produce debris flows—Continued

River Mile	Side	Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
76.0	L	Papago Creek	6.57	UR	-	-	Cape Royal
76.7	L	Red Canyon	10.52	Hance	9	10	Cape Royal
76.9	R	-	2.89	Hance	9	10	Cape Royal
START OF REACH 6, MILE 77.4							
78.0	L	Mineral Canyon	3.58	UR	-	-	Cape Royal
78.3	R	Asbestos Canyon	8.71	UR	-	-	Cape Royal
78.7	L	Hance Creek	23.54	Sockdolager	9	6	Cape Royal
79.0	R	-	1.32	UR	-	-	Cape Royal
79.4	L	-	0.51	-	-	-	Cape Royal
79.6	R	-	3.07	UR	-	-	Cape Royal
79.7	L	-	2.21	-	-	-	Cape Royal
80.2	R	-	0.26	-	-	-	Cape Royal
80.6	L	Cottonwood Creek	10.14	-	-	-	Cape Royal
81.2	R	Vishnu Creek	13.56	-	-	-	Cape Royal
81.5	L	Grapevine Creek	30.82	Grapevine	8	6	Phantom Ranch
81.6	R	-	7.01	Grapevine	8	6	Phantom Ranch
82.2	R	-	1.17	-	-	-	Phantom Ranch
82.3	L	-	1.09	-	-	-	Phantom Ranch
82.8	L	Boulder Creek	5.38	-	-	-	Phantom Ranch
83.1	L	-	1.03	-	-	-	Phantom Ranch
83.6	R	-	4.67	83-Mile	4	2	Phantom Ranch
83.9	L	Lonetree Canyon	2.61	-	-	-	Phantom Ranch
84.1	R	Clear Creek	93.14	UR	-	-	Phantom Ranch
84.5	L	-	0.62	-	-	-	Phantom Ranch
84.6	R	Zoroaster Canyon	4.10	Zoroaster	6	2	Phantom Ranch
85.0	L	-	0.36	85-Mile	3	-	Phantom Ranch
85.0	R	-	0.94	85-Mile	3	-	Phantom Ranch
85.6	L	Cremation Creek	12.07	UR	-	-	Phantom Ranch
85.7	R	-	2.17	-	-	-	Phantom Ranch
86.7	R	-	3.79	-	-	-	Phantom Ranch
86.9	L	-	0.12	-	-	-	Phantom Ranch
87.2	L	-	1.05	-	-	-	Phantom Ranch
87.8	R	Bright Angel Creek	260.33	Bright Angel	4	-	Phantom Ranch
87.9	L	-	1.89	-	-	-	Phantom Ranch
88.9	L	Pipe Creek	17.31	Pipe Springs	4	-	Phantom Ranch
88.9	R	-	2.27	Pipe Springs	4	-	Phantom Ranch
89.3	R	-	0.93	UR	-	-	Phantom Ranch
90.2	L	Horn Creek	4.28	Horn Creek	8	3	Grand Canyon
91.1	R	91- Mile Creek	5.69	-	-	-	Grand Canyon
91.5	R	Trinity Creek	20.05	-	-	-	Grand Canyon
92.0	R	-	1.22	UR	-	-	Grand Canyon

Appendix 2. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon that produce debris flows—Continued

River Mile	Side	Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
92.7	L	Salt Creek	3.22	Salt Creek	4	2	Grand Canyon
93.3	L	-	0.87	-	-	-	Grand Canyon
93.5	L	Monument Creek	9.73	Granite	9	6	Grand Canyon
93.5	R	-	2.27	Granite	9	6	Grand Canyon
94.3	L	-	0.51	-	-	-	Grand Canyon
94.3	R	94- Mile Creek	9.42	UR	-	-	Grand Canyon
95.0	L	Hermit Creek	31.98	Hermit	9	5	Grand Canyon
95.6	L	Travertine Canyon	3.84	-	-	-	Grand Canyon
96.0	R	-	2.88	-	-	-	Grand Canyon
96.7	L	Boucher Creek	16.79	Boucher	4	4	Grand Canyon
97.4	R	-	3.44	-	-	-	Shiva Temple
98.2	L	Slate Creek	12.12	Crystal	10	6	Shiva Temple
98.2	R	Crystal Creek	111.64	Crystal	10	6	Shiva Temple
99.3	R	Tuna Creek	59.62	Tuna Creek	6	3	Havasupai Point
99.6	L	-	0.83	Willie's Necktie	4	-	Havasupai Point
99.7	R	-	4.96	Willie's Necktie	4	-	Havasupai Point
100.6	L	Agate Canyon	4.36	Agate	3	-	Havasupai Point
101.3	L	Sapphire Canyon	7.78	Sapphire	7	2	Havasupai Point
101.3	R	-	2.02	Sapphire	7	2	Havasupai Point
102.0	L	Turquoise Canyon	14.64	Turquoise	4	1	Havasupai Point
102.0	R	-	0.29	Turquoise	4	1	Havasupai Point
102.6	L	-	3.62	UR	-	-	Havasupai Point
103.0	R	-	2.15	-	-	-	Havasupai Point
103.1	L	-	1.24	-	-	-	Havasupai Point
103.9	L	-	0.21	104-Mile	6	-	Havasupai Point
103.9	R	Emerald Canyon	4.08	104-Mile	6	-	Havasupai Point
104.3	R	-	1.72	-	-	-	Havasupai Point
104.6	L	Ruby Canyon	7.47	Ruby	6	4	Havasupai Point
104.6	R	Monodnock Amphitheater	9.65	Ruby	6	4	Havasupai Point
104.9	L	-	2.12	UR	-	-	Havasupai Point
105.7	L	-	1.54	-	-	-	Havasupai Point
105.7	R	-	0.93	-	-	-	Havasupai Point
106.0	L	Serpentine Canyon	3.96	Serpentine	7	4	Havasupai Point
106.3	R	-	2.07	UR	-	-	Havasupai Point
107.6	L	Bass Canyon	7.28	Bass	4	1	Havasupai Point
107.8	R	Hotauta Canyon	7.13	Bass	4	1	Havasupai Point
108.6	R	Shinumo Creek	221.98	Shinumo	4	3	Havasupai Point
109.6	R	-	0.67	-	-	-	Havasupai Point
109.8	L	-	1.05	110-Mile	1	-	Havasupai Point
110.2	L	Copper Canyon	6.06	-	-	-	Havasupai Point
110.2	R	-	0.76	-	-	-	Havasupai Point
110.4	L	-	0.25	-	-	-	Explorer's Monu.

Appendix 2. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon that produce debris flows—Continued

River Mile	Side	Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
110.8	R	Hakatai Canyon	9.48	Hakatai	4	3	Explorer's Monu.
111.2	R	-	0.68	-	-	-	Explorer's Monu.
111.3	L	-	0.52	-	-	-	Explorer's Monu.
112.2	L	-	1.78	Waltenburg	7	5	Explorer's Monu.
112.2	R	Waltenberg Canyon	14.27	Waltenburg	7	5	Explorer's Monu.
112.5	L	-	0.63	112.5-Mile	2	-	Explorer's Monu.
112.5	R	-	1.99	112.5-Mile	2	-	Explorer's Monu.
113.0	R	-	1.33	Rancid Tuna	6	-	Explorer's Monu.
113.3	R	-	0.67	-	-	-	Explorer's Monu.
113.6	L	-	1.12	-	-	-	Explorer's Monu.
113.9	R	-	0.53	-	-	-	Explorer's Monu.
114.4	R	-	0.37	-	-	-	Explorer's Monu.
114.5	L	Garnet Canyon	15.83	UR	-	-	Explorer's Monu.
115.1	L	-	4.93	UR	-	-	Explorer's Monu.
115.5	L	-	4.07	UR	-	-	Explorer's Monu.
START OF REACH 7, MILE 115.7							
115.8	R	-	0.67	-	-	-	Explorer's Monu.
116.1	L	-	1.00	-	-	-	Explorer's Monu.
116.5	L	Royal Arch Creek	30.86	UR	-	-	Explorer's Monu.
116.8	L	-	2.12	UR	-	-	Explorer's Monu.
117.7	L	-	1.88	UR	-	-	Explorer's Monu.
117.7	R	-	0.68	-	-	-	Explorer's Monu.
118.0	R	-	1.02	-	-	-	Explorer's Monu.
118.3	R	-	0.23	-	-	-	Explorer's Monu.
118.6	L	-	0.24	-	-	-	Explorer's Monu.
118.7	R	-	1.40	119-Mile	2	-	Explorer's Monu.
119.0	R	119- Mile Creek	2.77	-	-	-	Explorer's Monu.
119.2	L	-	0.62	-	-	-	Explorer's Monu.
119.2	R	-	1.86	-	-	-	Explorer's Monu.
119.7	R	-	0.51	-	-	-	Explorer's Monu.
120.1	R	Blacktail Canyon	24.15	Blacktail	3	-	Explorer's Monu.
120.6	L	-	1.73	-	-	-	Explorer's Monu.
120.8	L	-	0.40	-	-	-	Explorer's Monu.
121.7	L	-	7.96	122-Mile	5	-	Explorer's Monu.
122.2	R	122- Mile Creek	8.03	UR	-	-	Topocoba Hilltop
122.3	L	-	2.39	-	-	-	Topocoba Hilltop
122.5	L	-	0.44	-	-	-	Topocoba Hilltop
122.7	L	Forster Canyon	10.04	Forster	6	-	Topocoba Hilltop
123.1	L	-	0.19	-	-	-	Fossil Bay
123.3	L	-	0.42	-	-	-	Fossil Bay
123.5	L	-	2.29	UR	-	-	Fossil Bay

Appendix 2. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon that produce debris flows—Continued

River Mile	Side	Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
123.6	L	-	0.21	-	-	-	Fossil Bay
124.0	L	-	0.97	-	-	-	Fossil Bay
124.4	L	-	3.06	UR	-	-	Fossil Bay
125.0	L	Fossil Canyon	34.39	Fossil	6	5	Fossil Bay
START OF REACH 8, MILE 125.5							
125.5	R	-	0.30	-	-	-	Fossil Bay
125.6	L	-	0.29	-	-	-	Fossil Bay
125.8	R	-	4.44	-	-	-	Fossil Bay
126.3	L	-	0.53	Randy's Rock	2	-	Fossil Bay
126.6	R	-	0.29	-	-	-	Fossil Bay
126.7	R	-	0.10	-	-	-	Powell Plateau
126.9	L	-	0.57	127-Mile	3	-	Powell Plateau
126.9	R	127-Mile Creek	6.09	127-Mile	3	-	Powell Plateau
127.2	R	-	0.65	-	-	-	Powell Plateau
127.3	L	-	0.76	UR	-	-	Powell Plateau
127.5	R	-	0.98	-	-	-	Powell Plateau
127.6	L	"127.6- Mile Canyon"	1.75	"127.6-Mile"	-	-	Powell Plateau
127.9	L	-	0.98	-	-	-	Powell Plateau
128.5	R	128- Mile Creek	7.93	128-Mile	5	-	Powell Plateau
129.0	L	Specter Chasm	8.25	Specter	6	1	Powell Plateau
130.0	R	"130- Mile Creek"	6.40	-	-	-	Powell Plateau
130.5	R	Bedrock Canyon	21.14	Bedrock	8	3	Powell Plateau
130.9	L	-	2.01	UR	-	-	Powell Plateau
131.1	R	-	1.69	-	-	-	Powell Plateau
131.7	R	Galloway Canyon	12.27	Dubendorf	8	5	Powell Plateau
131.9	R	Stone Creek	6.76	Dubendorf	8	5	Powell Plateau
132.3	L	-	0.83	-	-	-	Powell Plateau
132.5	L	-	0.16	-	-	-	Powell Plateau
133.0	L	-	2.52	UR	-	-	Powell Plateau
133.0	R	133- Mile Creek	6.63	UR	-	-	Powell Plateau
133.4	L	-	0.31	-	-	-	Powell Plateau
133.8	R	Tapeats Creek	216.34	Tapeats	6	5	Powell Plateau
134.2	L	-	1.18	-	-	-	Tapeats Amph.
134.2	R	Bonita Creek	5.73	134-Mile	3	-	Tapeats Amph.
134.3	L	-	4.64	UR	-	-	Tapeats Amph.
134.8	R	-	0.86	135-MIle	5	-	Tapeats Amph.
135.4	R	-	0.22	-	-	-	Tapeats Amph.
135.9	L	-	1.60	-	-	-	Fishtail Mesa
136.2	R	Deer Creek	43.63	UR	-	-	Fishtail Mesa
136.5	L	-	0.07	-	-	-	Fishtail Mesa
136.7	L	-	4.07	-	-	-	Fishtail Mesa

Appendix 2. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon that produce debris flows—Continued

River Mile	Side	Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
136.8	L	-	0.41	-	-	-	Fishtail Mesa
137.6	L	-	0.11	-	-	-	Fishtail Mesa
137.7	R	-	0.78	-	-	-	Fishtail Mesa
137.8	L	-	0.81	137.5-Mile	6	-	Fishtail Mesa
138.3	L	-	0.53	-	-	-	Fishtail Mesa
138.4	L	-	0.17	-	-	-	Fishtail Mesa
138.5	R	-	5.20	138.5-Mile	4	-	Fishtail Mesa
138.9	L	-	1.44	-	-	-	Fishtail Mesa
139.1	R	Fishtail Canyon	19.63	Fishtail	6	3	Fishtail Mesa
139.5	R	-	0.26	-	-	-	Fishtail Mesa
139.9	L	140- Mile Canyon	25.76	UR	-	-	Fishtail Mesa
139.9	R	-	0.65	UR	-	-	Fishtail Mesa
START OF REACH 9, MILE 140.0							
140.9	L	-	0.59	-	-	-	Fishtail Mesa
141.3	L	-	0.88	-	-	-	Fishtail Mesa
141.3	R	-	2.08	141-Mile	2	-	Fishtail Mesa
143.1	L	-	3.42	-	-	-	Kanab Point
144.2	R	-	1.06	-	-	-	Kanab Point
144.8	R	-	7.14	144.5-Mile	2	-	Kanab Point
145.0	L	-	0.19	-	-	-	Havasu Falls
145.6	L	Olo Canyon	32.95	UR	-	-	Havasu Falls
147.9	L	Matkatamiba Canyon	86.84	Matkatamiba	2	-	Havasu Falls
148.5	L	-	2.81	-	-	-	Havasu Falls
148.6	L	-	0.72	-	-	-	Havasu Falls
149.7	R	150- Mile Canyon	81.04	Upset	8	5	Havasu Falls
152.4	R	-	1.60	-	-	-	Havasu Falls
153.1	L	-	0.70	-	-	-	Havasu Falls
153.3	L	Sinyella Canyon	12.28	Sinyala	4	-	Havasu Falls
153.5	L	-	0.50	-	-	-	Havasu Falls
153.8	L	-	0.90	-	-	-	Havasu Falls
153.9	L	-	0.22	-	-	-	Havasu Falls
155.6	R	-	5.49	UR	-	-	SB Point
157.6	R	-	11.11	UR	-	-	SB Point
158.2	R	-	2.40	-	-	-	SB Point
159.2	L	-	5.12	UR	-	-	SB Point
159.5	L	-	3.13	UR	-	-	SB Point
159.6	L	-	1.28	-	-	-	SB Point
START OF REACH 10, MILE 160.0							
160.8	R	-	3.37	UR	-	-	SB Point
161.6	L	-	15.18	UR	-	-	SB Point

Appendix 2. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon that produce debris flows—Continued

River Mile	Side	Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
163.3	R	-	1.29	-	-	-	SB Point
163.8	L	-	28.91	UR	-	-	SB Point
164.5	R	Tuckup Canyon	175.68	164-Mile	3	-	SB Point
166.4	L	National Canyon	407.12	National	2	-	Fern Glen Canyon
167.0	L	-	2.16	-	-	-	Fern Glen Canyon
167.2	L	-	6.08	-	-	-	Fern Glen Canyon
168.0	R	Fern Glen Canyon	39.97	Fern Glen	3	-	Fern Glen Canyon
168.3	R	-	2.58	-	-	-	Fern Glen Canyon
169.8	L	-	3.86	-	-	-	Gateway Rapids
170.2	L	-	7.49	-	-	-	Gateway Rapids
171.1	R	Stairway Canyon	7.97	Gateway	3	-	Gateway Rapids
171.5	L	Mohawk Canyon	214.40	Gateway	3	-	Gateway Rapids
172.1	L	-	0.53	-	-	-	Gateway Rapids
172.7	L	-	3.28	-	-	-	Gateway Rapids
173.0	L	-	1.80	-	-	-	Vulcan's Throne
173.0	R	Big Cove	2.02	UR	-	-	Gateway Rapids
174.0	R	-	0.46	-	-	-	Vulcan's Throne
174.4	R	Cove Canyon	26.62	UR	-	-	Vulcan's Throne
175.4	R	-	1.82	-	-	-	Vulcan's Throne
175.9	L	-	22.71	UR	-	-	Vulcan's Throne
176.4	R	Saddle Horse Canyon	3.80	UR	-	-	Vulcan's Throne
177.1	L	-	5.00	-	-	-	Vulcan's Throne
177.7	L	-	6.68	-	-	-	Vulcan's Throne
178.6	R	-	379.22	-	-	-	Vulcan's Throne
179.1	R	-	1.83	-	-	-	Vulcan's Throne
179.4	L	Prospect Canyon	257.22	Lava Falls	10	3	Vulcan's Throne
179.4	R	-	24.74	Lava Falls	10	3	Vulcan's Throne
179.8	R	-	1.23	-	-	-	Vulcan's Throne
180.8	L	-	0.97	UR	-	-	Vulcan's Throne
180.9	R	-	10.93	UR	-	-	Vulcan's Throne
181.8	R	-	12.77	UR	-	-	Vulcan's Throne
182.5	R	-	0.58	-	-	-	Vulcan's Throne
182.6	L	Hell's Hollow	23.12	-	-	-	Vulcan's Throne
183.1	L	-	7.60	UR	-	-	Whitmore Rapids
183.7	L	-	1.60	-	-	-	Whitmore Rapids
184.0	R	-	0.70	-	-	-	Whitmore Rapids
184.5	L	-	0.28	-	-	-	Whitmore Rapids
184.6	L	-	0.56	-	-	-	Whitmore Rapids
184.6	R	-	1.97	-	-	-	Whitmore Rapids
185.3	R	-	3.35	185-Mile	3	-	Whitmore Rapids
186.1	L	-	7.32	-	-	-	Whitmore Rapids
186.2	L	-	1.42	-	-	-	Whitmore Rapids

Appendix 2. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon that produce debris flows—Continued

River Mile	Side	Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
187.0	L	-	2.09	187-Mile	4	-	Whitmore Rapids
187.0	R	-	3.15	187-Mile	4	-	Whitmore Rapids
187.4	R	-	7.93	-	-	-	Whitmore Rapids
187.6	R	-	0.96	-	-	-	Whitmore Rapids
188.1	R	Whitmore Wash	312.28	Whitmore	3	-	Whitmore Rapids
188.5	R	-	3.76	UR	-	-	Whitmore Rapids
189.5	L	-	1.46	-	-	-	Whitmore Rapids
189.7	L	-	10.51	UR	-	-	Vulcan's Throne SW
190.3	L	-	24.22	-	-	-	Vulcan's Throne SW
190.8	L	-	0.45	UR	-	-	Vulcan's Throne SW
190.8	R	-	2.54	UR	-	-	Vulcan's Throne SW
191.1	R	-	4.86	UR	-	-	Vulcan's Throne SW
191.2	L	-	1.20	-	-	-	Vulcan's Throne SW
191.8	L	192- Mile Canyon	16.25	-	-	-	Vulcan's Throne SW
192.8	L	193- Mile Creek	57.89	UR	-	-	Vulcan's Throne SW
193.1	R	Boulder Wash	1.84	UR	-	-	Vulcan's Throne SW
193.7	L	-	0.60	-	-	-	Whitmore Point SE
194.0	R	-	0.97	-	-	-	Whitmore Point SE
194.1	L	-	2.95	-	-	-	Whitmore Point SE
194.5	L	194- Mile Canyon	8.64	UR	-	-	Whitmore Point SE
194.6	L	-	1.30	-	-	-	Whitmore Point SE
194.9	R	-	0.49	-	-	-	Whitmore Point SE
195.2	L	-	0.54	-	-	-	Whitmore Point SE
195.3	R	-	0.56	-	-	-	Whitmore Point SE
196.0	R	-	3.67	-	-	-	Whitmore Point SE
196.1	R	-	18.23	-	-	-	Whitmore Point SE
196.5	L	196- Mile Creek	11.74	UR	-	-	Whitmore Point SE
196.6	R	-	0.89	-	-	-	Whitmore Point SE
196.7	R	-	0.64	-	-	-	Whitmore Point SE
197.0	L	-	0.22	-	-	-	Whitmore Point SE
198.0	R	-	2.26	-	-	-	Whitmore Point SE
198.5	L	-	1.82	UR	-	-	Whitmore Point SE
198.5	R	Parashant Wash	934.12	UR	-	-	Whitmore Point SE
198.8	L	-	0.19	-	-	-	Whitmore Point SE
198.8	R	-	2.09	UR	-	-	Whitmore Point SE
199.5	R	-	0.93	UR	-	-	Whitmore Point SE
200.0	R	-	0.30	-	-	-	Whitmore Point SE
200.3	R	-	0.98	UR	-	-	Whitmore Point SE
200.9	R	-	1.11	-	-	-	Whitmore Point SE
201.1	L	-	0.87	-	-	-	Whitmore Point SE
201.1	R	-	4.76	-	-	-	Whitmore Point SE
202.0	R	-	10.99	-	-	-	Whitmore Point SE

Appendix 2. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon that produce debris flows—Continued

River Mile	Side	Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
202.1	L	-	0.55	-	-	-	Whitmore Point SE
202.4	R	-	0.94	-	-	-	Whitmore Point SE
202.5	R	-	1.41	-	-	-	Whitmore Point SE
203.0	L	-	0.94	-	-	-	Whitmore Point SE
203.0	R	-	0.54	-	-	-	Whitmore Point SE
204.0	R	-	4.26	-	-	-	Whitmore Point SE
204.2	L	-	0.75	-	-	-	Whitmore Point SE
204.3	L	-	0.49	-	-	-	Whitmore Point SE
204.3	R	Spring Canyon	50.38	UR	-	-	Whitmore Point SE
205.5	L	205- Mile Creek	27.54	205-Mile	7	4	Whitmore Point SE
206.0	R	-	2.04	UR	-	-	Granite Park
206.5	R	Indian Canyon	9.84	UR	-	-	Granite Park
207.4	L	-	0.40	UR	-	-	Granite Park
207.6	L	-	1.40	-	-	-	Granite Park
207.8	L	-	3.09	-	-	-	Granite Park
208.6	L	-	8.35	UR	-	-	Granite Park
208.6	R	209- Mile Canyon	95.46	209-Mile	7	-	Granite Park
208.8	L	Granite Park Canyon	126.22	209-Mile	7	-	Granite Park
209.8	R	-	1.71	UR	-	-	Granite Park
210.8	R	-	0.99	-	-	-	Granite Park
211.2	L	-	1.71	-	-	-	Granite Park
211.5	L	-	0.47	-	-	-	Granite Park
211.5	R	Fall Canyon	11.48	UR	-	-	Granite Park
212.2	L	-	0.48	Little Bastard	3	-	Granite Park
212.2	R	-	0.08	Little Bastard	3	-	Granite Park
212.7	R	-	3.45	-	-	-	Granite Park
213.8	L	-	2.00	-	-	-	Granite Park
START OF REACH 11, MILE 213.9							
214.0	R	214- Mile Creek	8.22	-	-	-	Granite Park
214.2	R	-	2.74	UR	-	-	Granite Park
214.5	L	-	0.55	UR	-	-	Granite Park
215.0	L	215- Mile Creek	5.89	-	-	-	Granite Park
215.7	L	Three Springs Canyon	24.17	Three Springs	2	-	Granite Park
215.7	R	-	0.60	Three Springs	2	-	Granite Park
216.2	R	-	2.45	UR	-	-	Granite Park
216.5	R	-	0.72	-	-	-	Diamond Peak
216.8	L	-	9.76	UR	-	-	Diamond Peak
217.4	L	217- Mile Canyon	23.98	217-Mile	7	5	Diamond Peak
217.7	R	-	1.46	UR	-	-	Diamond Peak
218.0	L	-	0.81	-	-	-	Diamond Peak
218.6	L	-	0.96	-	-	-	Diamond Peak

Appendix 2. List of geomorphically-significant tributary canyons of the Colorado River in Grand Canyon that produce debris flows—Continued

River Mile	Side	Tributary name	Drainage area (km^2)	Rapid name	Rapid rating	Water surface fall (m)	7.5-minute quadrangle name
219.4	R	Trail Canyon	50.08	Trail Canyon	3	-	Diamond Peak
219.9	L	-	0.59	-	-	-	Diamond Peak
220.0	R	220- Mile Canyon	26.94	UR	-	-	Diamond Peak
220.4	L	Granite Spring Canyon	37.14	Granite Spring	2	-	Diamond Peak
221.3	R	-	0.94	-	-	-	Diamond Peak
222.0	L	222- Mile Canyon	5.06	-	-	-	Diamond Peak
222.3	L	-	0.26	-	-	-	Diamond Peak
222.5	R	-	2.99	-	-	-	Diamond Peak
222.6	L	"222.6- Mile Canyon"	0.58	UR	-	-	Diamond Peak
223.1	L	-	1.04	UR	-	-	Diamond Peak
223.2	R	-	0.53	-	-	-	Diamond Peak
223.5	L	224- Mile Canyon	12.78	224-Mile	3	-	Diamond Peak
223.9	R	-	0.68	-	-	-	Diamond Peak
224.5	L	"224.5- Mile Canyyon"	0.45	-	-	-	Diamond Peak
224.6	R	-	2.73	-	-	-	Diamond Peak
225.3	R	-	23.32	-	-	-	Diamond Peak
225.8	L	Diamond Creek	716.74	Diamond Creek	4	8	Diamond Peak

Appendix 3. Selected drainage basin characteristics for 529 geomorphically-significant tributaries of the Colorado River in Grand Canyon

[Drainage basin characteristics reported here were derived from USGS 7.5-minute topographic quadrangle maps. Drainage areas, from appendix 2. Stream order, was determined according to the Horton System as modified by Strahler (1952), using USGS 7.5-minute quadrangle maps. Perimeter, is the vectorized-length of drainage-basin divide, determined from drainage-basin boundary vectors hand-digitized from USGS 7.5-minute quadrangle maps, using the vector statistics package located within the *Map and Image Processing System* (MIPS), a software package developed by Micro-Images Inc. of Lincoln, Nebraska (use of trade names does not imply endorsement by the U.S. Geological Survey). Maximum dimension, is the maximum, linear dimension of the drainage basin determined using drainage-basin boundary vectors and the vector satistics package located within MIPS. Roughness, refers to drainage-shape roughness, a unit-less number which describes the degree of irregularity of a drainage's shape; ie. a circle is assigned a value of 1, while a snowflake might be assigned a value of between 100 and 300. Roughness values were determined using drainage-basin boundary vectors and the vector satistics package located within MIPS. Aspect, is the dominant drainage basin orientation relative to true-North, and was determined by measuring the azimuth of an imaginary line connecting a drainage's pour-point (confluence with Colorado River), to its weighted-centroid; drainage-centroid coordinates were calculated using drainage-basin boundary vectors and the vector satistics package located within MIPS. Drainage length, was determined by measuring the length of the drainage channel mapped as a solid blue line on USGS 7.5-minute quadrangle maps. Maximum relief, is the elevation difference between the highest point on the drainage and the basin's pour-point (confluence with the Colorado River); these values were determined from USGS 7.5-minute quadrangle maps. (n.d.), no data; (-), tributary is unnamed]

River mile	Side	Tributary name	Drainage area, in km^2	Stream order	Perimeter, in meters	Maximum dimension, in meters	Roughness	Aspect (degrees)	Drainage length in meters	Maximum relief, in meters
2.2	L	-	2.53	3	7073	2783	7.8	290	3219	750
2.2	R	-	7.71	4	14882	5472	10.6	118	5311	1022
2.8	R	Cathedral Wash	17.27	4	20001	7109	8.2	93	8529	1112
3.4	L	-	5.26	2	10408	4134	8.2	310	4345	718
3.5	L	-	0.61	2	4586	2176	16.5	313	2253	174
3.9	L	-	4.29	3	11613	4913	13.3	315	5311	728
4.5	L	-	5.87	3	14044	5845	14.0	318	5793	843
5.1	L	"5 Mile Wash"	4.64	3	13594	5778	16.9	325	5793	805
5.7	R	Seven Mile Draw	18.65	3	21599	7007	8.1	108	6920	1148
7.9	L	Jackass Creek	52.24	5	45059	16583	14.3	345	18829	1010
7.9	R	Badger Canyon	47.01	5	35597	10289	7.8	102	12713	1254
8.6	R	-	2.09	3	6027	2063	6.0	86	2575	318
10.0	L	-	1.90	3	7262	3142	12.0	322	3540	421
10.2	L	-	1.37	3	7014	3028	15.5	337	3380	421
11.2	R	Soap Creek	90.26	6	48856	15028	8.1	76	10782	1315
11.8	L	Salt Water Wash	9.60	4	20366	9007	19.1	324	10139	622
12.1	L	-	9.81	4	21994	9793	22.0	336	10621	634
12.3	R	-	1.36	3	6048	2047	9.1	124	3219	418
12.8	R	-	7.99	3	14314	5618	10.1	56	6437	488
13.0	L	-	1.13	3	4796	1944	8.3	304	2414	469
13.0	R	-	1.19	2	5681	2377	11.4	38	2575	476
13.6	L	-	2.58	3	7571	3274	9.6	308	3380	530
14.3	L	Tanner Wash	182.55	4	110100	39256	23.7	335	41520	1265
15.1	L	-	7.40	3	19480	8853	23.3	328	9817	676
15.3	L	-	2.52	2	10100	4576	18.3	330	5793	587
16.3	L	Hanaa Ninadzidzahi	28.84	4	31907	13032	14.4	331	16415	804
16.8	R	House Rock Wash	770.52	7	157396	42891	8.8	90	54072	1865

Appendix 3. Selected drainage basin characteristics for 529 geomorphically-significant tributaries of the Colorado River in Grand Canyon—Continued

River mile	Side	Tributary name	Drainage area, in km²	Stream order	Perimeter, in meters	Maximum dimension, in meters	Roughness	Aspect (degrees)	Drainage length in meters	Maximum relief, in meters
17.4	L	-	3.75	3	10698	4603	13.1	312	4989	628
18.0	L	"18 Mile Wash"	5.06	3	15130	6540	19.6	324	7403	693
18.1	L	-	3.83	3	12412	5677	18.4	335	5954	677
19.0	R	"19 Mile Canyon"	1.12	2	4204	1434	5.4	145	1931	555
19.1	L	-	1.42	2	7493	3177	16.8	301	3219	625
19.3	R	-	2.48	3	7595	2771	8.5	60	3380	575
19.9	L	-	3.78	3	11414	4746	14.3	311	4989	658
20.5	R	North Canyon	407.72	6	126221	46117	14.3	56	54394	1902
21.1	L	-	0.04	1	1184	554	15.9	243	483	573
21.1	R	-	0.39	1	3136	1289	10.5	66	1127	596
21.4	L	-	13.96	4	26673	10358	19.8	308	12392	862
21.5	L	"22 Mile Wash"	1.59	2	7891	3465	17.2	304	4023	707
21.8	R	-	0.27	2	2304	942	8.1	105	805	597
22.2	L	-	3.05	3	10425	4637	15.8	311	4989	738
22.9	L	-	7.87	3	17457	7272	16.1	315	8368	820
23.2	R	-	0.12	1	1604	715	9.4	128	644	634
23.3	L	-	0.27	2	2608	1093	10.5	305	1127	689
23.4	R	-	0.15	2	1956	727	9.3	122	644	649
23.5	L	-	0.82	2	4411	1985	10.7	298	2092	707
24.0	L	-	1.71	3	7421	3268	14.2	300	3380	725
24.2	L	-	0.22	2	2078	840	7.8	295	805	674
24.2	R	-	0.35	2	2854	1083	8.7	164	966	680
24.4	L	Sheep Spring Wash	26.12	4	30400	11551	13.5	297	14645	887
24.7	L	-	1.16	2	5536	2484	11.9	327	2736	724
25.0	L	-	2.01	2	6704	2729	9.1	335	3058	725
25.3	L	-	0.74	2	3803	1700	8.7	340	1609	724
25.3	R	-	1.24	2	5216	1875	7.9	141	2414	695
25.4	L	-	0.07	1	1383	649	13.1	325	483	707
25.4	R	-	0.11	1	1650	647	9.9	140	644	683
26.6	L	Tiger Wash	51.89	4	42911	15730	13.0	309	16254	978
26.6	R	-	3.42	2	9261	3429	9.3	84	4506	748
26.8	R	-	0.02	1	689	314	11.3	88	161	341
27.2	L	-	1.24	2	4678	1798	6.8	314	2092	744
28.2	L	To Hajisho	20.22	4	26790	10514	13.9	299	11748	853
29.2	L	Shinumo Wash	186.55	4	86282	29355	13.6	304	33473	1113
30.2	L	-	6.03	3	12870	5422	11.6	318	5633	799
30.2	R	-	0.29	1	2600	1159	10.4	129	1287	757
30.5	R	-	0.95	2	4122	1523	6.6	100	1609	757
31.0	R	-	3.08	2	8881	3347	9.7	118	4023	765
31.6	R	South Canyon	193.12	4	74161	26845	10.3	47	28002	1931
31.8	R	-	0.49	2	3189	1321	8.7	40	1287	792

Appendix 3. Selected drainage basin characteristics for 529 geomorphically-significant tributaries of the Colorado River in Grand Canyon—Continued

River mile	Side	Tributary name	Drainage area, in km²	Stream order	Perimeter, in meters	Maximum dimension, in meters	Roughness	Aspect (degrees)	Drainage length in meters	Maximum relief, in meters
32.0	R	-	1.19	2	4533	1735	6.6	16	1770	805
32.6	L	-	0.14	1	1806	819	10.3	222	805	768
32.8	L	-	1.01	2	6113	2331	14.1	251	2575	805
34.2	R	-	0.94	2	4752	1910	9.7	54	1448	805
34.7	L	Nautiloid Canyon	10.59	3	16945	5438	8.7	267	5793	842
34.9	L	-	0.09	2	1385	588	8.7	248	644	415
35.2	L	-	0.70	2	3706	1446	7.7	253	1287	813
35.6	L	-	0.78	1	3610	1413	6.6	242	1448	805
36.0	L	-	2.01	2	5900	1958	5.7	276	2575	842
36.7	R	-	20.50	3	34950	14087	24.0	97	16093	1051
37.4	L	Tatahatso Wash	202.60	4	78790	23716	9.2	311	26393	1134
37.6	L	-	0.95	2	5895	1960	12.1	316	3219	975
37.7	L	-	1.49	2	7862	3055	16.2	340	3219	902
38.6	R	-	0.79	2	3573	1210	5.5	127	1287	866
39.0	R	"Redbud Alcove"	1.41	2	4779	1797	6.1	97	1770	902
41.0	R	Buck Farm Canyon	31.15	4	36976	16245	19.3	56	16415	1859
41.3	R	"Bert's Canyon"	1.81	2	5888	2503	8.1	63	2414	969
42.9	L	-	1.33	2	5007	1916	7.2	190	1287	907
43.0	L	-	0.65	2	3727	1531	8.8	210	1609	829
43.1	L	-	0.26	1	2963	1368	15.3	226	1448	829
43.2	L	Tatahoysa Wash	50.77	3	42343	15055	12.6	338	18346	1000
43.7	L	-	6.10	3	12986	5157	11.0	341	6437	985
44.6	L	-	2.66	2	7417	2746	7.7	357	3058	975
44.8	L	-	1.26	2	5441	2319	10.0	15	2253	981
45.8	L	-	0.61	2	4241	1653	11.4	342	1609	975
46.7	R	-	1.46	3	4979	1845	6.3	159	1448	975
46.8	R	-	1.30	3	4915	1835	7.0	99	1448	1002
47.0	R	Saddle Canyon	29.30	4	26632	11117	10.1	49	11909	1853
47.4	L	-	0.71	2	3402	1252	6.0	228	1287	975
47.4	R	-	0.49	2	3398	1521	10.6	36	1448	1000
47.8	L	-	0.28	1	2451	1085	9.4	237	1127	975
47.8	R	-	0.77	2	3954	1622	8.4	312	1609	1073
48.5	R	-	1.31	2	4885	2149	8.0	56	2414	1018
49.4	R	-	4.36	3	9822	4354	9.8	64	4184	1286
49.6	L	-	2.22	4	6524	2376	7.0	216	2092	975
49.8	R	-	3.39	3	11282	4853	16.2	52	5150	1353
49.9	L	-	0.15	1	2359	1067	16.7	244	966	981
50.0	L	-	0.12	1	2157	1015	18.9	244	966	981
50.1	L	-	0.13	1	2118	971	15.7	248	805	988
50.3	L	-	0.26	1	2581	1041	10.3	250	966	988
50.4	L	-	0.43	2	3035	1100	7.7	282	966	988

Appendix 3. Selected drainage basin characteristics for 529 geomorphically-significant tributaries of the Colorado River in Grand Canyon—Continued

River mile	Side	Tributary name	Drainage area, in km^2	Stream order	Perimeter, in meters	Maximum dimension, in meters	Roughness	Aspect (degrees)	Drainage length in meters	Maximum relief, in meters
50.8	L	-	0.36	1	2952	1187	9.8	286	966	1000
51.2	L	-	0.37	2	2778	1185	8.9	267	966	1000
51.7	R	Little Nankoweap Creek	10.59	4	15242	6117	8.8	98	7242	1609
52.2	R	Nankoweap Canyon	84.58	5	44576	13575	7.2	61	14806	1866
52.5	L	-	3.49	2	8304	2522	6.0	267	3862	1016
53.1	R	-	1.23	3	4725	1721	6.6	46	1609	1010
53.5	R	-	0.26	1	2547	1155	11.4	44	966	1010
53.8	R	-	0.75	3	4184	1661	9.3	58	1609	1028
54.0	R	-	0.39	1	3540	1611	14.6	233	1448	1028
54.5	R	-	1.66	3	5209	2001	6.3	47	2575	1079
55.0	L	-	0.60	2	3380	1344	7.6	220	2253	1006
55.4	R	-	0.70	3	3518	1439	7.3	69	1287	1036
56.0	R	Kwagunt Creek	39.25	4	35193	12823	11.5	62	15288	1744
56.3	L	-	4.58	3	9271	3044	6.2	263	2253	1024
56.6	R	-	0.12	1	2068	897	15.8	72	966	671
56.8	R	-	0.10	1	1796	817	15.2	86	805	805
56.9	L	-	0.93	4	4475	1692	8.1	266	1609	1024
57.3	L	-	0.61	3	3492	1437	8.3	250	1448	1024
57.5	R	Malgosa Canyon	6.98	3	12905	5155	9.5	63	5954	1256
57.7	L	-	0.39	2	2960	1124	8.5	258	805	1030
57.8	R	-	0.14	1	1964	899	12.3	65	966	847
58.0	R	Awatubi Canyon	5.54	3	11073	4712	9.4	56	5150	1256
58.5	L	-	0.74	3	3893	1521	8.0	246	1448	1024
58.8	R	-	1.19	3	4948	2102	8.7	57	2414	818
59.4	R	-	0.15	1	1907	872	10.7	77	644	573
59.6	L	-	9.49	3	15059	4759	7.6	217	5472	1039
59.6	R	60 Mile Canyon	9.69	4	15377	5636	8.9	67	6276	1365
59.7	L	-	0.39	3	3019	1339	10.5	233	966	1012
60.2	R	-	0.40	2	3214	1383	11.2	57	1287	817
60.3	L	-	1.42	3	5091	1922	6.9	238	1931	1012
60.5	L	-	0.40	2	2883	1071	7.7	244	1127	890
60.6	R	-	0.94	2	4549	2029	9.8	83	1931	1093
61.1	R	-	0.66	2	5015	2259	17.1	97	2414	1116
61.7	R	-	0.66	2	4724	1893	13.5	130	2092	1146
61.9	L	-	0.24	1	2304	1033	9.8	310	1287	1056
62.0	R	-	0.09	1	1534	693	12.2	127	644	658
62.1	L	-	0.21	1	2209	981	10.2	317	966	1056
62.2	R	-	0.37	2	2982	1267	10.3	132	1287	1122
62.5	R	-	0.67	3	3564	1421	7.6	119	1287	1164
62.6	L	-	0.19	1	2269	1044	12.6	271	1127	1056

Appendix 3. Selected drainage basin characteristics for 529 geomorphically-significant tributaries of the Colorado River in Grand Canyon—Continued

River mile	Side	Tributary name	Drainage area, in km^2	Stream order	Perimeter, in meters	Maximum dimension, in meters	Roughness	Aspect (degrees)	Drainage length in meters	Maximum relief, in meters
62.6	R	"Crash Canyon"	1.79	3	6062	2100	7.1	83	2092	1158
63.0	L	-	0.64	3	3638	1375	7.8	260	1287	1056
63.3	L	-	0.26	3	2479	1100	10.3	259	966	1049
63.3	R	-	0.66	3	3655	1332	7.3	74	1448	801
63.5	L	-	0.40	4	2933	1139	8.3	257	1127	1049
63.5	R	-	0.05	1	1418	675	17.4	75	644	402
63.8	L	-	0.37	3	2707	1107	8.0	282	966	1071
63.8	R	-	0.31	2	2514	1101	8.9	96	966	801
64.0	L	-	0.61	3	3547	1297	7.5	283	1287	1097
64.5	L	-	0.33	3	2551	1049	8.1	279	966	1104
64.6	R	Carbon Creek	11.40	4	17138	6537	9.8	136	8529	1164
65.3	L	-	0.60	3	4016	1530	10.2	250	1448	1104
65.5	L	Palisades Creek	4.06	4	9698	3492	8.4	293	4023	1195
65.5	R	Lava Canyon	54.71	5	38846	13531	9.6	121	15127	1756
66.3	L	-	1.15	2	4718	1963	8.1	275	1931	841
66.3	R	-	1.47	4	6004	2411	9.9	79	2414	774
66.8	L	Espejo Creek	1.73	3	6526	2832	10.7	281	2897	1109
67.2	L	Comanche Creek	5.40	3	11552	4082	8.7	295	4506	1351
67.6	R	-	1.22	3	4449	1694	6.2	108	1609	646
67.8	L	-	0.28	2	2906	1260	13.2	306	1287	488
68.0	L	-	0.63	2	3800	1596	9.6	300	1770	658
68.5	L	Tanner Canyon	19.25	4	24692	8281	10.6	352	9817	1451
68.8	R	-	0.15	1	1841	761	9.4	154	644	399
69.6	R	Basalt Canyon	14.06	4	18845	7647	10.3	142	8690	1355
70.0	L	-	4.74	4	9909	3843	8.0	332	4667	1110
70.3	R	-	0.88	3	4288	1905	9.3	157	1931	658
70.7	L	-	0.65	2	3796	1559	9.1	344	1609	610
70.9	L	Cardenas Creek	3.87	3	10467	4105	11.1	347	4989	1122
70.9	R	-	2.45	4	7809	3022	9.6	174	3540	1000
71.2	R	-	1.11	3	5789	2266	11.8	335	2414	695
72.1	R	-	1.16	4	4649	1679	6.7	161	1931	628
72.6	R	Unkar Creek	37.26	5	31445	9931	8.4	140	12231	1676
73.3	L	-	1.32	3	5234	1963	7.8	327	2092	604
73.9	R	-	3.56	4	9472	3556	9.5	122	3862	1172
74.5	R	-	0.39	1	2910	1315	9.7	107	1287	561
75.0	L	Escalante Creek	4.76	3	9810	4331	8.9	284	4828	1212
75.0	R	-	1.11	3	4353	1681	6.6	121	1770	781
75.5	L	75 Mile Creek	11.47	4	16210	5318	7.5	307	6920	1531
75.5	R	-	0.44	2	3148	1312	9.4	121	1287	781
76.0	L	Papago Creek	6.57	4	12524	4480	8.5	344	4828	1463
76.7	L	Red Canyon	10.52	4	14622	6097	8.5	11	6920	1438

Appendix 3. Selected drainage basin characteristics for 529 geomorphically-significant tributaries of the Colorado River in Grand Canyon—Continued

River mile	Side	Tributary name	Drainage area, in km^2	Stream order	Perimeter, in meters	Maximum dimension, in meters	Roughness	Aspect (degrees)	Drainage length in meters	Maximum relief, in meters
76.9	R	-	2.89	3	7521	3130	8.1	189	3540	939
78.0	L	Mineral Canyon	3.58	3	9014	3924	9.9	4	4506	1244
78.3	R	Asbestos Canyon	8.71	4	13299	5088	7.8	192	6437	1528
78.7	L	Hance Creek	23.54	4	25018	9481	10.1	11	12874	1530
79.0	R	-	1.32	3	5560	2367	10.0	199	2575	963
79.4	L	-	0.51	2	3621	1423	10.0	6	1609	573
79.6	R	-	3.07	3	9090	3927	11.6	207	4345	808
79.7	L	-	2.21	3	6903	2935	9.2	15	3058	843
80.2	R	-	0.26	2	2621	1131	11.4	152	1287	719
80.6	L	Cottonwood Creek	10.14	3	15202	5754	8.6	7	6759	1332
81.2	R	Vishnu Creek	13.56	3	20657	8429	12.8	223	11587	1646
81.5	L	Grapevine Creek	30.82	4	28223	8671	7.9	30	11265	1527
81.6	R	-	7.01	4	13234	5620	10.6	211	6920	1536
82.2	R	-	1.17	3	4428	1805	6.9	200	1931	866
82.3	L	-	1.09	3	4689	1989	8.6	26	2092	768
82.8	L	Boulder Creek	5.38	4	10106	3971	7.5	45	4345	1268
83.1	L	-	1.03	2	5080	2214	10.9	46	2253	1006
83.6	R	-	4.67	3	9636	3904	8.1	242	4184	1317
83.9	L	Lonetree Canyon	2.61	2	6975	2840	7.6	48	3219	1049
84.1	R	Clear Creek	93.14	4	46558	17693	8.8	213	22208	1853
84.5	L	-	0.62	1	4171	1814	12.2	45	1770	876
84.6	R	Zoroaster Canyon	4.10	3	11033	5012	13.5	191	5311	1558
85.0	L	-	0.36	2	2737	1203	9.2	355	1287	770
85.0	R	-	0.94	3	4495	1758	8.5	206	1931	866
85.6	L	Cremation Creek	12.07	4	15316	5689	7.2	17	6115	1481
85.7	R	-	2.17	3	6843	2826	8.9	224	3058	1146
86.7	R	-	3.79	4	8720	3515	8.1	221	3862	1440
86.9	L	-	0.12	1	1629	716	9.6	345	644	457
87.2	L	-	1.05	3	5053	2025	9.7	355	2253	856
87.8	R	Bright Angel Creek	260.33	5	78939	27457	8.3	191	29611	2063
87.9	L	-	1.89	3	5798	2102	6.5	350	2253	890
88.9	L	Pipe Creek	17.31	5	20995	6150	7.5	5	6759	1484
88.9	R	-	2.27	3	6291	2373	6.6	171	3219	915
89.3	R	-	0.93	2	4438	1771	8.4	158	1931	867
90.2	L	Horn Creek	4.28	3	8761	3502	7.2	29	3862	1434
91.1	R	91 Mile Creek	5.69	3	10555	3620	6.7	218	4506	1390
91.5	R	Trinity Creek	20.05	5	20366	6927	7.0	169	9334	1611
92.0	R	-	1.22	3	4650	1755	6.7	145	1931	892
92.7	L	Salt Creek	3.22	2	8309	3477	9.0	343	3540	1426
93.3	L	-	0.87	3	4241	1820	8.9	328	1931	1024
93.5	L	Monument Creek	9.73	3	12577	4664	6.0	359	4989	1413

Appendix 3. Selected drainage basin characteristics for 529 geomorphically-significant tributaries of the Colorado River in Grand Canyon—Continued

River mile	Side	Tributary name	Drainage area, in km^2	Stream order	Perimeter, in meters	Maximum dimension, in meters	Roughness	Aspect (degrees)	Drainage length in meters	Maximum relief, in meters
93.5	R	-	2.27	3	6180	2540	6.9	193	2736	1113
94.3	L	-	0.51	2	2795	1019	5.6	244	1127	673
94.3	R	94 Mile Creek	9.42	4	13987	5537	8.2	190	5954	1309
95.0	L	Hermit Creek	31.98	4	28991	9252	8.4	11	11426	1379
95.6	L	Travertine Canyon	3.84	3	8896	3620	8.4	38	3862	1324
96.0	R	-	2.88	3	7600	3285	8.7	220	3540	964
96.7	L	Boucher Creek	16.79	4	17378	6249	6.5	54	6920	1305
97.4	R	-	3.44	4	7680	3124	7.0	249	3540	1161
98.2	L	Slate Creek	12.12	4	17156	7032	10.0	56	6920	1305
98.2	R	Crystal Creek	111.64	6	54463	22787	11.1	217	26393	2008
99.3	R	Tuna Creek	59.62	5	57831	23378	22.7	203	29450	2036
99.6	L	-	0.83	3	4131	1430	7.1	22	1448	843
99.7	R	-	4.96	4	9518	3938	7.6	171	4506	1146
100.6	L	Agate Canyon	4.36	4	9244	3582	7.6	18	4023	1223
101.3	L	Sapphire Canyon	7.78	3	13323	5700	9.8	35	6115	1317
101.3	R	-	2.02	3	5904	2319	6.8	214	2414	939
102.0	L	Turquoise Canyon	14.64	4	16114	6111	6.7	214	6920	1329
102.0	R	-	0.29	3	2587	1184	10.6	128	1287	708
102.6	L	-	3.62	3	8098	3250	7.3	83	1931	717
103.0	R	-	2.15	3	6375	2601	7.7	267	2575	1095
103.1	L	-	1.24	3	4665	1990	7.5	93	1931	1000
103.9	L	-	0.21	2	2165	973	9.8	73	966	719
103.9	R	Emerald Canyon	4.08	3	9229	3548	8.0	267	3862	1201
104.3	R	-	1.72	3	6167	2782	10.0	257	3058	1024
104.6	L	Ruby Canyon	7.47	3	12882	5491	9.5	45	4184	1402
104.6	R	Monodnock Amphitheater	9.65	5	13935	4953	7.2	228	5311	1249
104.9	L	-	2.12	3	7070	3077	10.3	64	3380	1402
105.7	L	-	1.54	2	6040	2667	10.4	55	2897	1378
105.7	R	-	0.93	3	4111	1733	7.7	247	1770	893
106.0	L	Serpentine Canyon	3.96	3	9184	3518	8.2	64	3701	1384
106.3	R	-	2.07	3	6448	2722	8.5	253	2736	1069
107.6	L	Bass Canyon	7.28	3	11862	4895	8.0	44	5633	1170
107.8	R	Hotauta Canyon	7.13	3	11264	4349	6.9	265	4667	1274
108.6	R	Shinumo Creek	221.98	5	75400	24498	8.3	232	30738	2134
109.6	R	-	0.67	3	3808	1632	9.2	164	1609	894
109.8	L	-	1.05	3	4601	2023	8.9	352	1931	929
110.2	L	Copper Canyon	6.06	3	10737	4344	7.7	13	4828	1256
110.2	R	-	0.76	3	3933	1710	8.9	193	1770	894
110.4	L	-	0.25	1	2632	1183	12.6	40	1127	789
110.8	R	Hakatai Canyon	9.48	4	13197	5174	7.2	201	6598	1643

Appendix 3. Selected drainage basin characteristics for 529 geomorphically-significant tributaries of the Colorado River in Grand Canyon—Continued

River mile	Side	Tributary name	Drainage area, in km^2	Stream order	Perimeter, in meters	Maximum dimension, in meters	Roughness	Aspect (degrees)	Drainage length in meters	Maximum relief, in meters
111.2	R	-	0.68	2	3895	1706	9.8	180	1609	1025
111.3	L	-	0.52	2	3059	1229	7.2	338	1287	780
112.2	L	-	1.78	2	5396	2037	6.2	314	2253	1026
112.2	R	Waltenberg Canyon	14.27	5	20942	8412	12.4	195	9173	1658
112.5	L	-	0.63	2	3608	1482	8.5	322	2253	915
112.5	R	-	1.99	3	6221	2542	8.0	158	2736	1390
113.0	R	-	1.33	3	5272	2055	8.1	144	2092	1019
113.3	R	-	0.67	2	3543	1347	7.1	102	1127	920
113.6	L	-	1.12	2	5102	2253	10.3	274	2414	975
113.9	R	-	0.53	2	3181	1208	7.3	90	1287	579
114.4	R	-	0.37	3	2643	1055	7.5	108	1127	832
114.5	L	Garnet Canyon	15.83	4	21960	8077	11.2	298	9012	1426
115.1	L	-	4.93	3	10909	4604	10.2	301	5150	1378
115.5	L	-	4.07	4	9773	3866	9.3	330	4184	1359
115.8	R	-	0.67	2	3505	1312	6.9	157	966	838
116.1	L	-	1.00	2	5492	2263	12.4	351	2414	853
116.5	L	Royal Arch Creek	30.86	5	28592	9802	9.1	346	12553	1390
116.8	L	-	2.12	4	6654	2396	7.5	93	2253	1307
117.7	L	-	1.88	3	5816	2168	6.7	95	2253	1285
117.7	R	-	0.68	2	4162	1754	10.7	264	1609	850
118.0	R	-	1.02	3	5179	1891	9.6	259	1931	844
118.3	R	-	0.23	1	2549	1167	12.8	259	1127	780
118.6	L	-	0.24	2	2255	999	9.3	69	966	878
118.7	R	-	1.40	3	5224	2067	7.7	264	2253	933
119.0	R	119 Mile Creek	2.77	3	8938	3796	12.3	242	4023	1378
119.2	L	-	0.62	1	3998	1444	9.3	47	1448	878
119.2	R	-	1.86	3	7821	3535	14.9	226	4023	1134
119.7	R	-	0.51	1	3634	1645	11.8	230	1770	853
120.1	R	Blacktail Canyon	24.15	5	27980	12178	14.1	228	13357	1695
120.6	L	-	1.73	2	6334	2443	8.9	351	2575	963
120.8	L	-	0.40	2	2585	1059	6.8	15	1127	817
121.7	L	-	7.96	3	13205	5237	8.7	347	5472	1305
122.2	R	122 Mile Creek	8.03	4	14702	6297	11.5	226	6115	1390
122.3	L	-	2.39	3	6920	2869	8.3	2	3219	1328
122.5	L	-	0.44	1	3470	1555	12.2	15	1448	841
122.7	L	Forster Canyon	10.04	5	14155	4669	6.6	28	6759	1328
123.1	L	-	0.19	1	2224	1025	12.2	53	966	817
123.3	L	-	0.42	1	3495	1600	13.3	80	1448	896
123.5	L	-	2.29	3	6494	2463	7.0	70	2575	1278
123.6	L	-	0.21	2	2274	936	10.0	83	805	780
124.0	L	-	0.97	3	5408	2252	12.5	78	2092	1292

Appendix 3. Selected drainage basin characteristics for 529 geomorphically-significant tributaries of the Colorado River in Grand Canyon—Continued

River mile	Side	Tributary name	Drainage area, in km²	Stream order	Perimeter, in meters	Maximum dimension, in meters	Roughness	Aspect (degrees)	Drainage length in meters	Maximum relief, in meters
124.4	L	-	3.06	3	7323	2758	6.6	87	2897	1280
125.0	L	Fossil Canyon	34.39	5	28822	10472	8.8	167	13518	1426
125.5	R	-	0.30	2	2953	1325	13.0	341	1287	829
125.6	L	-	0.29	1	3186	1421	15.6	175	1448	866
125.8	R	-	4.44	4	11008	4274	10.6	293	4506	951
126.3	L	-	0.53	3	4091	1838	14.1	155	2897	914
126.6	R	-	0.29	2	3316	1357	15.8	287	1287	792
126.7	R	-	0.10	1	1844	835	14.9	321	966	671
126.9	L	-	0.57	2	3573	1560	9.9	282	1770	916
126.9	R	127 Mile Creek	6.09	4	13581	5847	13.0	120	6437	1475
127.2	R	-	0.65	2	3964	1800	10.9	270	1770	866
127.3	L	-	0.76	3	3967	1639	8.5	92	1770	1317
127.5	R	-	0.98	2	5118	2289	12.0	288	2414	890
127.6	L	"127.6 Mile Creek"	1.75	3	6313	2240	8.1	111	1609	917
127.9	L	-	0.98	2	5260	2199	11.7	136	1770	1317
128.5	R	128 Mile Creek	7.93	4	17204	7130	15.5	299	8047	1561
129.0	L	Specter Chasm	8.25	5	12050	4305	6.3	130	3540	1439
130.0	R	"130 Mile Creek"	6.40	3	13931	5907	12.9	326	6598	1561
130.5	R	Bedrock Canyon	21.14	5	22243	8432	8.9	284	8690	1725
130.9	L	-	2.01	3	5977	2548	7.6	127	2575	1439
131.1	R	-	1.69	2	6682	2913	11.6	290	3058	1012
131.7	R	Galloway Canyon	12.27	4	17039	6687	9.3	273	8529	1729
131.9	R	Stone Creek	6.76	4	12402	5461	10.0	250	5954	1661
132.3	L	-	0.83	3	4400	1827	9.6	70	1931	1049
132.5	L	-	0.16	2	1979	880	11.0	71	805	344
133.0	L	-	2.52	3	7551	3132	9.4	52	3540	1451
133.0	R	133 Mile Creek	6.63	4	11396	4294	7.4	250	4667	1317
133.4	L	-	0.31	2	2808	1264	11.3	56	1287	878
133.8	R	Tapeats Creek	216.34	5	76122	29578	10.4	263	34278	2206
134.2	L	-	1.18	3	6110	2765	14.3	14	2736	1414
134.2	R	Bonita Creek	5.73	4	12218	4653	9.9	193	5633	1146
134.3	L	-	4.64	4	10908	3819	9.0	44	5311	1463
134.8	R	-	0.86	3	4096	1414	6.7	230	1287	800
135.4	R	-	0.22	3	2279	972	10.0	225	1127	724
135.9	L	-	1.60	3	6638	2703	11.2	1	2897	1398
136.2	R	Deer Creek	43.63	5	34648	11219	8.9	214	14645	1683
136.5	L	-	0.07	1	1341	625	11.9	10	644	543
136.7	L	-	4.07	3	8750	3252	7.0	10	3540	1398
136.8	L	-	0.41	1	2742	1130	7.6	48	644	780
137.6	L	-	0.11	1	1682	793	12.7	28	644	744
137.7	R	-	0.78	2	4097	1503	7.9	239	1287	829

Appendix 3. Selected drainage basin characteristics for 529 geomorphically-significant tributaries of the Colorado River in Grand Canyon—Continued

River mile	Side	Tributary name	Drainage area, in km^2	Stream order	Perimeter, in meters	Maximum dimension, in meters	Roughness	Aspect (degrees)	Drainage length in meters	Maximum relief, in meters
137.8	L	-	0.81	2	4285	1824	9.6	7	1609	853
138.3	L	-	0.53	1	3933	1610	11.9	12	1609	841
138.4	L	-	0.17	1	2019	874	10.3	10	805	744
138.5	R	-	5.20	3	11304	4606	10.0	220	4667	893
138.9	L	-	1.44	1	6770	2756	13.0	5	3058	911
139.1	R	Fishtail Canyon	19.63	5	18511	6604	6.2	189	8851	1353
139.5	R	-	0.26	1	2722	1162	12.0	171	1127	780
139.9	L	140 Mile Canyon	25.76	5	24324	9083	8.6	181	9817	1426
139.9	R	-	0.65	1	3354	1346	6.9	353	1609	831
140.9	L	-	0.59	2	3459	1303	7.7	354	1287	792
141.3	L	-	0.88	2	4322	1837	9.0	174	1931	808
141.3	R	-	2.08	3	6511	2650	8.3	196	2897	1256
143.1	L	-	3.42	3	8837	3359	8.7	312	3540	808
144.2	R	-	1.06	3	4131	1688	6.6	161	1609	1170
144.8	R	-	7.14	5	10818	3741	5.7	130	3701	1188
145.0	L	-	0.19	2	2219	958	11.2	295	966	585
145.6	L	Olo Canyon	32.95	5	25374	9580	7.4	297	11104	1353
147.9	L	Matkatamiba Canyon	86.84	5	41877	14873	7.2	318	20760	1366
148.5	L	-	2.81	3	7256	2443	6.3	28	2736	758
148.6	L	-	0.72	2	4551	1865	11.7	73	1770	729
149.7	R	150 Mile Canyon	81.04	5	43821	16003	8.7	116	14001	1246
152.4	R	-	1.60	3	5090	2003	6.4	95	1931	1128
153.1	L	-	0.70	2	4466	1905	12.1	252	1931	705
153.3	L	Sinyella Canyon	12.28	4	17916	7231	10.6	304	7403	1270
153.5	L	-	0.50	1	3147	1344	8.4	330	1609	695
153.8	L	-	0.90	2	4300	1822	8.7	341	1931	707
153.9	L	-	0.22	2	2899	1301	17.5	360	1448	671
155.6	R	-	5.49	6	9450	3415	5.9	151	2897	1196
157.6	R	-	11.11	5	15353	4961	6.9	147	4828	1248
158.2	R	-	2.40	3	6473	2278	6.1	299	1931	1207
159.2	L	-	5.12	4	10408	3444	7.0	308	4023	1195
159.5	L	-	3.13	4	7420	2957	7.0	344	2897	1195
159.6	L	-	1.28	2	5012	1883	7.4	189	2092	1048
160.8	R	-	3.37	4	9571	3386	9.6	179	3380	1219
161.6	L	-	15.18	5	19719	8026	10.4	325	8690	1231
163.3	R	-	1.29	3	4873	2089	7.9	205	2092	1109
163.8	L	-	28.91	4	28441	11581	11.4	330	13518	1276
164.5	R	Tuckup Canyon	175.68	6	60588	17294	6.0	163	18829	1443
166.4	L	National Canyon	407.12	6	133885	53891	17.7	12	67108	1542
167.0	L	-	2.16	3	6631	2585	7.9	336	2897	835
167.2	L	-	6.08	3	10555	4452	7.7	11	4506	1280

Appendix 3. Selected drainage basin characteristics for 529 geomorphically-significant tributaries of the Colorado River in Grand Canyon—Continued

River mile	Side	Tributary name	Drainage area, in km²	Stream order	Perimeter, in meters	Maximum dimension, in meters	Roughness	Aspect (degrees)	Drainage length in meters	Maximum relief, in meters
168.0	R	Fern Glen Canyon	39.97	6	30011	9826	7.4	130	13518	1408
168.3	R	-	2.58	3	7053	2761	7.6	115	2897	842
169.8	L	-	3.86	4	9575	4007	9.9	330	4023	1305
170.2	L	-	7.49	3	16451	6745	14.8	351	7564	1369
171.1	R	Stairway Canyon	7.97	5	12523	4500	7.1	179	4828	1378
171.5	L	Mohawk Canyon	214.40	6	96176	36474	16.4	17	40554	1645
172.1	L	-	0.53	2	3444	1433	9.4	5	1609	817
172.7	L	-	3.28	3	7729	2943	6.9	9	2736	902
173.0	L	-	1.80	3	5694	2355	7.5	21	2575	897
173.0	R	Big Cove	2.02	4	5707	2313	6.5	208	2253	1280
174.0	R	-	0.46	2	3360	1438	10.4	204	1127	878
174.4	R	Cove Canyon	26.62	5	22017	7117	5.9	181	4828	1437
175.4	R	-	1.82	4	6290	2722	9.4	138	2736	1390
175.9	L	-	22.71	3	27952	10409	12.8	350	12231	1508
176.4	R	Saddle Horse Canyon	3.80	3	9941	3826	10.0	139	4023	1406
177.1	L	-	5.00	3	11180	4262	9.5	317	4667	1451
177.7	L	-	6.68	4	11444	4610	7.9	347	4667	1467
178.6	R	-	379.22	5	106372	32748	9.2	179	35887	1947
179.1	R	-	1.83	2	7221	3071	12.1	160	3540	1049
179.4	L	Prospect Canyon	257.22	5	125599	40258	19.7	11	42646	1747
179.4	R	-	24.74	4	30082	10822	13.2	134	13196	1848
179.8	R	-	1.23	2	5346	2050	8.9	161	2414	823
180.8	L	-	0.97	2	4354	1756	7.9	338	1127	722
180.9	R	-	10.93	5	13650	5196	6.5	164	5150	1294
181.8	R	-	12.77	4	18597	6589	9.6	133	5633	1440
182.5	R	-	0.58	2	3987	1665	11.5	158	1448	757
182.6	L	Hell's Hollow	23.12	4	23562	8943	9.1	353	9173	1466
183.1	L	-	7.60	4	11385	4112	6.2	10	4506	1424
183.7	L	-	1.60	3	7054	3088	13.6	27	3380	888
184.0	R	-	0.70	2	6356	2717	24.8	184	2253	956
184.5	L	-	0.28	2	2624	1182	10.9	326	966	744
184.6	L	-	0.56	3	4067	1835	13.4	351	1609	829
184.6	R	-	1.97	2	6896	2800	9.8	166	2575	1069
185.3	R	-	3.35	3	10085	4285	12.9	163	4345	1152
186.1	L	-	7.32	3	15957	6115	13.3	328	5954	1458
186.2	L	-	1.42	3	5883	2381	9.8	343	2253	940
187.0	L	-	2.09	4	6327	2444	7.4	335	2736	940
187.0	R	-	3.15	3	8989	4017	11.5	191	4184	914
187.4	R	-	7.93	4	15620	6728	13.3	193	7725	1338
187.6	R	-	0.96	2	6305	2761	18.2	112	644	293
188.1	R	Whitmore Wash	312.28	5	101032	30899	10.0	163	27841	1910

Appendix 3. Selected drainage basin characteristics for 529 geomorphically-significant tributaries of the Colorado River in Grand Canyon—Continued

River mile	Side	Tributary name	Drainage area, in km²	Stream order	Perimeter, in meters	Maximum dimension, in meters	Roughness	Aspect (degrees)	Drainage length in meters	Maximum relief, in meters
188.5	R	-	3.76	4	8102	2918	6.3	82	2092	669
189.5	L	-	1.46	3	5938	2097	8.5	231	1931	942
189.7	L	-	10.51	4	16171	5935	9.1	275	7725	1479
190.3	L	-	24.22	4	25075	9568	9.9	313	10300	1544
190.8	L	-	0.45	3	3314	1341	9.8	308	1287	721
190.8	R	-	2.54	4	7201	2739	7.8	138	2414	673
191.1	R	-	4.86	3	11932	4561	11.2	122	4506	1012
191.2	L	-	1.20	3	6021	2485	12.4	281	2414	1000
191.8	L	192 Mile Canyon	16.25	4	20522	7115	9.0	320	10139	1597
192.8	L	193 Mile Creek	57.89	5	41751	12193	8.8	4	15288	1634
193.1	R	Boulder Wash	1.84	3	6137	2310	7.7	198	2736	790
193.7	L	-	0.60	3	3606	1564	9.4	344	1770	671
194.0	R	-	0.97	3	4550	1725	8.1	163	1770	744
194.1	L	-	2.95	4	8983	3735	11.4	354	4023	1244
194.5	L	194 Mile Canyon	8.64	4	15377	6239	11.1	21	7725	1463
194.6	L	-	1.30	3	6513	2868	14.4	43	2897	825
194.9	R	-	0.49	3	3179	1305	8.5	210	1448	719
195.2	L	-	0.54	2	3390	1414	8.9	39	1448	780
195.3	R	-	0.56	3	3362	1448	8.8	240	1448	719
196.0	R	-	3.67	4	9473	3198	8.3	232	3058	861
196.1	R	-	18.23	5	19942	6058	6.6	175	7403	1175
196.5	L	196 Mile Creek	11.74	5	16563	6323	8.9	6	6598	1042
196.6	R	-	0.89	3	5080	1963	11.3	168	2253	732
196.7	R	-	0.64	3	4096	1876	12.0	168	1931	732
197.0	L	-	0.22	2	2006	710	6.3	18	805	658
198.0	R	-	2.26	3	6040	2180	5.8	186	2253	744
198.5	L	-	1.82	3	6771	2533	9.4	316	2414	714
198.5	R	Parashant Wash	934.12	6	166947	44223	7.9	139	63889	1607
198.8	L	-	0.19	2	1872	827	8.2	310	644	536
198.8	R	-	2.09	3	7739	3059	11.4	117	3219	1036
199.5	R	-	0.93	3	4313	1427	6.6	130	1609	829
200.0	R	-	0.30	3	2363	899	7.0	135	805	786
200.3	R	-	0.98	2	5818	2364	14.1	135	2414	853
200.9	R	-	1.11	2	7009	3077	19.4	140	2414	853
201.1	L	-	0.87	3	5042	1860	10.8	300	3380	1109
201.1	R	-	4.76	4	9903	4004	8.3	130	2092	834
202.0	R	-	10.99	4	15251	5915	8.2	117	4023	1097
202.1	L	-	0.55	2	3671	1426	9.5	285	6437	1490
202.4	R	-	0.94	3	4683	1906	9.5	97	1770	779
202.5	R	-	1.41	4	7108	2676	13.5	71	2414	963
203.0	L	-	0.94	3	4684	2006	10.0	234	3058	1073

Appendix 3. Selected drainage basin characteristics for 529 geomorphically-significant tributaries of the Colorado River in Grand Canyon—Continued

River mile	Side	Tributary name	Drainage area, in km²	Stream order	Perimeter, in meters	Maximum dimension, in meters	Roughness	Aspect (degrees)	Drainage length in meters	Maximum relief, in meters
203.0	R	-	0.54	3	3244	1166	7.0	71	2092	779
204.0	R	-	4.26	4	10784	4439	11.2	122	4506	1351
204.2	L	-	0.75	3	4597	1988	12.2	225	1931	732
204.3	L	-	0.49	3	3103	1168	7.3	252	1448	610
204.3	R	Spring Canyon	50.38	5	33113	10325	6.8	99	8207	1557
205.5	L	205 Mile Creek	27.54	5	24920	7177	6.5	230	8047	1548
206.0	R	-	2.04	4	6487	2326	7.4	106	2092	856
206.5	R	Indian Canyon	9.84	4	16377	6009	10.0	81	6759	1061
207.4	L	-	0.40	2	3421	1519	12.9	192	1609	756
207.6	L	-	1.40	3	6110	2417	10.6	207	2575	1039
207.8	L	-	3.09	4	8992	3881	11.3	230	4345	1548
208.6	L	-	8.35	5	12571	4593	6.9	236	5633	1565
208.6	R	209 Mile Canyon	95.46	5	62470	18862	12.3	85	15610	1567
208.8	L	Granite Park Canyon	126.22	5	62430	17251	8.5	272	24783	1760
209.8	R	-	1.71	3	6445	2549	9.6	89	2736	867
210.8	R	-	0.99	3	4703	1895	9.0	92	1931	867
211.2	L	-	1.71	3	5805	2232	7.6	294	1931	720
211.5	L	-	0.47	2	3706	1547	12.3	302	1770	720
211.5	R	Fall Canyon	11.48	5	18009	6642	10.4	87	7403	1483
212.2	L	-	0.48	3	2984	1145	7.1	288	1287	671
212.2	R	-	0.08	1	1924	923	21.8	112	966	683
212.7	R	-	3.45	4	8773	3437	8.7	108	3701	1158
213.8	L	-	2.00	4	6255	2535	7.9	220	2897	720
214.0	R	214 Mile Creek	8.22	5	13437	5256	8.6	93	6115	1462
214.2	R	-	2.74	4	7615	2848	7.9	40	3058	814
214.5	L	-	0.55	3	3664	1629	10.8	206	1770	652
215.0	L	215 Mile Creek	5.89	5	10952	3767	7.0	212	4506	728
215.7	L	Three Springs Canyon	24.17	5	25996	7991	8.6	272	7242	1762
215.7	R	-	0.60	3	4012	1653	11.1	92	1609	683
216.2	R	-	2.45	4	7746	2770	8.8	97	2897	814
216.5	R	-	0.72	3	4079	1724	9.8	84	1770	792
216.8	L	-	9.76	4	17633	6877	12.4	281	7403	1762
217.4	L	217 Mile Canyon	23.98	5	24967	8603	9.0	303	10460	1773
217.7	R	-	1.46	3	5544	2170	8.3	108	1931	842
218.0	L	-	0.81	4	4001	1583	7.8	317	1448	712
218.6	L	-	0.96	3	4124	1572	6.8	307	1448	712
219.4	R	Trail Canyon	50.08	6	33711	10798	7.3	128	12713	1496
219.9	L	-	0.59	2	3357	1412	8.0	259	1448	667
220.0	R	220 Mile Canyon	26.94	6	25275	9227	8.7	82	8851	1469
220.4	L	Granite Spring Canyon	37.14	5	29581	9220	7.3	302	13035	1673

Appendix 3. Selected drainage basin characteristics for 529 geomorphically-significant tributaries of the Colorado River in Grand Canyon—Continued

River mile	Side	Tributary name	Drainage area, in km^2	Stream order	Perimeter, in meters	Maximum dimension, in meters	Roughness	Aspect (degrees)	Drainage length in meters	Maximum relief, in meters
221.3	R	-	0.94	3	4517	1839	8.9	87	3540	758
222.0	L	222 Mile Canyon	5.06	4	10414	3995	8.2	301	4989	1122
222.3	L	-	0.26	2	2578	1105	11.1	300	1127	512
222.5	R	-	2.99	4	7417	2551	6.3	115	3701	857
222.6	L	"222.6 Mile Canyon"	0.58	3	3678	1580	10.1	302	1609	664
223.1	L	-	1.04	3	5010	2173	10.4	286	2253	925
223.2	R	-	0.53	2	3637	1618	11.1	124	1609	857
223.5	L	224 Mile Canyon	12.78	4	16156	5444	6.9	298	7242	1255
223.9	R	-	0.68	2	3877	1683	9.6	151	1609	805
224.5	L	"224.5 Mile Canyon"	0.45	2	2742	1006	6.2	331	1127	668
224.6	R	-	2.73	3	7680	2872	8.1	162	1609	927
225.3	R	-	23.32	5	28165	9463	11.4	136	12392	1481
225.8	L	Diamond Creek	716.74	7	189335	55251	14.6	347	34761	1851

Appendix 4. List of photographic views of Glen, Marble and Grand Canyons taken by Franklin A. Nims and Robert Brewster Stanton between July 1889 and March 1890

[All photographs were obtained from the Still Picture Branch of the National Archives in Washington, D.C., except numbers 286, 308, 341, 386, 496, and 619, which were obtained from the New York Public Library. Number, refers to the large number on album prints that were assigned by Stanton. These numbers are the same among the four archives that contain albums. Smaller numbers that appear on some prints and negatives are inconsistent. Numbers with letters refer to negatives exposed using the detective camera; the numbers were assigned by the National Archives. Date of original, was obtained from Stantons diary and is exactly known for all but a few of Nims' negatives, which were not specifically recorded in a diary. Date of repeat, is exactly known. When more than one replicate was made, the first two columns and the last column appear blank. Stake number, is a number assigned for permanent storage of replicate negatives in the repeat photography collection at the Desert Laboratory, University of Arizona, Tucson. Letters following a number indicate a swing of two or more views; not all swings were assigned stake numbers with letters, however. River mile, was estimated to the nearest tenth of a mile using the 1990 revision of a popular river guide (Stevens, 1990). Side, direction, (R) and (L), refers to the side of the channel when facing downstream of the camera station and the relative direction of the view. (US), upstream; (DS), downstream; (AC), across the Colorado River; (UC), up a side canyon; (DC), down a side canyon. Location, is the name of a geographical feature at or near the camera station. Wherever possible, names were obtained from 7.5-minute quadrangle maps, but some names are generally recognized and used in a popular river guide (Stevens, 1990). Subject(s), designated by footnotes, refer to the type of information that was interpreted from the view. (---), view contained little of interest in terms of geomorphology or biotic habitat]

Stanton's number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
235	12/23/1889	10/29/1992	2638a	-14.7	L, US	Glen Canyon Dam	(2,13,15,17)
236	12/23/1889	10/29/1992	2638b	-14.7	L, DS	Glen Canyon Dam	(15)
237	12/23/1889	6/11/1975	757	-13.6	L, US	Ropes Trail	(17,15, 7,16,12, 10)
		12/19/1989	757	-13.6	L, US	Ropes Trail	
		10/29/1992	757	-13.6	L, US	Ropes Trail	
238	12/23/1889	6/11/1975	2600	-13.6	L, DS	Ropes Trail	(10,15,7)
		2/10/1992	2600	-13.6	L, DS	Ropes Trail	
239	12/23/1889	6/10/1975	754	-12.3	L, US	Obscure location	(17,15,16,12)
		12/19/1989	754	-12.3	L, US	Obscure location	
240	12/23/1889	6/10/1975	753	-12.3	L, DS	Obscure location	(17,15,16,13,2)
		12/19/1989	753	-12.3	L, DS	Obscure location	
241	12/23/1889	2/10/1992	2602a	-10.2	R, US	Obscure location	(7,17,15)
242	12/23/1889	2/10/1992	2602b	-10.2	R, DS	Obscure location	(7,17,15)
243	12/24/1889	6/10/1975	751	-7.0	R, US	Obscure location	(17,15)
		12/19/1989	751	-7.0	R, US	Obscure location	
244	12/24/1889	6/10/1975	752	-7.0	R, DS	Obscure location	(17,15)
		12/19/1989	752	-7.0	R, DS	Obscure location	
245	12/24/1889	6/11/1975	750	-4.0	L, US	4-Mile Bar	(7,15,13,17)
		9/14/1976	750	-4.0	L, US	4-Mile Bar	
		12/20/1989	750	-4.0	L, US	4-Mile Bar	
		10/30/1992	750	-4.0	L, US	4-Mile Bar	
246	12/26/1889	2/11/1992	2603a	-3.0	L, US	3-Mile Bar	(7,17,10)
247	12/26/1889	2/11/1992	2603b	-3.0	L, DS	3-Mile Bar	(7,17,10)
248	12/26/1889	2/11/1992	2605	-2.6	L, UC	Fall Creek	(7,10)
249	12/26/1889	6/11/1975	755b	-2.0	L, US	Obscure location	(7,17,10)
		12/20/1989	755b	-2.0	L, US	Obscure location	

Appendix 4. List of photographic views of Glen and Grand Canyon taken by Franklin A. Nims and Robert Brewster Stanton between July 1889 and March 1890—Continued

Stanton's number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
		10/28/1992	755b	-2.0	L, US	Obscure location	
250	12/26/1889	9/14/1976	755a	-2.0	L, DS	Obscure location	(17,7,5,2,10)
		12/20/1989	755a	-2.0	L, DS	Obscure location	
250	12/26/1889	10/28/1992	755a	-2.0	L, DS	Obscure location	
268	12/25/1889	1/17/1990	1399	-0.2	R, DS	Fort at Lees Ferry	(13)
259	12/28/1889	12/30/1991	1552b	0.0	L, US	Paria Riffle	(15,7,3,10)
260	12/28/1889	1/29/1991	1552a	0.0	L, DS	Paria Riffle	(5,14,17,15)
261	12/28/1889	12/20/1989	1396	0.0	L, AC	Paria Riffle	(5,15,12)
269	12/28/1889	2/11/1992	2562	1.2	L, US	Lees Backbone	(5,7,14,10)
270	12/28/1889	2/11/1992	2563	1.2	L, DS	Lees Backbone	(17,13,15)
271	12/28/1889	1/29/1991	2300	2.9	R, US	Cathedral Wash	(17,7,2,12,15)
272	12/28/1889	1/29/1991	2301	2.9	R, DS	Cathedral Wash	(17,5,7)
273	12/28/1889	1/29/1991	1553	5.0	L, US	Below Navajo Bridge	(17,7,15,12,16,2)
320	7/09/1889	1/29/1991	1554	5.0	L, US	Below Navajo Bridge	(16,17)
274	7/09/1889	1/17/1990	1400	5.1	L, DS	5-Mile Wash	(17,7,15)
275	12/28/1889	1/19/1990	1402a	6.4	L, US	6-Mile Wash	(17,7,15)
276	12/28/1889	12/31/1991	1402b	6.4	L, DS	6-Mile Wash	(17,16)
278	7/09/1889	1/20/1990	1403	8.0	L, US	Badger Creek Rapid	(5,6,14,12)
277	12/29/1889	1/20/1990	1406a	8.1	R, US	Badger Creek Rapid	(17,14,5,6,15)
		1/30/1991	1406a	8.1	R, US	Badger Creek Rapid	
279	12/29/1889	1/30/1991	1406b	8.1	R, DS	Badger Creek Rapid	(7,15,17)
280	12/30/1889	1/30/1991	2302a	10.3	L, US	10-Mile Rock	(7,17)
281	12/30/1889	1/30/1991	2302b	10.3	L, DS	10-Mile Rock	(17,7,16)
282	12/30/1889	1/30/1991	2303	11.1	L, US	Soap Creek Rapid	(7,15,17,16)
283	12/30/1889	1/18/1990	1407	11.1	L, DS	Soap Creek Rapid	(15,14,5,17)
284	7/09/1889	1/31/1991	1556	11.4	R, US	Below Soap Creek Rapid	(17,14,8,7,9)
285	12/31/1889	12/31/1991	2246	11.4	L, DS	Below Soap Creek Rapid	(15,7,17)
288	12/31/1889	1/19/1990	1412	11.8	L, DS	Salt Water Wash	(5,17,7,4)
286	12/31/1889	2/22/1995	3088	12.1	L, US	Below Salt Water Wash	(5,15,17)
287	7/10/1889	1/31/1991	1557	12.7	R, DS	13-Mile Rapid	(7,6,14,16,17)
289	12/31/1889	1/01/1992	2247	14.3	L, US	Sheer Wall Rapid	(14,5,6,2)
291	7/11/1889	1/31/1991	1558	14.5	L, US	Below Sheer Wall Rapid	(16)
292	7/11/1889	2/12/1992	2564	14.5	L, DS	Below Sheer Wall Rapid	(5)
290	1/01/1890	1/19/1990	1413	15.1	L, DS	Obscure location	(5,6,17)
294	7/11/1889	1/01/1992	2523	16.8	R, DS	Above House Rock Rapid	(14,5,6,15,17)
293	7/11/1889	1/01/1992	2071	17.0	R, US	Below House Rock Rapid	(14,17,13,16,6)
295	1/06/1890	2/02/1991	2306a	18.4	R, US	Boulder Narrows	(17,15)
296	1/06/1890	2/02/1991	2306b	18.4	R, DS	Boulder Narrows	(5,8,17,15)
297	7/12/1889	1/01/1992	2072	18.7	R, US	Below Boulder Narrows	(12)

Appendix 4. List of photographic views of Glen and Grand Canyon taken by Franklin A. Nims and Robert Brewster Stanton between July 1889 and March 1890—Continued

Stanton's number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
298	7/12/1889	1/01/1992	2248b	20.6	R, US	Below North Canyon Rapid	(14,17)
299	7/12/1889	1/01/1992	2248a	20.6	R, DS	Below North Canyon Rapid	(17)
300	1/06/1890	2/02/1991	1715	21.3	L, DS	22-Mile Wash	(5,17,8,6)
50	7/12/1889	1/02/1992	2074	21.4	L, DS	22-Mile Wash	(17,6,5,16,14)
303	7/12/1889	1/02/1992	2073	21.5	L, US	22-Mile Wash	(17,5,6,16,14)
301	1/07/1890	11/16/1990	1702a	23.3	L, US	Indian Dick Rapid	(5,6,7,12,17)
309	1/07/1890	2/02/1991	1716	23.3	L, DS	Indian Dick Rapid	(5,7,12,16,17)
302	1/07/1890	1/02/1992	1702b	23.3	L, DS	Indian Dick Rapid	(5,7,12,16,17)
304	7/13/1889	2/02/1991	2307	23.5	L, DS	23.5-Mile Rapid	(17,5,8,16,12)
305	7/14/1889	1/20/1990	1559	24.5	L, US	24.5-Mile Canyon	(7,5,6,14,12)
306	7/14/1889	1/20/1990	1414	24.5	L, UC	24.5-Mile Canyon	(6,7)
		2/02/1991	1414	24.5	L, UC	24.5-Mile Canyon	
307	7/14/1889	2/02/1991	1560	24.5	L, DC	24.5-Mile Canyon	(6,7)
308	7/14/1889	2/23/1995	3090	24.5	L, US	24.5-Mile Canyon	(5,14,15,17)
310	7/15/1889	4/24/1964	2075	24.9	L, US	25-Mile Rapid	(5,6,17)
		1/02/1992	2075	24.9	L, US	25-Mile Rapid	
311	1/13/1890	1/20/1990	1417	25.4	R, US	Cave Springs Rapid	(17,7,14,6,16)
312	1/13/1890	1/20/1990	1415	25.4	R, DS	Cave Springs Rapid	(17,7,6,5)
313	7/16/1889	2/23/1993	2643	25.7	R, US	Below Cave Springs Rapid	(5,17)
314	7/16/1889	2/23/1993	2642	25.7	R, DS	Below Cave Springs Rapid	(7,8,17,3)
316	1/13/1890	2/02/1991	1561a	26.7	L, US	Tiger Wash	(7,6,5,12,14)
317	1/13/1890	2/02/1991	1561b	26.7	L, DS	Tiger Wash	(7,14,16,17,12)
318	7/16/1889	2/02/1991	1562	26.7	L, DS	Tiger Wash	(5,12,6)
34D	1/13/1890	2/13/1992	2565	26.7	L, AC	Tiger Wash	(6,14,17,5)
319	7/16/1889	2/23/1993	2644	29.1	L, US	Shinumo Wash	(7,17,5,15)
321	7/16/1889	2/23/1993	2729	30.0	L, US	Fence Fault Camp	(7,6,17)
322	7/16/1889	1/02/1992	2250	30.0	L, DS	Fence Fault Camp	(5,17,7,6)
323	1/14/1890	1/02/1992	2525b	30.2	R, US	Above 30-Mile Camp	(7,5,17)
324	1/14/1890	1/02/1992	2525a	30.2	R, DS	Above 30-Mile Camp	(5,17,7,6)
325	7/17/1889	1/02/1992	2526	31.5	R, US	South Canyon	(2,17,5,6)
326	7/17/1889	2/13/1992	2566	31.5	R, UC	South Canyon	(6)
327	7/17/1889	2/03/1991	2308	31.5	R, DS	South Canyon	(17,15,13,5,6)
328	7/17/1889	1/03/1992	2527	31.9	R, DS	Vasey's Paradise	(4,5,7,16,14)
329	1/15/1890	1/20/1990	1418	31.9	R, US	Vasey's Paradise	(4)
330	1/15/1890	1/03/1992	2076	32.0	R, DS	Below Vasey's Paradise	(4,11)
331	1/15/1890	1/03/1992	1419b	33.0	L, US	Redwall Cavern	(17)
332	1/15/1890	1/20/1990	1419a	33.0	L, DS	Redwall Cavern	(17,4)
		1/03/1992	1419a	33.0	L, DS	Redwall Cavern	
288.5	1/15/1890	2/03/1991	2309	35.0	L, US	Below Nautiloid Canyon	(17,5,6)

Appendix 4. List of photographic views of Glen and Grand Canyon taken by Franklin A. Nims and Robert Brewster Stanton between July 1889 and March 1890—Continued

Stanton's number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
335	1/16/1890	2/03/1991	1564	36.0	L, US	36-Mile Rapid	(7,17)
336	1/16/1890	2/03/1991	1563	36.0	L, DS	36-Mile Rapid	(5,7,17)
337	1/16/1890	2/03/1991	1734a	38.0	L, US	Obscure location	(17,5,6)
338	1/16/1890	2/03/1991	1734b	38.0	L, DS	Obscure location	(17,9)
339	1/16/1890	2/03/1991	1565a	39.0	R, US	Marble Canyon dam site	(17,2)
340	1/16/1890	2/23/1993	1565b	39.0	R, DS	Marble Canyon dam site	(17,5,15)
341	1/16/1890	9/10/1994	2865	41.3	R, US	Berts Canyon	(12,15,17)
343	1/16/1890	2/23/1993	1735b	43.1	L, US	Anasazi Bridge	(17,15,8)
344	1/16/1890	2/03/1991	1735a	43.1	L, DS	Anasazi Bridge	(17,5,6,15)
345	1/17/1890	1/21/1990	1420a	43.8	L, US	President Harding Rapid	(17,5,6,7)
		2/03/1991	1420a	43.8	L, US	President Harding Rapid	
346	1/17/1890	2/03/1991	1420b	43.8	L, DS	President Harding Rapid	(17,12)
4D	1/17/1890	2/14/1992	2567	43.8	L, US	President Harding Rapid	(5,14)
347	1/17/1890	2/23/1993	2732	44.6	R, DS	Below Eminence Camp	(5,17,7,15)
348	1/17/1890	2/04/1991	1736a	46.8	R, US	Above Saddle Canyon	(7,17,4,15,10)
349	1/17/1890	2/04/1991	1736b	46.8	R, DS	Above Saddle Canyon	(17,7,4,10)
350	1/17/1890	2/04/1991	2311	48.8	L, US	Obscure location	(17,7,12)
351	1/17/1890	2/04/1991	2310	48.8	L, DS	Obscure location	(7,4,17,12)
352	1/17/1890	2/04/1991	2312b	51.5	L, US	Above Little Nankoweap	(7,15,5,6,17)
		2/24/1993	2312b	51.5	L, US	Above Little Nankoweap	
353	1/17/1890	2/04/1991	2312a	51.5	L, DS	Above Little Nankoweap	(7,15,4,17)
354	1/18/1890	1/04/1992	1422b	51.8	R, UC	Little Nankoweap Creek	(7,6)
		2/24/1993	1422b	51.8	R, UC	Little Nankoweap Creek	
355	1/18/1890	11/01/1973	1422a	51.8	R, US	Little Nankoweap Creek	(17,4,7,12)
		1/22/1990	1422a	51.8	R, US	Little Nankoweap Creek	
356	1/18/1890	1/22/1990	1423	51.8	R, DS	Little Nankoweap Creek	(7,6)
357	1/18/1890	2/05/1991	1739a	52.5	R, US	Nankoweap Creek	(7,3)
358	1/18/1890	2/05/1991	1739b	52.5	R, DS	Nankoweap Creek	(7)
359	1/18/1890	2/05/1991	1741	52.8	R, DS	Nankoweap Creek	(7,1)
360	1/18/1890	1/22/1990	1424a	52.8	R, DS	Nankoweap Creek	(7)
		1/23/1990	1424a	52.8	R, DS	Nankoweap Creek	
		2/05/1991	1424a	52.8	R, DS	Nankoweap Creek	
361	1/18/1890	1/23/1990	1424b	52.8	R, DS	Nankoweap Creek	(17,4,12)
		2/05/1991	1424b	52.8	R, DS	Nankoweap Creek	
362	1/18/1890	2/05/1991	2313b	55.8	L, US	Above Kwagunt Creek	(17,7,6,12)
363	1/18/1890	2/05/1991	2313a	55.8	L, DS	Above Kwagunt Creek	(17,7)
364	1/18/1890	1/05/1992	2077	56.1	R, UC	Kwagunt Creek	(7)
365	1/20/1890	2/05/1991	1566	58.0	R, US	Awatubi Canyon	(17,7,12)
366	1/20/1890	2/05/1991	1567	58.1	R, UC	Awatubi Canyon	(6,7,9)

Appendix 4. List of photographic views of Glen and Grand Canyon taken by Franklin A. Nims and Robert Brewster Stanton between July 1889 and March 1890—Continued

Stanton's number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
367	1/20/1890	2/05/1991	1568	58.1	R, DS	Awatubi Canyon	(7,17,5,9,6)
368	1/20/1890	1/05/1992	2251a	59.0	L, DS	Above 60-Mile Canyon	(4,17,7,6,12)
369	1/20/1890	1/05/1992	2251b	59.0	L, US	Above 60-Mile Canyon	(7,4,17,5,6)
370	1/20/1890	2/05/1991	1569a	60.7	L, US	Above Little Colorado River	(7,5,17,12)
371	1/20/1890	2/05/1991	1569b	60.7	L, DS	Above Little Colorado River	(4,17,7,2,13,12)
372	1/20/1890	1/23/1990	1426	61.4	L, US	Little Colorado River	(4,17,12,7)
		2/24/1993	1426	61.4	L, US	Little Colorado River	
373	1/20/1890	1/05/1992	1427b	61.4	R, AC	Little Colorado River	(17,4,7,16)
374	1/20/1890	1/23/1990	1428	61.4	L, UC	Little Colorado River	(7,15)
		2/24/1993	1428	61.4	L, UC	Little Colorado River	
375	1/20/1890	1/23/1990	1427a	61.4	R, DS	Little Colorado River	(7,4,6,17)
376	1/20/1890	1/23/1990	2314b	62.6	R, US	Crash Canyon	(14,5,17,6,12)
		11/19/1990	2314b	62.6	R, US	Crash Canyon	
		2/05/1991	2314b	62.6	R, US	Crash Canyon	
377	1/21/1890	2/05/1991	2314a	62.6	R, DS	Crash Canyon	(5,17,7,6)
378	1/21/1890	1/22/1990	1430	63.7	R, US	Hopi Salt Mines	(12,2,13,17,6)
379	1/21/1890	2/05/1991	2315	63.7	R, DS	Hopi Salt Mines	(17,6,12,14,16)
380	1/21/1890	2/07/1991	1431c	65.5	R, US	Lava Canyon	(7,17,6,12,14)
381	1/21/1890	1/23/1990	1431a	65.5	R, UC	Lava Canyon	(7,12)
		2/07/1991	1431a	65.5	R, UC	Lava Canyon	
382	1/21/1890	2/07/1991	1431b	65.5	R, DS	Lava Canyon	(7,4,17,16,12)
383	1/22/1890	2/06/1991	1434b	65.5	L, US	Palisades Creek	(7,4 ,17,6,12)
384	1/22/1890	1/24/1990	1434a	65.5	L, AC	Palisades Creek	(7,4,17,14,5)
		2/06/1991	1434a	65.5	L, AC	Palisades Creek	
385	1/22/1890	1/24/1990	1434c	65.5	L, DS	Palisades Creek	(17,5,12,6,14)
		2/06/1991	1434c	65.5	L, DS	Palisades Creek	
386	1/21/1890	9/12/1994	2930	65.5	L, US	Palisades Creek	(5,6,14,15,17)
387	1/22/1890	1/24/1990	1436	66.3	L, US	Below Palisades Creek	(17,4,15)
388	1/22/1890	1/24/1990	1437	66.3	L, DS	Below Palisades Creek	(15)
389	1/22/1890	1/25/1990	1438a	67.2	L, US	Comanche Creek	(6,7)
390	1/22/1890	2/08/1991	1438b	67.2	L, DS	Comanche Creek	(5,7,12,17)
392	1/22/1890	2/08/1991	2316b	68.5	L, AC	Tanner Rapid	(7,9,4,12,14)
393	1/22/1890	2/08/1991	2316a	68.5	L, US	Tanner Rapid	(7,4,17)
391	1/23/1890	2/08/1991	1742	69.0	L, DS	Below Tanner Rapid	(4,9,8,17)
394	1/23/1890	2/08/1991	1572	69.5	R, US	Basalt Creek	(17,4,7,12)
395	1/23/1890	2/08/1991	1571	69.8	R, DS	Basalt Creek	(17,7,12)
396	1/23/1890	1/25/1990	1440	71.3	L, US	Cardenas Creek	(17,4,12,6)
		2/26/1993	1440	71.3	L, US	Cardenas Creek	
397	1/23/1890	2/10/1991	1745	71.5	L, AC	Across from Unkar Rapid	(17,5,7,12)

Appendix 4. List of photographic views of Glen and Grand Canyon taken by Franklin A. Nims and Robert Brewster Stanton between July 1889 and March 1890—Continued

Stanton's number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
398	1/23/1890	2/10/1991	1746	71.5	L, DS	Across from Unkar Rapid	(5,6)
399	1/23/1890	1/25/1990	1439	71.5	L, UC	Cardenas Hilltop Ruin	(7,1)
400	1/24/1890	1/26/1990	1442	72.7	R, US	Unkar Creek	(7,5,6,17)
		2/26/1993	1442	72.7	R, US	Unkar Creek	
401	1/24/1890	1/26/1990	1441	72.7	R, DC	Unkar Creek	(14,7,17)
402	1/24/1890	2/10/1991	1573	73.2	R, AC	Unkar Creek	(7)
403	1/24/1890	2/10/1991	1575	73.7	R, US	Below Unkar Creek	(17,4,15,12,9)
404	1/24/1890	2/10/1991	1574	73.7	L, DS	Below Unkar Creek	(17,15,4)
405	1/24/1890	2/10/1991	1748	74.2	R, US	Above Escalante Creek	(7,15,17)
406	1/24/1890	2/10/1991	1747	74.2	R, DS	Above Escalante Creek	(17,15,13,2,16)
407	1/25/1890	1/27/1990	1445	75.5	L, US	75-Mile Canyon	(6,5,8,17)
		2/10/1991	1445	75.5	L, US	75-Mile Canyon	
408	1/25/1890	1/06/1992	2252	75.6	L, DS	75-Mile Canyon	(7,17,5,14,12)
		2/26/1993	2252	75.6	L, DS	75-Mile Canyon	
409	1/25/1890	2/11/1991	1749a	75.6	L, US	Below Nevills Rapid	(17,4,15)
410	1/25/1890	2/11/1991	1749b	75.6	L, DS	Below Nevills Rapid	(17,5,6,4,12)
411	1/27/1890	1/27/1990	1444	76.7	L, US	Hance Rapid	(15,5,14,7,12)
412	1/27/1890	1/27/1990	1446	76.7	L, US	Hance Rapid	(14,5,8)
413	1/27/1890	1/27/1990	1448	76.7	L, DS	Hance Rapid	(5,2,8,9)
414	1/27/1890	2/11/1991	1576	77.1	R, DS	Lower Hance Rapid	(14,4,17)
415	1/27/1890	2/11/1991	1751a	77.5	L, US	Start of Vishnu Schist	(17,5,2)
416	1/27/1890	2/11/1991	1751b	77.5	L, DS	Start of Vishnu Schist	(4)
417	1/28/1890	2/11/1991	2317a	78.7	L, US	Sockdolager Rapid	(6,14)
418	1/28/1890	2/11/1991	2317b	78.7	L, DS	Sockdolager Rapid	(14,7,2,16)
419	1/28/1890	1/06/1992	2529a	78.8	L, US	Below Sockdolager Rapid	(14)
		2/26/1993	2529a	78.8	L, US	Below Sockdolager Rapid	
420	1/28/1890	1/06/1992	2529b	78.8	L, DS	Below Sockdolager Rapid	
421	1/29/1890	1/06/1992	2253a	79.9	R, US	Obscure location	(5,14)
422	1/29/1890	1/06/1992	2253b	79.9	R, DS	Obscure location	(14,5)
423	1/29/1890	1/06/1992	2080b	80.2	R, US	Above Cottonwood Creek	(7,14,17)
424	1/29/1890	1/06/1992	2080a	80.2	R, DS	Above Cottonwood Creek	(17,5,11)
425	1/29/1890	2/12/1991	2318a	81.3	L, US	Grapevine Camp	(17)
426	1/29/1890	2/26/1993	2318b	81.3	L, DS	Grapevine Camp	(17,2,13,16)
427	1/29/1890	1/07/1992	2554a	81.5	R, US	Grapevine Rapid	(2,13,14)
428	1/29/1890	1/07/1992	2554b	81.5	R, DS	Grapevine Rapid	(14,5)
429	2/01/1890	1/07/1992	2531	81.7	R, US	Bottom of Grapevine Rapid	(14,2,13,11)
430	2/01/1890	1/07/1992	2530	81.7	R, DS	Bottom of Grapevine Rapid	(14,7)
431	2/04/1890	1/28/1990	1453	82.0	R, US	Below Grapevine Rapid	(13)
432	2/04/1890	1/07/1992	1454c	82.9	L, US	Boulder Creek	(17,2,13,5,6)

Appendix 4. List of photographic views of Glen and Grand Canyon taken by Franklin A. Nims and Robert Brewster Stanton between July 1889 and March 1890—Continued

Stanton's number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
433	2/04/1890	1/07/1992	1454b	82.9	L, DS	Boulder Creek	(8,7,5)
434	2/04/1890	1/28/1990	1454a	82.9	L, US	Boulder Creek	(17,2,13,5,6)
435	2/04/1890	2/12/1991	2319	84.0	R, US	Lone Tree Canyon	(7)
436	2/05/1890	2/26/1993	2645	84.0	R, DS	Lone Tree Canyon	(14,17)
437	2/05/1890	2/12/1991	1572b	84.1	L, AC	Clear Creek	(14)
438	2/05/1890	2/12/1991	1572a	84.1	L, DS	Clear Creek	(17,5,4,2,7,14)
439	2/05/1890	11/23/1990	1708	85.5	L, US	Below 85-Mile Rapid	(7,14)
440	2/05/1890	1/08/1992	2555	85.5	L, DS	Below 85-Mile Rapid	(7,15,16,4)
441	2/05/1890	1/08/1992	2532b	85.5	L, US	Above Cremation Creek	(2,13,17,14)
442	2/05/1890	1/08/1992	2532a	85.5	L, DS	Above Cremation Creek	(17,7)
443	2/05/1890	11/23/1990	1709	87.4	R, US	Black Bridge	(17,5)
445	2/05/1890	2/13/1991	2320	87.8	R, US	Bright Angel Creek	(5,7,17)
446	2/05/1890	1/08/1992	2533	87.9	L, AC	Silver Bridge	(8,5,17)
447	2/05/1890	11/23/1990	1710	87.9	L, US	Silver Bridge	(17,8,7,6,10)
448	2/05/1890	1/08/1992	2556	87.9	R, DS	Silver Bridge	(4,7,14,6,10)
449	2/06/1890	2/16/1992	2536	87.9	L, DS	Silver Bridge	(17,7,12)
450	2/06/1890	1/28/1990	1455	88.5	R, US	Above Pipe Creek	(4,17)
		2/27/1993	1455	88.5	R, US	Above Pipe Creek	
451	2/06/1890	2/13/1991	1577	88.8	R, AC	Pipe Creek	(17,15)
		2/17/1992	2537b	88.8	R, AC	Pipe Creek	
452	2/06/1890	2/13/1991	2537a	88.8	R, DS	Pipe Creek	(11,17,4)
453	2/06/1890	11/23/1990	1711	89.2	L, US	Pipe Creek	(17,4,14)
454	2/06/1890	2/17/1992	2082b	89.9	L, US	Obscure location	(16,14)
455	2/06/1890	2/17/1992	2082a	89.9	L, DS	Obscure location	(2,7)
456	2/06/1890	2/13/1991	1753a	90.2	L, US	Horn Creek Rapid	(5,14)
457	2/06/1890	2/13/1991	1753b	90.2	L, DS	Horn Creek Rapid	(14,7)
458	2/07/1890	2/17/1992	2571a	91.5	L, US	Trinity Creek	(17,11,16,8,13)
459	2/07/1890	2/17/1992	2571b	91.5	L, DS	Trinity Creek	(5,14,17,11)
460	2/07/1890	1/29/1990	1456	92.5	L, US	Above Salt Creek	(17,7,12)
461	2/07/1890	1/29/1990	1457	92.5	L, DS	Above Salt Creek	(17,5)
462	2/07/1890	1/30/1990	1461	92.8	L, US	Salt Creek	(4,14,17,6)
463	2/07/1890	1/30/1990	1463	92.8	L, DS	Salt Creek	(5,17,16)
464	2/07/1890	1/29/1990	1458	93.3	L, US	Granite Rapid	(14,17,7,6)
465	2/07/1890	1/30/1990	1460	93.3	L, AC	Granite Rapid	(14,6,17,9,7)
466	2/07/1890	1/29/1990	1459	93.3	L, DS	Granite Rapid	(4,17,2,13,14,6)
467	2/07/1890	2/18/1992	1465b	94.3	L, US	94-Mile Creek	(2,13,5,6,17)
468	2/07/1890	1/31/1990	1465a	94.3	L, AC	94-Mile Creek	(14,5,17,6)
		2/18/1992	1465a	94.3	L, AC	94-Mile Creek	
469	2/07/1890	2/18/1992	1465c	94.3	L, US	94-Mile Creek	(5,6,17,14,7)

Appendix 4. List of photographic views of Glen and Grand Canyon taken by Franklin A. Nims and Robert Brewster Stanton between July 1889 and March 1890—Continued

Stanton's number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
470	2/08/1890	2/18/1992	2539	94.9	L, UC	Hermit Creek	(15,5,7)
		2/27/1993	2539	94.9	L, UC	Hermit Creek	
471	2/08/1890	2/18/1992	2083	94.9	L, US	Hermit Rapid	(7,17)
472	2/08/1890	1/31/1990	1464	95.0	L, DS	Hermit Rapid	(14,5,17)
473	2/08/1890	2/18/1992	2085	96.1	L, US	Obscure location	(2,13,17,7,6)
474	2/08/1890	2/18/1992	2084	96.1	L, DS	Obscure location	(7,17)
475	2/08/1890	2/18/1992	2572	96.8	L, US	Boucher Rapid	(14,5,6,17)
476	2/08/1890	2/18/1992	2573	96.8	L, DS	Boucher Rapid	(17,14,6,5)
484	2/10/1890	2/01/1990	1470	98.0	R, AC	Crystal Rapid	(14,5,17)
487	2/11/1890	9/20/1979	2528	98.0	R, AC	Tower of Ra	(7)
477	2/08/1890	2/01/1990	1468	98.2	R, US	Crystal Rapid	(7,17,3,15)
478	2/08/1890	2/01/1990	1471	98.2	R, DS	Crystal Rapid	(14,3,17,7,6)
479	2/08/1890	2/01/1990	1472	98.2	R, UC	Crystal Creek	(6,7)
		2/27/1993	1472	98.2	R, UC	Crystal Creek	
480	2/09/1890	2/01/1990	1473	98.2	R, UC	Crystal Creek	(7,15)
481	2/09/1890	2/01/1990	1467	98.2	R, AC	Crystal Rapid	(14,6,5)
482	2/09/1890	2/14/1991	1578	98.3	R, DS	Crystal Rapid	(7,13,1)
482.5	2/09/1890	2/14/1991	1578	98.3	R, DS	Crystal Rapid	(7,13,1)
483	2/09/1890	2/01/1990	1469	98.4	R, DS	Crystal Rapid	(4,7,17,6,14)
		2/18/1992	1469	98.4	R, DS	Crystal Rapid	
488	2/12/1890	2/02/1990	1474a	99.3	L, US	Tuna Creek Rapid	(14,6,17,12,7)
489	2/12/1890	2/15/1991	1474b	99.3	L, DS	Tuna Creek Rapid	(6,14,7,3)
490	2/13/1890	2/19/1992	2087	100.4	L, US	Above Agate Rapid	(5)
491	2/13/1890	2/19/1992	2086	100.4	L, DS	Above Agate Rapid	
492	2/13/1890	2/14/1991	2322	100.6	R, US	Agate Rapid	(6,7)
493	2/13/1890	2/14/1991	2321	100.6	R, DS	Agate Rapid	(2,13,8,6,7)
494	2/13/1890	2/19/1992	2606	101.1	L, US	Above Sapphire Rapid	(5,14,7,11)
495	2/13/1890	2/02/1990	1475	101.3	R, US	Sapphire Rapid	(14,17,5,6,7)
496	2/13/1890	2/28/1995	3099	101.3	R, DS	Sapphire Rapid	(7,14,15)
497	2/15/1890	2/19/1992	2574b	102.6	L, US	Obscure location	(7,17)
498	2/15/1890	2/19/1992	2574a	102.6	L, DS	Obscure location	(7,17)
499	2/15/1890	2/19/1992	2540	103.0	R, US	Obscure location	(14,5,7,17,6)
500	2/15/1890	2/19/1992	2541	103.0	R, DS	Obscure location	(17,7)
500	2/15/1890	2/19/1992	2541	103.0	R, DS	Obscure location	(17,7)
501	2/15/1890	2/02/1990	1476a	103.8	R, US	104-Mile Rapid	(5,14,17,7)
		2/28/1993	1476a	103.8	R, US	104-Mile Rapid	
502	2/15/1890	2/28/1993	1476b	103.8	R, DS	104-Mile Rapid	(7)
503	2/15/1890	2/02/1990	1477a	104.7	L, US	Ruby Rapid	(14,5,17,6)
		2/14/1991	1477a	104.7	L, US	Ruby Rapid	

Appendix 4. List of photographic views of Glen and Grand Canyon taken by Franklin A. Nims and Robert Brewster Stanton between July 1889 and March 1890—Continued

Stanton's number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
504	2/15/1890	2/19/1992	1477b	104.7	L, DS	Ruby Rapid	(7)
505	2/16/1890	2/14/1991	2323	106.0	L, US	Serpentine Rapid	(14,17)
508	2/17/1890	2/02/1990	1478	106.0	L, UC	Serpentine Canyon	(7)
		2/28/1993	1478	106.0	L, UC	Serpentine Canyon	
506	2/16/1890	2/19/1992	2575	106.1	L, US	Serpentine Rapid	(7,14,16,17)
507	2/16/1890	2/19/1992	2576	106.1	L, DS	Serpentine Rapid	(7,5,17)
509	2/17/1890	2/15/1991	1754c	107.6	R, US	Above Bass Rapid	(7,17)
510	2/17/1890	2/15/1991	1754b	107.6	R, US	Above Bass Rapid	(7,17)
511	2/17/1890	2/15/1991	1754a	107.6	R, DS	Above Bass Rapid	(17,7)
512	2/17/1890	2/14/1991	1755b	107.7	R, US	Hotauta Canyon	(7)
513	2/17/1890	2/14/1991	1755a	107.7	R, DS	Hotauta Canyon	(7,1,17)
514	2/17/1890	2/14/1991	1756b	107.8	L, US	Bass Rapid	(7,17,14)
515	2/17/1890	2/14/1991	1756a	107.8	L, DS	Bass Rapid	(14,17,5,7)
516	2/17/1890	2/15/1991	1580	108.3	R, US	Bass Camp	(7,17)
517	2/17/1890	2/15/1991	1579	108.3	R, DS	Bass Camp	(7)
518	2/17/1890	2/02/1990	1479	108.5	R, US	Bass Camp	(7)
		2/20/1992	1479	108.5	R, US	Bass Camp	
519	2/17/1890	2/15/1991	1581a	108.6	L, AC	Shinumo Creek	(14,5,7,17)
520	2/17/1890	2/15/1991	1581b	108.6	L, DS	Shinumo Creek	(7,17,14)
521	2/17/1890	2/03/1990	1480a	109.3	R, US	110-Mile Beach	(17,8,11)
		2/28/1993	1480a	109.3	R, US	110-Mile Beach	
522	2/17/1890	2/15/1991	1480b	109.3	R, DS	110-Mile Beach	(17,8,11)
		2/28/1993	1480b	109.3	R, DS	110-Mile Beach	
523	2/18/1890	2/21/1992	2577b	109.8	R, US	110-Mile Rapid	(2,13,5,17,14,16)
524	2/18/1890	2/21/1992	2577a	109.8	R, DS	110-Mile Rapid	(14,7)
525	2/18/1890	2/21/1992	2089	110.1	L, US	Copper Canyon	(2,13,17,7)
526	2/18/1890	2/21/1992	2090	110.6	R, US	Hakatai Rapid	(13,2,17,7)
527	2/18/1890	2/21/1992	2091	110.6	L, DS	Hakatai Rapid	(7,14)
528	2/18/1890	2/21/1992	2608	112.2	R, US	Waltenberg Rapid	(2,13,17)
529	2/19/1890	2/15/1991	1757	112.2	L, AC	Waltenberg Rapid	(17,2,13)
530	2/19/1890	2/03/1990	1482	112.2	L, DS	Waltenberg Rapid	(17)
531	2/19/1890	2/03/1990	1481a	112.2	L, US	Waltenberg Rapid	(14,5,6,13)
		2/15/1991	1481a	112.2	L, US	Waltenberg Rapid	
532	2/19/1890	2/15/1991	1481b	112.2	L, DS	Waltenberg Rapid	(4,2,16,14)
533	2/19/1890	2/21/1992	2579	112.9	R, US	Rancid Tuna Rapid	(5,17)
534	2/19/1890	2/21/1992	2578	112.9	R, DS	Rancid Tuna Rapid	(14,5,4,7)
536	2/19/1890	2/21/1992	2543	113.3	R, US	Obscure location	(13,16,17)
537	2/19/1890	2/21/1992	2545	113.3	R, DS	Obscure location	(17,13,7)
539	2/19/1890	2/21/1992	2544	114.2	R, US	Obscure location	(7,17,3,6)

Appendix 4. List of photographic views of Glen and Grand Canyon taken by Franklin A. Nims and Robert Brewster Stanton between July 1889 and March 1890—Continued

Stanton's number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
		3/01/1993	2544	114.2	R, US	Obscure location	
540	2/19/1890	3/01/1993	2649	114.2	R, DS	Obscure location	(17,7)
541	2/19/1890	2/21/1992	2609	115.4	L, US	Obscure location	(7,17,6)
542	2/19/1890	9/22/1976	802	115.6	L, US	Obscure location	(2,13,17,7)
		10/25/1983	802	115.6	L, US	Obscure location	
		8/21/1984	802	115.6	L, US	Obscure location	
		2/03/1990	802	115.6	L, US	Obscure location	
		2/22/1992	802	115.6	L, US	Obscure location	
543	2/19/1890	2/22/1992	2092	115.6	L, DS	Obscure location	(7)
544	2/20/1890	2/15/1991	2326	116.4	L, US	Elves Chasm	(17,12,7)
545	2/20/1890	2/15/1991	2325	116.4	L, DS	Elves Chasm	(5,14,6,17,7)
546	2/20/1890	2/03/1990	1483	116.9	L, DS	Below Elves Chasm	(8,17,7)
547	2/20/1890	2/22/1992	2093	117.2	L, DS	Obscure location	(17,7,16)
548	2/20/1890	2/03/1990	1484	119.0	R, US	119-Mile Creek	(17,5,7,14)
549	2/20/1890	2/03/1990	1486	119.0	R, DS	119-Mile Creek	(17,7)
550	2/20/1890	2/03/1990	1485a	119.7	R, US	above Blacktail Canyon	(17,7)
		3/01/1993	1485a	119.7	R, US	above Blacktail Canyon	
551	2/20/1890	2/03/1990	1485b	119.7	R, DS	above Blacktail Canyon	(17,5,6)
		3/01/1993	1485b	119.7	R, DS	above Blacktail Canyon	
552	2/20/1890	2/15/1991	2328	121.9	L, US	122-Mile Rapid	(7)
553	2/20/1890	2/15/1991	2327	121.9	L, DS	122-Mile Rapid	(7,13,17)
554	2/20/1890	2/16/1991	1759b	122.8	L, US	Forster Rapid	(17,7,8)
		3/01/1993	1759b	122.8	L, US	Forster Rapid	
555	2/20/1890	2/16/1991	1759a	122.8	L, DS	Forster Rapid	(7,2,5,17)
		3/01/1993	1759a	122.8	L, DS	Forster Rapid	
556	2/20/1890	2/16/1991	1760a	122.8	L, US	Forster Canyon	(7,14,17,9)
557	2/20/1890	2/16/1991	1760b	122.8	L, DS	Forster Canyon	(7,9,4)
558	2/20/1890	2/04/1990	1487	122.8	L, UC	Forster Canyon	(7,9)
559	2/21/1890	2/16/1991	1761a	124.6	L, US	Above Fossil Rapid	(7,14,4,17,6)
		3/01/1993	1761a	124.6	L, US	Above Fossil Rapid	
315	2/21/1890	3/01/1993	1761b	124.8	L, DS	Above Fossil Rapid	(17,5,7)
561	2/21/1890	3/01/1993	2651	125.1	L, US	Lower Fossil Rapid	(7,9,5)
562	2/21/1890	2/04/1990	1489	125.0	L, DS	Lower Fossil Rapid	(9,4,17,14)
563	2/21/1890	2/16/1991	2330a	126.3	R, US	Above Randy's Rock	(6,5,2,4)
564	2/21/1890	2/16/1991	2330b	126.3	R, DS	Above Randy's Rock	(17,13,15)
		3/02/1993	2330b	126.3	R, DS	Above Randy's Rock	
565	2/22/1890	2/16/1991	2329a	126.4	R, US	Above Randy's Rock	(17,5,6,7)
		3/02/1993	2329a	126.4	R, US	Above Randy's Rock	
566	2/22/1890	2/16/1991	2329b	126.4	R, DS	Above Randy's Rock	(17,5,6,7)

Appendix 4. List of photographic views of Glen and Grand Canyon taken by Franklin A. Nims and Robert Brewster Stanton between July 1889 and March 1890—Continued

Stanton's number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
567	2/22/1890	2/16/1991	1582b	127.9	L, US	Obscure location	(7,6)
568	2/22/1890	2/16/1991	1582a	127.9	L, DS	Obscure location	(7)
569	2/22/1890	2/05/1990	1491	128.4	R, UC	128-Mile Canyon	(7,6)
		3/02/1993	1491	128.4	R, UC	128-Mile Canyon	
570	2/22/1890	2/23/1992	2580	128.4	R, US	128-Mile Canyon	(7,6,5)
571	2/22/1890	2/23/1992	2581	130.4	R, US	Bedrock Canyon	(7)
572	2/22/1890	2/17/1991	2331	130.5	R, UC	Bedrock Canyon	(7)
573	2/22/1890	2/23/1992	2700	130.6	R, US	Bedrock Rapid	(7)
574	2/22/1890	2/07/1990	1492	130.5	R, DS	Bedrock Rapid	(7,17,5,6)
		2/17/1991	1492	130.5	R, DS	Bedrock Rapid	
575	2/22/1890	2/23/1992	2547b	130.9	L, US	Below Bedrock Rapid	(5,6,17,7)
576	2/22/1890	2/23/1992	2547a	130.9	L, DS	Below Bedrock Rapid	(5,7,8,17)
577	2/22/1890	2/07/1990	1494	131.8	R, US	Dubendorff Rapid	(17,14,12,5)
578	2/22/1890	2/07/1990	1493	131.8	R, DS	Dubendorff Rapid	(5,17,14,7)
579	2/23/1890	2/17/1991	1500a	132.7	L, US	Obscure location	(15)
580	2/23/1890	2/08/1990	1500b	132.7	L, DS	Obscure location	(7)
581	2/23/1890	2/23/1992	2095	133.1	L, DS	133-Mile Creek	(2,13,6,7,17)
582	2/23/1890	2/08/1990	1501	133.1	L, UC	133-Mile Creek	(13,7)
		3/04/1993	1501	133.1	L, UC	133-Mile Creek	
583	2/24/1890	2/08/1990	1502b	133.8	L, AC	Tapeats Rapid	(14,5,7)
		3/04/1993	1502b	133.8	L, AC	Tapeats Rapid	
584	2/24/1890	2/08/1990	1502a	133.8	L, DS	Tapeats Rapid	(14,7,17)
585	2/24/1890	2/08/1990	1503	134.1	L, DS	134-Mile Rapid	(8,17,14,7)
586	2/24/1890	2/17/1991	2332b	134.9	L, US	Granite Narrows	(7,17)
587	2/24/1890	2/17/1991	2332a	134.9	L, DS	Granite Narrows	(7)
588	2/24/1890	2/25/1991	1764b	136.1	L, US	Deer Creek Falls	(2,5,17,7)
589	2/24/1890	2/17/1991	1764a	136.1	L, DS	Deer Creek Falls	(7,17)
		3/04/1993	1764a	136.1	L, DS	Deer Creek Falls	
590	2/24/1890	2/17/1991	1762	136.1	L, AC	Deer Creek Falls	(5,7)
591	2/24/1890	2/18/1991	1765b	137.6	R, US	Above Doris Rapid	(7,17)
592	2/24/1890	2/18/1991	1765a	137.6	R, DS	Above Doris Rapid	(7,14)
593	2/24/1890	2/25/1991	2702b	139.1	R, US	Fishtail Rapid	(17,7,5)
594	2/24/1890	2/25/1991	2702a	139.1	R, DS	Fishtail Rapid	(7,17,5)
595	2/24/1890	2/25/1991	2548	141.7	R, US	Obscure location	(7,6,16,12)
596	2/24/1890	2/25/1991	1504b	143.4	R, US	Kanab Creek	(7,17,5,16)
597	2/24/1890	2/09/1990	1504a	143.4	R, DS	Kanab Creek	(14,5,6,17,7)
598	2/25/1890	2/18/1991	2333b	145.0	L, US	144.5 Mile Rapid	(7,5,17,14)
		3/04/1993	2333b	145.0	L, US	144.5 Mile Rapid	
599	2/25/1890	2/18/1991	2333a	145.0	L, DS	144.5 Mile Rapid	(7)

Appendix 4. List of photographic views of Glen and Grand Canyon taken by Franklin A. Nims and Robert Brewster Stanton between July 1889 and March 1890—Continued

Stanton's number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
		3/04/1993	2333a	145.0	L, DS	144.5 Mile Rapid	
600	2/25/1890	2/18/1991	1583b	147.7	L, US	Above Matkatamiba Rapid	(7)
601	2/25/1890	2/18/1991	1583a	147.7	L, DS	Above Matkatamiba Rapid	(7,17,14)
602	2/25/1890	2/09/1990	1507	151.5	R, US	Ledges Camp	(7,6)
603	2/25/1890	2/18/1991	2334	151.7	R, DS	Ledges Camp	(7,17)
604	2/25/1890	3/05/1993	2549b	155.5	R, US	Paradise Canyon	(7,16)
607	2/25/1890	2/26/1992	2549a	155.5	R, DS	Paradise Canyon	(5,7,16)
605	2/26/1890	2/26/1992	2612a	159.0	R, US	Obscure location	(2,13,17,16)
606	2/26/1890	2/26/1992	2612b	159.0	R, DS	Obscure location	(13,17)
608	2/26/1890	2/26/1992	1508b	164.4	L, US	Tuckup Canyon	(7)
609	2/26/1890	2/10/1990	1508a	164.4	L, DS	Tuckup Canyon	(7,14,13,17,6,16)
		3/05/1993	1508a	164.4	L, DS	Tuckup Canyon	
610	2/26/1890	2/19/1991	1584a	167.1	L, US	Below National Canyon	(17,7,8)
611	2/26/1890	2/19/1991	1584b	167.1	L, DS	Below National Canyon	(7,17)
612	2/26/1890	2/26/1992	2099	169.6	L, DS	Obscure location	(2,17,7,12,13,16)
613	2/26/1890	2/10/1990	1509	171.5	L, US	Mohawk Canyon	(17,5,15)
		3/06/1993	1509	171.5	L, US	Mohawk Canyon	
614	2/26/1890	2/19/1991	1767a	176.0	L, US	Red Slide	(5,6,7,14)
616	2/26/1890	2/19/1991	1767b	176.0	L, DS	Red Slide	(17,7)
615	2/26/1890	2/19/1991	1767	176.0	L	Red Slide (double exposure)	---
617	2/26/1890	2/19/1991	2335	178.2	L, US	Vulcan's Anvil	(7,17)
		3/10/1993	2335	178.2	L, US	Vulcan's Anvil	
618	2/26/1890	2/19/1991	2336	178.3	L, DS	Below Vulcan's Anvil	(7,14)
		3/10/1993	2336	178.3	L, DS	Below Vulcan's Anvil	
619	2/27/1890	2/11/1990	1510c	179.3	L, US	Lava Falls Rapid	(7)
		2/20/1991	1510c	179.3	L, US	Lava Falls Rapid	
		3/10/1993	1510c	179.3	L, US	Lava Falls Rapid	
620	2/27/1890	2/11/1990	1510a	179.3	L, UC	Lava Falls Rapid	(7)
		2/20/1991	1510a	179.3	L, UC	Lava Falls Rapid	
		3/06/1995	1510a	179.3	L, UC	Lava Falls Rapid	
621	2/27/1890	2/11/1990	1510b	179.3	L, DS	Lava Falls Rapid	(14,5,6,7)
		2/20/1991	1510b	179.3	L, DS	Lava Falls Rapid	
		3/06/1995	1510b	179.3	L, DS	Lava Falls Rapid	
622	2/27/1890	2/27/1992	2704	179.8	R, DS	Lower Lava Rapid	
623	2/27/1890	3/12/1993	1771b	182.7	L, US	Hell's Hollow area	(5,17,15)
624	2/27/1890	2/21/1991	1771a	182.7	L, DS	Hell's Hollow area	(17,13,2,15)
		3/12/1993	1771a	182.7	L, DS	Hell's Hollow area	
625	2/27/1890	2/27/1992	2614	185.2	R, US	185-Mile Rapid	(15,17,16,7,10)
626	2/27/1890	2/11/1990	1513	187.0	R, US	187-Mile Rapid	(2,17,12,15)

Appendix 4. List of photographic views of Glen and Grand Canyon taken by Franklin A. Nims and Robert Brewster Stanton between July 1889 and March 1890—Continued

Stanton's number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
627	2/27/1890	2/21/1991	1514b	189.0	R, US	Below Whitmore Rapid	(7,17,10)
628	2/27/1890	2/11/1990	1514a	189.0	R, DS	Below Whitmore Rapid	(7,17,10)
629	2/28/1890	2/21/1991	1590	190.5	L, US	Obscure location	(5,6,7,17)
		3/12/1993	1590	190.5	L, US	Obscure location	
631	2/28/1890	2/21/1991	2337	193.0	L, US	193-Mile Canyon	(7,6,17,5,12)
632	2/28/1890	2/12/1990	1515	193.0	L, DS	193-Mile Canyon	(17,7,12,4)
		2/21/1991	1515	193.0	L, DS	193-Mile Canyon	
633	2/28/1890	2/22/1991	2006	194.5	L, DS	194-Mile Canyon	(7,17,12)
634	2/28/1890	2/22/1991	1772a	198.5	R, US	Parashant Wash	(5,17,12)
635	2/28/1890	2/22/1991	1772b	198.5	R, DS	Parashant Wash	(5,6,17,15)
636	2/28/1890	2/22/1991	2007	202.2	R, US	Obscure location	(7,17,4,10)
637	2/28/1890	2/22/1991	2008	202.2	R, DS	Obscure location	(5,12,7,17,10)
638	2/28/1890	2/22/1991	1591a	204.3	L, US	Spring Canyon	(5,6,17,12)
639	2/28/1890	2/22/1991	1591b	204.3	L, DS	Spring Canyon	(17,5,2,12)
640	3/01/1890	2/22/1991	2338a	205.5	L, US	205-Mile Rapid	(17,14,16)
641	3/01/1890	2/22/1991	2338b	205.5	L, DS	205-Mile Rapid	(11,17)
642	3/01/1890	2/23/1991	1773	206.7	R, US	Indian Canyon	(7,2,13,17,12,10)
643	3/01/1890	2/12/1990	1516	206.7	R, DS	Indian Canyon	(7,17,12,10)
		2/23/1991	1516	206.7	R, DS	Indian Canyon	
644	3/01/1890	2/13/1990	700b	208.2	L, US	Above Granite Park	(17,5,6)
		4/04/1992	700b	208.2	L, US	Above Granite Park	
645	3/01/1890	7/03/1972	700a	208.2	L, DS	Above Granite Park	(13,1,15,17)
		2/13/1990	700a	208.2	L, DS	Above Granite Park	
646	3/01/1890	2/14/1990	1517a	209.3	L, US	Bottom of 209-Mile Rapid	(17,5,14,16,12)
647	3/01/1890	2/14/1990	1517b	209.3	L, DS	Bottom of 209-Mile Rapid	(13,17,5,14)
648	3/01/1890	2/24/1991	1777	211.4	R, DS	Above Fall Canyon	(17,5,14,4)
649	3/01/1890	2/24/1991	1778	211.6	R, DS	Fall Canyon	(9)
650	3/01/1890	2/24/1991	2009a	215.2	L, US	215-Mile Canyon	(17,5,7,12)
651	3/01/1890	2/24/1991	2009b	215.2	L, DS	215-Mile Canyon	(7,17,4,12)
652	3/01/1890	2/26/1991	1779a	216.3	R, US	Obscure location	(17,15,12,5)
653	3/01/1890	2/26/1991	1779b	216.3	R, DS	Obscure location	(17,15)
654	3/01/1890	2/26/1991	1780a	217.5	L, US	217-Mile Rapid	(17,11,8,5)
655	3/01/1890	2/26/1991	1780b	217.5	L, DS	217-Mile Rapid	(17,3,11)
656	3/01/1890	2/14/1990	1520a	219.2	R, US	Trail Canyon	(7,17,12,10)
		2/26/1991	1520a	219.2	R, US	Trail Canyon	
657	3/01/1890	2/26/1991	1520b	219.2	R, DS	Trail Canyon	(6,14,7,17,12,10)
658	3/01/1890	2/26/1991	2010	222.4	R, US	Obscure location	(7,17,12,3,10)
659	3/01/1890	2/14/1990	1521a	222.6	L, US	Obscure location	(7,17,5,12)
		2/26/1991	1521a	222.6	L, US	Obscure location	

Appendix 4. List of photographic views of Glen and Grand Canyon taken by Franklin A. Nims and Robert Brewster Stanton between July 1889 and March 1890—Continued

Stanton's number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
660	3/01/1890	2/14/1990	1521b	222.6	L, DS	Obscure location	(4,17,5,7,6)
		2/26/1991	1521b	222.6	L, DS	Obscure location	
661	3/01/1890	2/26/1991	1522b	224.5	L, US	Obscure location	(17,5,6)
662	3/01/1890	2/15/1990	1522a	224.5	L, DS	Obscure location	(5,13,17)
		2/26/1991	1522a	224.5	L, DS	Obscure location	
663	3/11/1890	3/14/1993	2749	224.6	L, US	Obscure location	(17,14)
664	3/11/1890	2/29/1992	2615	225.5	L, UC	Diamond Creek	(7,6)
		3/14/1993	2615	225.5	L, UC	Diamond Creek	
665	3/11/1890	3/14/1993	2665a	225.5	L, US	Diamond Creek	(17,6)
666	3/11/1890	3/14/1993	2665b	225.5	L, DS	Diamond Creek	(17,5,14,15)
667	3/12/1890	2/15/1990	1523	226.1	R, US	Below Diamond Creek Rapid	(4,14,8)
668	3/12/1890	2/29/1992	2552	226.1	R, DS	Below Diamond Creek Rapid	(17,8,4)
669	3/12/1890	2/29/1992	2616	226.9	L, US	Obscure location	(14,17,5,4)
670	3/12/1890	2/29/1992	2617	226.9	L, DS	Obscure location	(5,7,14,17)
671	3/12/1890	2/15/1990	1524	228.1	L, US	228-Mile Canyon	(17,5,6)
672	3/12/1890	2/29/1992	2104	228.1	L, DS	228-Mile Canyon	(7,17,14)
673	3/12/1890	2/29/1992	2553a	229.0	L, US	Travertine Canyon	(7,6)
674	3/12/1890	2/29/1992	2553b	229.0	L, DS	Travertine Canyon	(13,6,17,14)
675	3/12/1890	2/29/1992	2105	229.0	L, UC	Travertine Canyon	(13,7)
676	3/12/1890	2/29/1992	2618	229.0	L, UC	Travertine Canyon	
677	3/12/1890	3/01/1992	2619a	229.8	R, US	Obscure location	(4,7,5,14)
678	3/12/1890	3/01/1992	2619b	229.8	R, DS	Obscure location	(4,7,17,8)
679	3/12/1890	3/15/1993	2555b	230.8	R, US	231-Mile Rapid	(7,17)
680	3/12/1890	3/01/1992	2555a	230.8	R, DS	231-Mile Rapid	(13,14,17,8,6)
681	3/13/1890	3/15/1993	3012	231.5	R, US	Obscure location	(16,7)
682	3/13/1890	3/15/1993	3013	231.5	R, DS	Obscure location	(17,16,7)
683	3/13/1890	3/15/1993	2666	232.3	R, DS	232-Mile Rapid	(14)
684	3/13/1890	3/15/1993	2667	233.4	R, US	Above 234-Mile Rapid	(2)
685	3/13/1890	3/15/1993	3057	234.4	L, US	Obscure location	(17,5,7)
686	3/13/1890	3/15/1993	3056	234.4	L, DS	Obscure location	(8,17,7)
687	3/13/1890	3/15/1993	2750a	235.3	L, US	Bridge Canyon Rapid	(5,13,15)
688	3/13/1890	3/15/1993	2750b	235.3	L, DS	Bridge Canyon Rapid	(17,5)
689	3/13/1890	3/15/1993	2751a	235.9	L, US	Gneiss Canyon Rapid	(5,18)
690	3/13/1890	3/15/1993	2751b	235.9	L, DS	Gneiss Canyon Rapid	(5,18)
691	3/13/1890	3/15/1993	3015	236.9	L,US	Obscure location	(18)
692	3/13/1890	3/15/1993	3014	236.9	L,DS	Obscure location	(7,18)
693	3/13/1890	3/15/1993	3058	238.2	L,US	Obscure location	(7,18)
694	3/13/1890	3/15/1993	3059	238.2	L,DS	Obscure location	(7,18)
695	3/13/1890	3/15/1993	3016b	238.1	R,US	Above Separation Canyon	(18)

Appendix 4. List of photographic views of Glen and Grand Canyon taken by Franklin A. Nims and Robert Brewster Stanton between July 1889 and March 1890—Continued

Stanton's number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
696	3/13/1890	3/15/1993	3016a	239.1	R,DS	Above Separation Canyon	(18)
697	3/14/1890	3/16/1993	3060	239.1	R,DS	Obscure location	(18)

[1]Archaeology, the view contained an archaeological site.

[2]Boats, one or more boats of the Stanton expedition appear in the view.

[3]Cryptobiotic soils, the view contains a significant amount of cryptobiotic soils.

[4]Debris bar, a debris bar in the Colorado River appears in the view.

[5]Debris fan, a debris fan appears in the view, but not all views with debris fans are listed.

[6]Debris flow, a debris flow has occurred during the last century in the view.

[7]Desert, the view contained desert vegetation.

[8]Driftwood, the view contains driftwood at or near the highest flood stage of the Colorado River during the last century.

[9]Eolian sand, the view contains eolian sand.

[10]Grazing, desert vegetation in the view was grazed by domestic livestock (at or upstream of Lees Ferry), heavily grazed by deer, or heavily grazed by burros.

[11]New desert, the view contains significant amounts of desert vegetation that has invaded the new high-water zone.

[12]Old high-water line, the view contained vegetation of the old high-water zone, but not all views could be interpreted for change.

[13]People, member(s) of the Stanton expedition appears in the view.

[14]Rapid, the view contains a rapid.

[15]Riparian, the view contained riparian vegetation that could be interpreted for change.

[16]Rockfall, a rockfall has occurred in the view during the last century.

[17]Sand bars, the view contains sand bars.

[18]Lake, matched views show Lake Mead.

Appendix 5. List of photographic views of the Colorado River between Glen Canyon Dam and Lake Mead taken by Eugene C. LaRue between 1921 and 1923

[All photographs were obtained from the U.S. Geological Survey Photographic Library in Lakewood, Colorado, except those with numbers larger than 1,000, which were obtained from the Kolb Collection in Special Collections at Northern Arizona University. Number, refers to the large number on album prints that were assigned by LaRue. Smaller numbers that appear on some prints and negatives are inconsistent. Date of original, was obtained from LaRue's captions or from the unpublished diary of Claude Birdseye, the head of the expedition. Date of repeat, is exactly known in all cases. When more than one replicate was made, the first two columns and the last column appear blank. Stake number, is a number assigned for permanent storage of replicate negatives in the repeat photography collection at the Desert Laboratory, University of Arizona, Tucson. Letters following a number indicate a swing of two or more views; not all swings were assigned stake numbers with letters, however. Many of LaRue's views required multiple panning exposures for full coverage. River mile, was estimated to the nearest tenth of a mile using the 1990 revision of a popular river guide (Stevens,1990). Side, direction, refers to the side of the channel when facing downstream of the camera station and the relative direction of the view. (R), photograph taken from river-right; (L), photograph taken from river-left; (US), upstream; (DS), downstream; (AC), across the Colorado River; (UC), up a side canyon; (DC), down a side canyon. Location, is the name of a geographical feature at or near the camera station. Wherever possible, names were obtained from 7.5-minute quadrangle maps, but some names are generally recognized and used in a popular river guide (Stevens, 1990). Subject(s), designated by footnotes, refer to the type of information that was interpreted from the view. (---), view contained little of interest in terms of geomorphology or biotic habitat]

LaRue Number	Date of Original	Date of Repeat	Stake Number	River Mile	Side, direction	Location	Subject(s)
251	8/29/1915	10/29/1992	2639	-10.2	R, US	Glen Canyon	(17,15)
255	8/10/1921	2/10/1992	2601	-9.1	L, AC	Glen Canyon	---
286	5/08/1921	10/30/1992	2640	-4.2	L, US	Water Holes Canyon	(7,15,17)
289	5/08/1921	2/11/1992	2604	-3.6	L, DS	Glen Canyon	(15,17)
331	8/01/1923	2/24/1994	2756	5.1	L, US	Five-Mile Wash	(16,17)
328	7/23/1923	12/30/1991	2069	0.4	R, US	Mouth of Paria River	(17,15)
334	7/22/1923	10/02/1991	2057	7.8	R, AC	Badger Rapid	(17)
335	8/02/1923	1/18/1990	1404	8.3	L, US	Badger Rapid	(14,5)
337	8/02/1923	2/25/1994	2758	9.9	L, US	Ten-Mile Rock	(15,17)
338	8/02/1923	6/27/1972	672	10.5	L, DS	Above Soap Creek Rapid	(17,2,13)
		8/22/1972	672	10.5	L, DS	Above Soap Creek Rapid	
		10/05/1982	672	10.5	L, DS	Above Soap Creek Rapid	
		10/17/1983	672	10.5	L, DS	Above Soap Creek Rapid	
		8/13/1984	672	10.5	L, DS	Above Soap Creek Rapid	
		10/07/1991	672	10.5	L, DS	Above Soap Creek Rapid	
306	5/09/1921	10/12/1988	1249	11.2	L, DS	Soap Creek Rapid overlook	((5)
308	5/09/1921	10/12/1988	1247	11.2	L, AC	Soap Creek Rapid overlook	(5,14)
309	5/09/1921	10/12/1988	1248	11.2	L, US	Soap Creek Rapid overlook	(5,14,7)
339	8/02/1923	10/17/1983	1091	11.2	R, US	Soap Creek Rapid	(17,14)
		8/13/1984	1091	11.2	R, US	Soap Creek Rapid	
		1/05/1991	1091	11.2	R, US	Soap Creek Rapid	
340	8/03/1923	12/30/1991	2200	11.2	R, AC	Soap Creek Rapid	(14,2,13,6)
348	8/04/1923	11/16/1990	1701	16.7	R, US	House Rock Rapid	(17,14,2)
350	8/04/1923	11/16/1990	1700	16.7	R, AC	House Rock Rapid	(14)
349	8/04/1923	2/25/1994	2759	16.9	R, DS	House Rock Rapid	(14,16,17)
351	8/05/1923	1/01/1992	2524	18.4	L, DS	Boulder Narrows	(4,5)
352	8/05/1923	2/12/1992	2534	20.3	L, DS	Above North Canyon	(17,5)
353	8/06/1923	8/23/1972	714	21.5	L, DS	22-Mile Wash	(15)
		10/01/1982	714	21.5	L, DS	22-Mile Wash	
		10/18/1983	714	21.5	L, DS	22-Mile Wash	

Appendix 5. List of photographic views of the Colorado River between Glen Canyon Dam and Lake Mead taken by Eugene C. LaRue between 1921 and 1923—Continued

LaRue Number	Date of Original	Date of Repeat	Stake Number	River Mile	Side, direction	Location	Subject(s)
354	8/06/1923	10/08/1991	2501	24.1	L, US	24-Mile Rapid	(14,17,6,7)
355	8/06/1923	9/16/1976	797	24.5	L, US	24.5 Mile Rapid	(14,2,13)
		10/08/1983	797	24.5	L, US	24.5 Mile Rapid	
		8/13/1984	797	24.5	L, US	24.5 Mile Rapid	
		10/08/1991	797	24.5	L, US	24.5 Mile Rapid	
356	8/06/1923	10/08/1991	2503	24.6	L, DS	24.5 Mile Rapid	(14,17,6)
357	8/06/1923	10/08/1991	2502	24.6	L, US	24.5 Mile Rapid	(17,14)
366	8/07/1923	10/08/1991	2202	28.2	L, DS	Above Shinumo Wash	(7)
367	8/07/1923	2/23/1993	3000	28.2	L, US	Above Shinumo Wash	(5,7,17,15)
369	8/07/1923	1/02/1992	2249	30.0	L, US	Fence Fault Camp	(7,17,5,6)
368	8/07/1923	11/17/1990	1703	30.4	R, US	Below Fence Fault	(5,17)
370	8/08/1923	6/28/1972	674	31.6	R, DS	Vasey's Paradise	(7)
		10/18/1983	674	31.6	R, DS	Vasey's Paradise	
371	8/08/1923	6/28/1972	675	31.9	R, US	Vasey's Paradise	(15,17)
378	8/08/1923	10/09/1991	2201	32.8	L, DS	Redwall Cavern	(17,13)
379	8/08/1923	10/09/1991	2201	32.8	L, DS	Redwall Cavern	(17,13)
386	8/10/1923	6/28/1972	678	43.5	L, DS	President Harding Rapid	(17,7,2,13)
387	8/10/1923	6/28/1972	677	43.5	L, AC	President Harding Rapid	(17,7,14,2)
		8/23/1972	677	43.5	L, DS	President Harding Rapid	
		10/07/1982	677	43.5	L, DS	President Harding Rapid	
		10/19/1983	677	43.5	L, DS	President Harding Rapid	
390	8/11/1923	3/18/1974	798	46.5	R, DS	Triple Alcoves	(17)
		9/17/1976	798	46.5	R, DS	Triple Alcoves	
		10/08/1982	798	46.5	R, DS	Triple Alcoves	
		10/20/1983	798	46.5	R, DS	Triple Alcoves	
		8/15/1984	798	46.5	R, DS	Triple Alcoves	
		11/17/1990	798	46.5	R, DS	Triple Alcoves	
391	8/11/1923	3/18/1974	1705	46.7	L, DS	Saddle Canyon	(17,2,13)
		11/17/1990	1705	46.7	L, DS	Saddle Canyon	
394	8/12/1923	9/18/1976	799	52.5	R, DS	Nankoweap Creek	(17,7,13)
401	8/13/1923	10/10/1991	2203	61.5	R, AC	Little Colorado River	(17,7)
402	8/13/1923	10/10/1991	2203	61.5	R, DS	Little Colorado River	(17,7)
406	8/14/1923	10/22/1983	1092	65.5	L, US	Lava Canyon Rapid	(17,14,7)
407	8/14/1923	7/26/1974	1707a	65.5	L, DS	Lava Canyon Rapid	(17,14,7)
		11/22/1990	1707a	65.5	L, DS	Lava Canyon Rapid	
		10/10/1991	1707a	65.5	L, DS	Lava Canyon Rapid	
408	8/14/1923	2/06/1991	1570	65.4	L, AC	Above Lava Canyon Rapid	(17,7)
409	8/14/1923	10/10/1991	1707b	65.5	L, AC	Lava Canyon Rapid	(14,17,7,6)
410	8/14/1923	10/12/1991	2204	67.6	R, DS	Comanche Creek	(17,7)
411	8/15/1923	10/12/1991	2505	74.4	R, US	Obscure location	(17,2,13)
412	8/15/1923	10/12/1991	2506	74.4	R, DS	Obscure location	(17,7)
413	8/16/1923	10/23/1983	1093	75.7	L, DS	Nevills Rapid	(17,6,7)

Appendix 5. List of photographic views of the Colorado River between Glen Canyon Dam and Lake Mead taken by Eugene C. LaRue between 1921 and 1923—Continued

LaRue Number	Date of Original	Date of Repeat	Stake Number	River Mile	Side, direction	Location	Subject(s)
		10/14/1991	1093	75.7	L, DS	Nevills Rapid	
414	8/20/1923	?/?/1974	1156	77.0	L, DS	Lower Hance Rapid	(17,14)
		8/18/1984	1156	77.0	L, DS	Lower Hance Rapid	(17,14)
421	8/21/1923	2/26/1993	2591	78.8	L, DS	Sockdolager Rapid	(14)
434.5	8/23/1923	1/08/1992	2081	84.5	R, DS	Zoroaster Rapid	(14,7)
439	8/26/1923	3/03/1994	2900	87.8	R,US	Phantom boat beach	(17,14)
438	8/26/1923	2/16/1992	2569	87.4	R, DS	Bright Angel Creek	(5,17,7)
441	8/26/1923	2/27/1993	2593	87.4	L, DS	Bright Angel Creek	(17,15,5)
442	8/26/1923	3/03/1994	2901	87.8	R, US	Bright Angel Creek	(5,6,7,17,14)
452	8/28/1923	11/24/1990	1712	88.7	R, US	Pipe Creek	(17)
449	8/28/1923	2/17/1992	2570	88.9	L, DS	Pipe Creek	(17,6,7)
454	8/26/1923	3/03/1994	2809	89.2	L, DS	Below Pipe Creek	(7,17,14)
457	8/28/1923	11/24/1990	1713	95.0	L, DS	Hermit Rapid	(17,14)
458	8/29/1923	10/16/1991	1713	95.0	L, DS	Hermit Rapid	(7,5)
459	8/30/1923	10/16/1991	2516	96.7	L, US	Above Boucher Rapid	(17,2,7)
460	8/30/1923	8/11/1991	2349	98.1	R, DS	Crystal Rapid	(17,7,2)
461	8/31/1923	4/14/1991	2056	98.3	R, AC	Crystal Rapid	(17,7,2,13)
462	8/30/1923	8/10/1991	2348	98.2	R, UC	Crystal Creek	(6,7)
467	8/31/1923	10/16/1991	2362	99.3	R, UC	Tuna Creek	(6,7)
469	8/31/1923	10/16/1991	2363	99.3	R, US	Tuna Creek	(6,7)
470	8/31/1923	6/30/1972	687	99.3	R, US	Tuna Creek	---
475	9/01/1923	11/25/1990	1714	103.9	R, DS	104-Mile Rapid	(17,7,14,2)
		2/28/1993	1714	103.9	R, DS	104-Mile Rapid	
476	9/01/1923	10/16/1991	2228	104.2	L, US	Below 104-Mile Rapid	(17,7,6,14)
480	9/02/1923	2/20/1992	2542	107.6	R, DS	Hotauta Canyon	(7,5,17)
		2/28/1993	2542	107.6	R, DS	Hotauta Canyon	
481	9/02/1923	2/20/1992	2542	107.6	R, DS	Hotauta Canyon	(15,17)
		2/28/1993	2542	107.6	R, DS	Hotauta Canyon	
483	9/03/1923	10/17/1991	2360	108.7	R, UC	Shinumo Creek	(13,7,6)
487	9/04/1923	10/17/1991	2364	110.8	R, US	Hakatai Rapid	(13,17)
492	9/04/1923	2/15/1991	1789	112.2	R, DS	Waltenberg Rapid	(17,14,7)
		8/10/1991	1789	112.2	R, DS	Waltenberg Rapid	
493	9/04/1923	8/11/1991	2350	112.2	R, US	Waltenberg Rapid	(17,7)
494	9/05/1923	10/17/1991	2230	112.2	L, US	Waltenberg Rapid	(6,14)
496	9/05/1923	2/15/1991	1758	112.2	L, DS	Waltenberg Rapid	(17,14,7)
		3/01/1993	1758	112.2	L, DS	Waltenberg Rapid	
497	9/05/1923	3/01/1993	2594	112.2	L, DS	Waltenberg Rapid	(4,14)
498	9/05/1923	10/17/1991	2229	112.3	L, US	Waltenberg Rapid	(14,7,17,6)
501	9/05/1923	3/01/1993	2546	115.2	L, US	Garnet Canyon	(7)
502	9/05/1923	2/22/1992	2546	115.2	L, DS	Garnet Canyon	(7,14)
503	9/05/1923	2/22/1992	2546	115.2	L, US	Garnet Canyon	(7,17)
		3/01/1993	2546	115.2	L, US	Garnet Canyon	

Appendix 5. List of photographic views of the Colorado River between Glen Canyon Dam and Lake Mead taken by Eugene C. LaRue between 1921 and 1923—Continued

LaRue Number	Date of Original	Date of Repeat	Stake Number	River Mile	Side, direction	Location	Subject(s)
504	9/05/1923	2/22/1992	2546c	115.2	L, DS	Garnet Canyon	(7,6,17)
505	9/05/1923	10/17/1991	2517	116.5	L, DS	Elves Chasm	(14,17,6)
507	9/05/1923	7/01/1972	689	116.5	L, UC	Elves Chasm	(7,6)
		10/17/1991	689	116.5	L, UC	Elves Chasm	
513	9/06/1923	7/01/1972	690	124.8	R, DS	Fossil Canyon	(17,5,7)
		9/22/1976	690	124.8	R, DS	Fossil Canyon	
		10/26/1983	690	124.8	R, DS	Fossil Canyon	
		8/21/1984	690	124.8	R, DS	Fossil Canyon	
513	9/06/1923	10/18/1991	690	124.8	R, DS	Fossil Canyon	
514	9/06/1923	7/01/1972	691	124.8	R, DS	Fossil Canyon	(7,17)
		9/22/1976	691	124.8	R, DS	Fossil Canyon	
		10/19/1991	691	124.8	R, DS	Fossil Canyon	
518	9/06/1923	10/18/1991	2518	126.1	R, DS	Randy's Rock	(17)
519	9/06/1923	10/18/1991	2234	126.9	L, DS	127-Mile Rapid	(17,5)
520	9/06/1923	8/13/1991	2034	129.5	L, US	128-Mile Rapid	(14,5)
532	9/07/1923	2/23/1992	2096	133.5	L, AC	133-Mile Creek	(5,17,7)
533	9/09/1923	2/24/1992	2097	133.8	R, US	Tapeats Creek	(5,7,17)
		2/29/1992	2097	133.8	R, US	Tapeats Creek	
546	9/10/1923	8/24/1972	717A	136.3	L, AC	Deer Creek Falls	(17,7)
		10/28/1991	717A	136.3	L, AC	Deer Creek Falls	---
		2/17/1991	717A	136.3	L, AC	Deer Creek Falls	---
547	9/10/1923	7/01/1972	692	136.3	R, AC	Deer Creek Falls	(5)
550	9/10/1923	8/24/1972	717B	136.3	L, AC	Deer Creek Falls	(5)
		10/28/1983	717B	136.3	L, AC	Deer Creek Falls	
551	9/10/1923	10/20/1991	2520	139.0	L, US	Fishtail Canyon	(17,7,2,13)
552	9/10/1923	8/14/1991	1791	143.5	L, US	Kanab Creek	(7)
553	9/10/1923	8/24/1972	718	143.5	L, US	Kanab Creek	(17,7,5)
		10/29/1983	718	143.5	L, US	Kanab Creek	
		8/23/1984	718	143.5	L, US	Kanab Creek	
		8/14/1991	718	143.5	L, US	Kanab Creek	
		3/04/1993	718	143.5	L, US	Kanab Creek	
554	9/11/1923	8/14/1991	2041	143.5	R, DC	Kanab Creek	(7,15,6)
555	9/11/1923	3/10/1994	2830	143.5	R,US	Kanab Creek	(5,15,17)
564	9/13/1923	10/20/1991	2237	150.5	L, DS	Upset Rapid	(5,17)
569	9/13/1923	10/20/1991	2367	156.9	L, UC	Havasu Creek	(7)
571	9/14/1923	3/05/1993	2596	156.9	L, US	Havasu Creek	(5,14)
572	9/14/1923	3/05/1993	2597	156.9	L, DC	Havasu Creek	(7)
575	9/13/1923	10/20/1991	2238	156.9	L, UC	Havasu Creek	(7,15,6)
582	9/15/1923	2/26/1992	2703	160.6	L, DS	Obscure location	---
586	9/16/1923	11/30/1990	1718	166.5	L, DS	National Canyon	(17,2)
587	9/16/1923	11/30/1990	1720	166.5	L, UC	National Canyon	(6)
589	9/16/1923	11/30/1990	1720	166.5	L, UC	National Canyon	(6)

Appendix 5. List of photographic views of the Colorado River between Glen Canyon Dam and Lake Mead taken by Eugene C. LaRue between 1921 and 1923—Continued

LaRue Number	Date of Original	Date of Repeat	Stake Number	River Mile	Side, direction	Location	Subject(s)
592	9/17/1923	10/21/1991	2521	171.0	R, DS	Stairway Canyon	(17,5,7)
593	9/18/1923	10/21/1991	2239	171.5	L, DS	Mohawk Canyon	(5,17,7)
594	9/18/1923	2/26/1992	2100	177.4	L, US	Obscure location	---
596	9/18/1923	3/12/1994	2833	178.0	L, US	Vulcan's Anvil	(7,15,17)
600	9/18/1923	3/10/1993	697	178.6	L, US	Above Lava Falls Rapid	(17,7)
601	9/18/1923	3/08/1993	697	179.0	L, DS	Above Lava Falls Rapid	(17,7,5)
88K	9/18/1923	7/03/1972	698	179.8	L, DS	Lava Falls Rapid	(15)
603	9/18/1923	3/12/1994	2769	179.3	L, DS	Lava Falls Rapid	(7,14,15,17)
605	9/18/1923	12/01/1990	1732	179.3	L, US	Lava Falls Rapid	(14,7)
606	9/18/1923	10/21/1991	2368	179.3	L, US	Lava Falls Rapid	(14,7)
619	9/22/1923	10/22/1991	2370	182.8	L, DS	Hell's Hollow	(7)
622	9/22/1923	10/22/1991	2522	184.5	L, US	Obscure location	(7,17)
623	9/22/1923	10/22/1991	2522	184.5	L, US	Obscure location	(17,7)
627	9/23/1923	10/22/1983	2369	190.1	L, US	Obscure location	(17,7)
626	9/23/1923	8/25/1972	719	189.8	L, DS	Obscure location	(17)
		10/31/1983	719	189.8	L, DS	Obscure location	
		3/12/1993	719	189.8	L, DS	Obscure location	
628	9/25/1923	8/25/1972	720	194.6	L, DS	194 Mile Canyon	(17,7,2,13)
		11/01/1983	720	194.6	L, DS	194 Mile Canyon	
629		3/14/1994	720	194.6	L, DS	194 Mile Canyon	
630	9/25/1923	12/02/1990	1733	198.7	R, US	Parashant Wash	(17,7,5)
631	9/27/1923	7/03/1972	699	204.4	R, US	Spring Canyon	(17,7)
632	9/27/1923	10/23/1991	2241	204.4	R, UC	Spring Canyon	(7,15)
633	9/27/1923	8/03/1974	1802	204.4	R, US	Spring Canyon	(17,7)
		8/17/1991	1802	204.4	R, US	Spring Canyon	
634	9/27/1923	10/22/1991	2240	204.4	R, DS	Spring Canyon	(17,7)
635	9/27/1923	8/17/1991	1796	204.4	R, DS	Spring Canyon	(5,17,7,6)
636	9/27/1923	2/23/1991	1774	206.7	R, US	Indian Canyon	(17,7)
637	9/27/1923	2/23/1991	1775	206.7	R, DS	Indian Canyon	(17)
638	9/27/1923	10/23/1991	2242	206.7	R, UC	Indian Canyon	(7)
639	9/27/1923	8/03/1974	1776	206.8	R, US	Indian Canyon	(17,7)
		2/23/1991	1776	206.8	R, US	Indian Canyon	
645	9/28/1923	8/25/1972	721	208.9	L, AC	Granite Park	(17,7)
		11/01/1983	721	208.9	L, AC	Granite Park	
		8/26/1984	721	208.9	L, AC	Granite Park	
646	9/28/1923	8/25/1972	721	208.9	L, AC	Granite Park	(17,7)
		11/01/1983	721	208.9	L, AC	Granite Park	
		8/26/1984	721	208.9	L, AC	Granite Park	
647	9/29/1923	10/24/1991	2243a	213.0	R, US	Pumpkin Spring	(5,17,7)
648	9/29/1923	10/24/1991	2243b	213.0	R, DS	Pumpkin Springs	(17,7)
650	9/30/1923	3/13/1993	701	215.5	L, US	Three Springs Canyon	(17,7)
651	9/30/1923	10/24/1991	2371	215.5	L, UC	Three Springs Canyon	(7,15)

Appendix 5. List of photographic views of the Colorado River between Glen Canyon Dam and Lake Mead taken by Eugene C. LaRue between 1921 and 1923—Continued

LaRue Number	Date of Original	Date of Repeat	Stake Number	River Mile	Side, direction	Location	Subject(s)
652	9/30/1923	3/13/1993	702	217.3	L, US	217 -Mile Rapid	(17,7,5)
653	9/30/1923	7/04/1972	703	217.5	L, DS	217-Mile Rapid	(5,17,14,7)
654	10/01/1923	2/28/1992	2101	220.6	R, DS	220-Mile Canyon	(7,17,6)
657.5	10/01/1923	2/28/1992	2101	220.6	R, DS	220-Mile Canyon	(7,17,6)
655	10/01/1923	2/28/1992	2705	220.3	L, US	220-Mile Canyon	(7,6)
656	10/01/1923	2/28/1992	2550	220.3	R, UC	220-Mile Canyon	(7,6)
657	10/01/1923	2/28/1992	2102	220.6	R, DS	220-Mile Canyon	(17,7,6)
658	10/01/1923	2/28/1992	2551	220.3	R, DS	220-Mile Canyon	(5,14,17,7,15)
659	10/01/1923	10/24/1991	2372	220.1	R, US	220-Mile Canyon	(17,7)
660	10/01/1923	8/03/1974	1101	222.3	L, DS	Obscure location	(17,7)
		11/02/1983	1101	222.3	L, DS	Obscure location	
		10/25/1991	1101	222.3	L, DS	Obscure location	
661.5	10/01/1923	10/25/1991	2373	223.2	R, DS	Obscure location	(17,7)
662	10/02/1923	10/25/1991	2373	223.2	R, DS	Obscure location	(5,17,14,7)
664	10/01/1923	8/25/1972	722	223.3	L, DS	Obscure location	(17,7)
		11/02/1983	722	223.3	L, DS	Obscure location	
665	10/02/1923	9/29/1976	804	224.5	L, DS	Obscure location	(17,7)
		11/02/1983	804	224.5	L, DS	Obscure location	
		8/17/1991	804	224.5	L, DS	Obscure location	
665.5	10/02/1923	10/25/1991	804	224.5	L, DS	Obscure location	(17,7)
675	9/22/1923	9/29/1976	805	225.5	L, US	Diamond Creek	(5,17,15)
		11/02/1983	805	225.5	L, US	Diamond Creek	
		3/14/1993	805	225.7	L, US	Diamond Creek	
677	10/06/1923	10/12/1993	2671	225.7	UC	Diamond Creek	(6,7)
678	10/06/1923	10/12/1993	2670	225.7	UC	Diamond Creek	(6,7)
684	10/06/1923	10/11/1993	2668	225.7	L, DS	Diamond Creek	(17,7)
685	10/06/1923	10/11/1993	2669	225.7	L, DS	Diamond Creek	(17,7,2)
686	10/07/1923	2/29/1992	2103	226.3	R, US	Below Diamond Creek Rapid	(17,7,14,6,4)
		3/14/1993	2103	226.3	R, US	Below Diamond Creek Rapid	
690	10/07/1923	8/26/1972	724	229.0	R, DS	Above Travertine Canyon	(17,7,2)
693	10/07/1923	2/29/1992	2554	229.0	L, US	Travertine Canyon	(7,4,6)
701	10/08/1923	3/01/1992	2620	231.3	R, DS	Obscure location	(5,17,7)
747	10/13/1923	8/26/1972	725	252.1	L, AC	Maxon Canyon	(15,18)

[1]Archaeology, the view contained an archaeological site.

[2]Boats, one or more boats of the USGS-Birdseye expedition appear in the view.

[3]Cryptobiotic soils, the view contains a significant amount of cryptobiotic soils.

[4]Debris bar, a debris bar in the Colorado River appears in the view.

[5]Debris fan, a debris fan appears in the view, but not all views with debris fans are listed.

[6]Debris flow, a debris flow has occurred during the last century in the view.

[7]Desert, the view contained desert vegetation.

[8]Driftwood, the view contains driftwood at or near the highest flood stage of the Colorado River during the last century.

9Eolian sand, the view contains eolian sand.

[10]Grazing, desert vegetation in the view was grazed by domestic livestock (at or upstream of Lees Ferry), heavily grazed by deer, or heavily grazed by burros.

[11]New desert, the view contains significant amounts of desert vegetation that has invaded the new high-water zone.

[12]Old high-water line, the view contained vegetation of the old high-water zone, but not all views could be interpreted for change.

[13]People, member(s) of the USGS-Birdseye expedition appears in the view.

[14]Rapid, the view contains a rapid.

[15]Riparian, the view contained riparian vegetation that could be interpreted for change.

[16]Rockfall, a rockfall has occurred in the view during the last century.

[17]Sand bars, the view contains sand bars.

[18]Lake, matched views show Lake Mead.

Appendix 6. List of the photographic views taken by other photographers of the Colorado River corridor in Grand Canyon which were replicated in this study

[Photographs were obtained from various sources. Photographer, is the last name of the photographer of the original view (if known). New, indicates a new camera station was established by personnel of the U.S. Geological Survey to monitor some aspect of the river corridor. Number, refers to the large number on album prints that were assigned by the original photographer or photographic archive. Date of original, was obtained from either captions in a photographic album, diaries of river trips, or written accounts. Date of repeat, is exactly known. When more than one replicate was made, the first three columns and the last column appear blank in the lines referring to the replicate(s). Stake number, is a number assigned for permanent storage of replicate negatives in the repeat photography collection at the Desert Laboratory, University of Arizona, Tucson. Letters following a number indicate a swing of two or more views; not all swings were assigned stake numbers with letters, however. River mile, was estimated to the nearest tenth of a mile using the 1990 revision of a popular river guide (Stevens, 1990). Side, direction, (R), and (L), refers to the side of the channel when facing downstream of the camera station and the relative direction of the view. (US), upstream; (DS), downstream; (MS), midstream; (AC), across the Colorado River, (UC), up a side canyon; (DC), down a side canyon. Location, is the name of a geographical feature at or near the camera station. Wherever possible, names were obtained from 7.5-minute quadrangle maps, but some names are generally recognized and used in a popular river guide (Stevens, 1990). Subject(s), designated by footnotes, refer to the type of information that was interpreted from the view. (---), view contained little of interest in terms of geomorphology or biotic habitat; (n.d.), no data; (n.a.), not applicable; (n.m.), photograph was analyzed, but not matched; (?), the exact date of the photograph is uncertain]

Photographer	Number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
new	750	6/10/1975	6/10/1975	750	-4.0	L,DS	Obscure location	(15,17)
			10/30/1992	750	-4.0	L, DS	Obscure location	
Phillips	14	9/14/1976	10/30/1992	2641	-4.0	L, US	Obscure location	(7,15,4)
new	755y	6/11/1975	6/11/1975	755y	-3.0	L, US	Obscure location	(7,15)
			12/20/1989	755y	-3.0	L, US	Obscure location	
Wheeler	68	1872	6/11/1975	756	-3.0	L, US	Obscure location	(15)
Wheeler	161	1872	10/30/1992	2724	-1.5	L, US	Obscure location	(7,10,15)
Wheeler	221	1872	10/30/1992	2722	-1.5	L, US	Obscure location	(7,10,15)
Freeman	308	7/20/1923	8/22/1972	710	-0.2	L, DS	Lees Ferry	(7,15)
Wheeler	70	1872	8/22/1972	706	-0.1	L, AC	Lees Ferry	(15)
Ransome	1359	n.d.	8/22/1972	707a	0.0	L, DS	Lees Ferry	(5,14,15)
Gregory	215	6/05/1915	8/22/1972	708a	0.0	L, AC	Lees Ferry	(15)
Gregory	286	6/06/1915	8/22/1972	708b	0.0	R, AC	Lees Ferry	(15)
Gregory	287	6/06/1915	8/22/1972	709	0.0	L, DS	Lees Ferry	(15,17)
Wheeler	267	1872	5/25/1992	2254a	0.0	R, UC	Paria River	(7)
Wheeler	265	1872	5/25/1992	2254b	0.0	R, UC	Paria River	(7)
Wheeler	353	1872	5/25/1992	2254c	0.0	R, UC	Paria River	(7)
Wheeler	280	1872	5/25/1992	2254d	0.0	R, DC	Paria River	(7)
Wheeler	273	1872	5/25/1992	2255a	0.0	R, UC	Paria River	(7)
Wheeler	277	1872	5/25/1992	2255b	0.0	R, UC	Paria River	(7)
Wheeler	589	1872	5/25/1992	2255c	0.0	R, DC	Paria River	(7)
Ransome	1360	n.d.	8/22/1972	707b	0.1	L, AC	Lees Ferry	(15)
new	707c	8/22/1972	8/22/1972	707c	0.1	L, US	Lees Ferry	(15)
new	707d	8/22/1972	8/22/1972	707d	0.1	L, US	Lees Ferry	(15)
Stuart	2679	10/?/1939	4/19/1991	1781	0.2	R, DS	Paria River	(15,17)
Wheeler	339	1872	6/27/1972	716	0.8	R, AC	Paria River	(15)
James	P44010	12/01/1897	2/24/1994	2801	1.2	L, US	Below Paria Riffle	(6,7,13,14,17)
James	P44008	12/01/1897	2/24/1994	2802	1.3	L, US	Below Paria Riffle	(7,17)
James	P44002	12/01/1897	2/24/1994	2800	1.3	L, DS	Below Paria Riffle	(4,7,17)

Appendix 6. List of the photographic views taken by other photographers of the Colorado River corridor in Grand Canyon that were replicated in this study—Continued

Photo-grapher	Number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
James	P43993	12/01/1897	2/24/1994	2752	2.0	L, US	Near Cathedral Wash	(2,13,17)
James	P44000	12/01/1897	2/24/1994	2753	4.0	L, US	4-Mile Wash	(5,17)
Leding	2354	10/21/1952	8/21/1972	704	4.3	US	On Navajo Bridge	(15,17)
			6/11/1975	704	4.3	US	On Navajo Bridge	
James	P43994	12/01/1897	2/24/1994	2754	4.4	R, US	Below Navajo Bridge	(17)
Wheeler	II-12	1872	4/19/1991	2011	4.5	R, US	Marble Canyon	(15,17)
James	P43995	12/01/1897	2/24/1994	2755	5.0	R, US	Below Navajo Bridge	(17
Freeman	16	7/22/1923	12/20/1989	1397	7.8	R, AC	Badger Creek Rapid	(5,14,15,17)
			10/02/1991	1397	7.8	R, AC	Badger Creek Rapid	
James	P9812	12/01/1897	10/07/1991	2353	8.0	R, US	Badger Creek Rapid	(5,14,15,17)
James	P43990	12/01/1897	2/21/1995	3086	8.0	L, AC	Badger Creek Rapid	(5,6,14,15,17)
Cogswell	768	10/28/1909	10/05/1991	2351	8.0	L, US	Badger Creek Rapid	(5,14,15,17)
Kolb	263-3423	11/08/1911	1/18/1990	1404	8.0	L, US	Badger Creek Rapid	(5,14)
Tadje	n.a.	12/15/1914	10/07/1991	2354	8.0	R, US	Badger Creek Rapid	(5,14,15,17)
Eddy	59	7/18/1927	2/25/1994	2757	8.0	R, US	Badger Creek Rapid	(13,14)
Eddy	277.8.9	12/04/1927	1/18/1990	1405	8.0	L, AC	Badger Creek Rapid	(5,14,15,17)
Fahrni	3-116	3/16/1934	2/21/1995	3087	8.0	l, AC	Badger Creek Rapid	(2,14,15)
Clover	2:13:02	7/15/1938	2/22/1993	2727	8.0	L, AC	Badger Creek Rapid	(5,14,15,17)
Heald	3:06:12	7/15/1941	2/21/1993	2726	8.0	L, US	Badger Creek Rapid	(14,15,17)
Wilson	4:06:12	7/15/1942	2/21/1993	2725	8.0	L, US	Badger Creek Rapid	(14,15,17)
Belknap	n.d.	7/11/1952	4/21/1991	2016	8.0	L, AC	Badger Creek Rapid	(5,14,15,17)
			10/04/1991	2016	8.0	L, AC	Badger Creek Rapid	
Belknap	n.d.	7/12/1952	4/21/1991	2017	8.0	L, DS	Badger Creek Rapid	(5,14,15,17)
			10/04/1991	2017	8.0	L, DS	Badger Creek Rapid	
Belknap	n.d.	7/12/1952	10/04/1991	2048	8.0	L, DS	Badger Creek Rapid	(5,17)
NPS	2333	9/21/1952	10/04/1991	2059	8.0	L, DS	Badger Creek Rapid	(5,14,15,17)
Nichols	n.d.	1952	2/21/1995	2938	8.0	L, DS	Badger Creek Rapid	(5,6,14,15,17)
Marston	559	9/13/1955	4/21/1991	2012	8.0	R, US	Badger Creek Rapid	(5,14,15,17)
Nichols	n.d.	1956	10/04/1991	2060	8.0	L, DS	Badger Creek Rapid	(5,14,15,17)
Rowlands	n.d.	6/19/1956	10/04/1991	2062	8.0	L, AC	Badger Creek Rapid	(5,14,15,17)
Atherton	103	5/31/1956	10/04/1991	2064	8.0	L, AC	Badger Creek Rapid	(5,14,15,17)
Marston	598	8/28/1959	10/06/1991	2352	8.0	L, AC	Badger Creek Rapid	(5,14,15,17)
Marston	8.28.12	9/13/1959	8/03/1991	1787	8.0	L, AC	Badger Creek Rapid	(5,14,15,17)
Marston	599.8.11	9/26/1959	8/03/1991	1788	8.0	L, DS	Badger Creek Rapid	(5,14,15,17)
Marston	566.8.7	6/19/1959	4/21/1991	2013	8.0	L, AC	Badger Creek Rapid	(5,14,15,17)
Marston	8.28.22	8/28/1959	4/21/1991	2014	8.0	L, DS	Badger Creek Rapid	(5,14,15,17)
Marston	586.8.8	6/02/1959	10/04/1991	2015	8.0	L, DS	Badger Creek Rapid	(5,14,15,17)
Reilly	56-02	6/24/1962	10/04/1991	2063	8.0	L, AC	Badger Creek Rapid	(5,14,15,17)
Reilly	L66-15	6/17/1963	10/04/1991	2061a	8.0	L, DS	Badger Creek Rapid	(5,14,15,17)
Reilly	L78-01	6/17/1963	10/04/1991	2061b	8.0	L, AC	Badger Creek Rapid	(5,14,15,17)
Nichols	n.d.	8/?/1964	9/5/1994	2862	8.0	L, DS	Badger Creek Rapid	(5,6,14,15,17)
			2/21/1995	2862	8.0	L, DS	Badger Creek Rapid	

Appendix 6. List of the photographic views taken by other photographers of the Colorado River corridor in Grand Canyon that were replicated in this study—Continued

Photo-grapher	Number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
Davis	423A	1967	12/31/1991	2070	8.0	R, US	Badger Creek Rapid	(5,14)
Nichols	n.d.	10/?/1968	9/5/1994	2862	8.0	L, DS	Badger Creek Rapid	(5,6,14,15,17)
Weeden	I-5	1973	5/01/1985	2018a	8.0	L, DS	Badger Creek Rapid	(15,17)
			8/03/1991	2018a	8.0	L, DS	Badger Creek Rapid	
Weeden	I-4	1973	5/01/1985	2018b	8.0	L, US	Badger Creek Rapid	(15,17)
			8/03/1991	2018b	8.0	L, US	Badger Creek Rapid	
Weeden	I-7	1973	8/03/1991	1786a	8.0	R, US	Badger Creek Rapid	(14,15,17)
Weeden	I-8	1973	8/03/1991	1786b	8.0	R, AC	Badger Creek Rapid	(14,15,17)
Howard	785-6	1974	9/05/1991	2355	8.0	L, AC	Badger Creek Rapid	(15,17)
Howard	786	1975	10/07/1991	2357	8.0	R, AC	Badger Creek Rapid	(17)
Howard	785-9	1975	9/06/1991	2356	8.0	L, US	Badger Creek Rapid	(5,15,17)
Blaustein	10	pre-1977	10/04/1991	2065	8.0	L, DS	Badger Creek Rapid	(5,14,15,17)
Marston	477.8.1	7/12/1947	8/03/1991	2019	8.1	L, US	Badger Creek Rapid	(5,17)
Jones	8	1953	2/22/1995	2939	10.0	MS, US	10-Mile Rock	(15,17)
Wheeler	7	1872	12/21/1989	1398	11.0	R, DS	Soap Creek Rapid	(5,14,15)
Wheeler	II-13	1872	4/20/1991	2011	11.0	R, DS	Soap Creek Rapid	(5,14,15)
Cogswell	772	10/29/1909	1/31/1991	1555	11.2	L, AC	Soap Creek Rapid	(5,14)
Cogswell	771	10/29/1909	2/22/1995	2942	11.2	L, DS	Soap Creek Rapid	(5,14,15,17)
Kolb	568-1033	11/08/1911	2/22/1993	1411	11.0	R, DS	Soap Creek Rapid	(5,7,15,17)
Kolb	568-3053	8/3/1923	1/18/1990	1408	11.2	R, DS	Soap Creek Rapid	(6,14)
Kolb	568-3244	8/3/1923	1/18/1990	1409	11.2	R, AC	Soap Creek Rapid	(6,14)
Kolb	n.d.	8/3/1923	1/18/1990	1410	11.2	R, AC	Soap Creek Rapid	(6,14)
Frost	n.d.	1952	2/22/1995	2940	11.2	R, DS	Soap Creek Rapid	(2,4,13,15)
Litton	n.d.	1972	2/22/1995	2941	11.2	R, US	Soap Creek Rapid	(2,13,14)
Kolb	568-887	11/08/1911	2/22/1993	2571	11.3	R, US	Soap Creek Rapid	(14,17)
Heald	3:02:09	7/15/1941	2/22/1993	2588	11.3	R, US	Soap Creek Rapid	(5,14,15)
Wilson	4:09:11	7/15/1942	2/22/1993	2589	11.3	R, US	Soap Creek Rapid	(14,15)
Marston	12.4	6/09/1958	2/22/1993	2572	12.1	L, US	Salt Water Wash	(5,7,14,15)
Marston	12.5	6/09/1958	2/22/1993	2590	12.1	L, DS	Salt Water Wash	(5,7,15,17)
new	3062	2/01/1991	2/22/1993	3062	18.0	R, US	18-Mile Wash	(5,15,17)
			2/22/1995	3062	18.0	R, US	18-Mile Wash	
Schmidt	2001	1985	2/22/1993	2001	18.0	L, AC	18-Mile Wash	(5,14,17)
			2/25/1994	2001	18.0	L, AC	18-Mile Wash	
			2/22/1995	2001	18.0	L, AC	18-Mile Wash	
new	1704	2/01/1991	2/22/1993	1704	18.0	L, DS	18-Mile Wash	(5,14,15)
			2/22/1995	1704	18.0	L, DS	18-Mile Wash	
new	3062	10/18/1987	2/25/1994	3062	18.0	R, US	18-Mile Wash	(5)
			2/22/1995	3062	18.0	R, US	18-Mile Wash	
new	3061	10/18/1987	2/25/1994	3061	18.0	R, US	18-Mile Wash	(5)
			2/22/1995	3061	18.0	R, US	18-Mile Wash	
Weeden	I-13	1973	2/22/1993	2728	18.1	L, AC	Below 18-Mile Rapid	(14,17)
Frost	n.d.	1953	2/22/1995	3089	20.5	R, DS	North Canyon Rapid	(5,13,14,17)

Appendix 6. List of the photographic views taken by other photographers of the Colorado River corridor in Grand Canyon that were replicated in this study—Continued

Photo-grapher	Number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
Sharp	n.d.	10/?/1937	8/03/1991	2020	20.6	R, AC	North Canyon Rapid	(2,13,14)
Kolb	629	11/13/1911	1/20/1990	1416	25.3	R, AC	Cave Springs Rapid	(2,5,13,14)
Hillers	445	8/20/1872	9/04/1968	673	28.3	L, US	Shinumo Wash	(2,5,15)
Hillers	445	8/20/1872	6/28/1972	673	28.3	L, US	Shinumo Wash	
			8/23/1972	673	28.3	L, US	Shinumo Wash	
Goldwater	CR 36	8/07/1940	2/23/1993	2730	31.6	R, UC	South Canyon	(5,15)
Fahrni	3-77	7/24/1934	2/23/1993	2731	31.6	R, US	South Canyon	(5,14,17)
Freeman	27	8/08/1923	2/26/1994	2806	31.8	MS, AC	Vasey's Paradise	(4,14)
Jones	10	1953	2/23/1995	3091	31.8	MS, AC	Vasey's Paradise	(15)
Kolb	n.d.	11/13/1911	2/23/1995	3092	32.8	L, DS	Redwall Cavern	(15,17)
Freeman	173	8/08/1923	6/28/1972	676	32.8	L, DS	Redwall Cavern	(2,13,17)
			3/17/1974	676	32.8	L, DS	Redwall Cavern	
			8/14/1984	676	32.8	L, DS	Redwall Cavern	
			9/10/1994	676	32.8	L, DS	Redwall Cavern	
Nichols	n.d.	7/?/1951	9/10/1994	2926	32.8	L, US	Redwall Cavern	(2,13,17)
Nichols	n.d.	7/?/1951	9/10/1994	2863	32.8	L, US	Redwall Cavern	(2,13,17)
Nichols	n.d.	7/?/1951	9/10/1994	2927	32.8	L, DS	Redwall Cavern	(2,13,17)
Hillers	850	8/21/1872	2/23/1995	3093	34.0	L, DS	Obscure location	(2,5,6,15,17)
Kolb	n.d.	11/13/1911	2/23/1995	3093	34.0	L, DS	Obscure location	(2,5,6,15,17)
Stephens	850	9/5/1968	2/23/1995	3093	34.0	L, DS	Obscure location	(2,5,6,15,17)
Freeman	32	8/09/1923	2/26/1994	2805	36.4	L, US	Below 36-Mile Rapid	(5,7,14)
Freeman	335	8/10/1923	1/21/1990	1421	43.4	L, DS	President Harding Rapid	(15,17)
new	8401-37	6/29/1972	10/19/1983	679	43.7	L, DS	Point Hansbrough	(5,15)
new	680	6/29/1972	10/07/1982	680	43.7	L, US	President Harding Rapid	(15,17)
Hillers	854	8/22/1872	9/06/1968	681	49.6	L, US	Below Triple Alcoves	(7,15,17)
			6/29/1972	681	49.6	L, US	Below Triple Alcoves	
			8/23/1972	681	49.6	L, US	Below Triple Alcoves	
			10/20/1983	681	49.6	L, US	Below Triple Alcoves	
			2/04/1991	681	49.6	L, US	Below Triple Alcoves	
			8/04/1991	681	49.6	L, US	Below Triple Alcoves	
			2/04/1991	681	49.6	L, US	Below Triple Alcoves	
			8/04/1991	681	49.6	L, US	Below Triple Alcoves	
Reilly	L04-12	7/15/1949	8/04/1991	2022	52.2	R, DS	Nankoweap Creek	(15,17)
Kolb	45	8/12/1923	6/29/1972	682	52.3	R, DS	Nankoweap Creek	(5,6,17)
			10/08/1982	682	52.3	R, DS	Nankoweap Creek	
			10/20/1983	682	52.3	R, DS	Nankoweap Creek	
Reilly	L14-01	6/23/1955	8/04/1991	2021	52.3	R, DS	Nankoweap Creek	(15,17)
Richardson	n.d.	7/08/1978	2/05/1991	1740	52.3	R, DS	Nankoweap Creek	(15,17)
new	1079	10/08/1982	8/13/1984	1079	52.5	R, AC	Nankoweap Creek	(5,14,15)
Kolb	45	8/12/1923	3/19/1974	2504	52.6	R, DS	Granaries	(4,7,17)
			10/10/1991	2504	52.6	R, DS	Granaries	
Nichols	n.d.	1957	9/11/1994	2928	59.7	L, DS	60-Mile Rapid	(5,14,15,17)

Appendix 6. List of the photographic views taken by other photographers of the Colorado River corridor in Grand Canyon that were replicated in this study—Continued

Photo-grapher	Number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
Nichols	n.d.	1957	9/11/1994	2929	59.7	L, AC	60-Mile Rapid	(5,14,15,17)
Sharp	n.d.	10/?/1937	1/05/1992	2078	59.9	R, US	Obscure location	(5,15,17)
Blaisdell	4278	7/13/1963	9/02/1973	729	61.3	L, US	Cape Solitude	(4,5,15,17)
			5/24/1992	729	61.3	L, US	Cape Solitude	
Blaisdell	4288	7/13/1963	9/02/1973	730	61.3	L, US	Cape Solitude	(4,5,15,17)
			5/24/1992	730	61.3	L, US	Cape Solitude	
Blaisdell	4283	7/13/1963	9/02/1973	731	61.3	L, DS	Cape Solitude	(5,15,17)
			5/24/1992	731	61.3	L, DS	Cape Solitude	
Hillers	766	8/22/1872	9/08/1968	683	61.4	L, US	Little Colorado	(15,17)
			6/29/1972	683	61.4	L, US	Little Colorado	
			10/10/1982	683	61.4	L, US	Little Colorado	
			10/21/1983	683	61.4	L, US	Little Colorado	
			8/17/1984	683	61.4	L, US	Little Colorado	
Hillers	894	8/22/1872	9/08/1968	683	61.4	L, US	Little Colorado	(7,17)
			6/29/1972	683	61.4	L, US	Little Colorado	
			10/10/1982	683	61.4	L, US	Little Colorado	
			10/21/1983	683	61.4	L, US	Little Colorado	
			8/17/1984	683	61.4	L, US	Little Colorado	
Hillers	885	8/22/1872	9/08/1968	685	61.4	L, US	Little Colorado	(2,15)
			6/29/1972	685	61.4	L, US	Little Colorado	
			8/23/1972	685	61.4	L, US	Little Colorado	
			10/10/1982	685	61.4	L, US	Little Colorado	
			10/21/1983	685	61.4	L, US	Little Colorado	
			9/12/1994	685	61.4	L, US	Little Colorado	
new	2022	8/05/1991	8/05/1991	2022	62.5	R, AC	US of Crash Canyon	(5,6,7,12,14)
			3/01/1994	2022	62.5	R, AC	US of Crash Canyon	
			2/23/1995	2022	62.5	R, AC	US of Crash Canyon	
new	2023	8/05/1991	8/05/1991	2023	62.6	L, DS	Crash Canyon	(5,17)
			2/23/1995	2023	62.6	L, DS	Crash Canyon	
new	2256	8/06/1991	3/01/1994	2256	62.6	R, AC	Crash Canyon	(5,6,17)
			2/23/1995	2256	62.6	R, AC	Crash Canyon	
Sharp	n.d.	10/?/1937	8/06/1991	2024	62.8	L, US	Below Crash Canyon	(5,15,17)
new	2025	8/06/1991	8/06/1991	2025	63.3	R, AC	Below Crash Canyon	(5,6,14,17)
			3/01/1994	2025	63.3	R, AC	Below Crash Canyon	
Hillers	863	8/25/1872	7/26/1974	1433	65.2	R, US	Lava Canyon Rapid	(15)
			1/23/1990	1433	65.2	R, US	Lava Canyon Rapid	
Hillers	858	8/25/1872	9/09/1968	1080	65.5	R, AC	Lava Canyon Rapid	(15,17)
			6/29/1972	1080	65.5	R, AC	Lava Canyon Rapid	
			10/11/1982	1080	65.5	R, AC	Lava Canyon Rapid	
			10/22/1983	1080	65.5	R, AC	Lava Canyon Rapid	
			1/23/1990	1080	65.5	R, AC	Lava Canyon Rapid	
Wilson	4:07:11	7/19/1942	2/25/1993	2734	65.5	L, AC	Lava Canyon Rapid	(5,17)

Appendix 6. List of the photographic views taken by other photographers of the Colorado River corridor in Grand Canyon that were replicated in this study—Continued

Photo-grapher	Number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
Reilly	L44-26	6/25/1959	8/06/1991	2026	65.5	R, DS	Lava Canyon Rapid	(14,17)
Sharp	n.d.	10/?/1937	8/07/1991	2358	65.5	L, US	Lava Canyon Rapid	(15,17)
new	1431	1990	1/26/1990	1431	65.5	L, AC	Lava Canyon Rapid	(14,15,17)
Heald	3:06:09	7/19/1941	2/25/1993	2733	65.6	L, US	Lava Canyon Rapid	(5,15,17)
Weeden	I-90	1973	8/06/1991	2344	65.6	R, AC	Lava Canyon Rapid	(5,14,15)
Weeden	I-91	1973	8/06/1991	2345	65.6	R, DS	Lava Canyon Rapid	(5,14,15)
Beer	n.d.	4/19/1995	9/12/1994		67.0	MS, AC	Comanche Creek	(15,17)
new	2672	9/24/1993	3/01/1994	2672	68.5	R, AC	Tanner Rapid	(5,6,14,15)
			2/25/1995	2672	68.5	R, AC	Tanner Rapid	(5,6,14,15)
new	2807	3/01/1994	2/25/1994	2807	68.5	R, DS	Tanner Rapid	(5,6,14)
new	2808	3/01/1994	2/25/1994	2808	68.5	R, DS	Tanner Rapid	(5,6,14)
new	2760x	3/01/1994	2/25/1994	2760x	68.5	L, DS	Tanner Rapid	(5,6,14)
Fahmi	3-117	1934	2/27/1995	3094	70.2	MS, DS	Below Basalt Creek	(15,17)
new	2673	9/24/1993	3/02/1994	2673	70.9	R, AC	Cardenas Creek	(5,6,14)
			2/27/1995	2673	70.9	R, AC	Cardenas Creek	
new	2027b	8/7/1991	3/02/1994	2027b	72.1	R, AC	Above Unkar Creek	(5,6,7,12)
			2/27/1995	2027b	72.1	R, AC	Above Unkar Creek	
new	2027a	8/7/1991	3/02/1994	2027a	72.1	R, UC	Above Unkar Creek	(6,7)
			2/27/1995	2027a	72.1	R, UC	Above Unkar Creek	
Cogswell	99B	11/01/1909	1/26/1990	1443	73.0	R, AC	Obscure location	(5)
Kolb	568-5136	8/16/1923	1/27/1990	1447	75.7	L, DS	Nevills Rapid	(5,14,17)
Kolb	568-5834	8/16/1923	1/27/1990	1451	76.5	L, DS	Hance Rapid	(5,14)
Freeman	36	8/16/1923	8/23/1972	715	76.5	L, DS	Hance Rapid	(15,17)
Freeman	332	8/16/1923	9/19/1976	800	76.5	L, DS	Hance Rapid	(15,17)
Sharp	n.d.	11/01/1937	1/06/1992	2079	76.7	L, AC	Hance Rapid	(5)
Kolb	568-3245	8/16/1923	1/27/1990	1452	76.8	L, DS	Hance Rapid	(15,17)
Kolb	4994	8/16/1923	1/27/1990	1450	76.8	L, AC	Hance Rapid	---
Kolb	5835	8/16/1923	1/27/1990	1449	76.8	L, US	Hance Rapid	(5,14)
Jones		1962	2/27/1995	3095	76.8	L, DS	Hance Rapid	(4,9,14,15,17)
Hillers	449	8/29/1872	9/11/1968	2535	78.6	R, US	Sockdolager Rapid	(14)
			3/20/1974	2535	78.6	R, US	Sockdolager Rapid	
			2/15/1992	2535	78.6	R, US	Sockdolager Rapid	
Sharp	n.d.	11/01/1937	2/15/1992	2568	78.7	R, DS	Sockdolager Rapid	(14,17)
Blaisdell	4250	6/19/1963	3/21/1974	1094	87.4	R, DS	Bright Angel Creek	(5,14,15,17)
			10/23/1983	1094	87.4	R, DS	Bright Angel Creek	
Leding	2245	6/28/1952	3/21/1974	1094	87.4	R, DS	Bright Angel Creek	
Leding	2349	10/?/52	6/19/1963	716	87.4	L, AC	Bright Angel Creek	(5,14,15)
			8/23/1972	716	87.4	L, AC	Bright Angel Creek	(5,14,15)
			10/12/1982	716	87.4	L, AC	Bright Angel Creek	(5,14,15)
			10/12/1983	716	87.4	L, AC	Bright Angel Creek	(5,14,15)
			8/19/1984	716	87.4	L, AC	Bright Angel Creek	(5,14,15)
			3/03/1994	716	87.4	L, AC	Bright Angel Creek	(5,14,15)

Appendix 6. List of the photographic views taken by other photographers of the Colorado River corridor in Grand Canyon that were replicated in this study—Continued

Photo-grapher	Number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
new	8402-36	10/23/1983	8/19/1984	716n	87.5	L, AC	Bright Angel Creek	(2,5,13,15)
			3/03/1994	716n	87.5	L, AC	Bright Angel Creek	
Nevills	589	7/22/1938	2/27/1993	2592	87.9	R, DS	Phantom Ranch	(5,15,17)
MacDougal	A1-41	2/?/1903	9/20/1976	801	88.9	R, DS	Obscure location	(5,15,17)
Cogswell	808	11/06/1909	2/27/1995	3096	90.3	L, US	Horn Creek Rapid	(14,17)
Cogswell	807	11/06/1909	2/27/1995	3097	90.3	L, DS	Horn Creek Rapid	(14)
Heald	3:02:19	7/23/1941	2/27/1993	3001	90.3	R, AC	Horn Creek Rapid	(5,14,17)
Wilson	4:13:16	7/23/1942	2/27/1993	3002	90.3	R, AC	Horn Creek Rapid	(4,14,17)
Reilly	R02-03	7/19/1950	2/01/1992	2538	93.5	L, AC	Monument Creek	(5,15)
Burg	n.d.	10/26/1938	8/10/1991	2346	93.5	L, US	Monument Creek	(5,14,15,17)
Hillers	871	9/01/1872	9/16/1968	1462	93.6	L, US	Granite Rapid	(2,5,14)
			1/30/1990	1462	93.6	L, US	Granite Rapid	
Hillers	872	9/01/1872	9/16/1968	1257	93.6	L, US	Granite Rapid	(5,14)
			3/27/1986	1257	93.6	L, US	Granite Rapid	
Cogswell	828	11/06/1909	2/27/1995	2943	93.5	L, US	Granite Rapid	(2,5,6,13,14)
Nichols	n.d.	1952	2/27/1995	2944	93.5	L, US	Granite Rapid	(2,5,6,14)
Butchart	1227	8/29/1962	2/27/1993	2646	93.6	L, DS	Granite Rapid	(5,14,17)
Butchart	1226	8/29/1962	2/27/1993	2647	93.6	L, US	Granite Rapid	(5,14,17)
Clover	2:14:07	7/23/1938	2/27/1993	2735	93.6	L, AC	Granite Rapid	(5,14,17)
Cogswell	1033	11/06/1909	3/04/1994	2811	95.0	L, US	Hermit Rapid	(14,5)
Cogswell	1034	11/06/1909	3/04/1994	2810	95.0	L, DS	Hermit Rapid	(14,5)
Cogswell	1036	11/06/1909	3/04/1994	2812	95.0	L, US	Hermit Rapid	(14)
Clover	2:14:08	7/23/1938	2/27/1993	2648	95.0	L, AC	Hermit Rapid	(5,14)
Jackson	n.d.	1902	2/28/1995	3098	96.7	L, DS	Boucher Rapid	(7,14)
Euler	n.d.	1967	3/06/1994	2813a	98.3	R, AC	Crystal Rapid	(1,3,7)
Aldridge	n.d.	2/06/1967	2/27/1993	2736	98.3	R, AC	Crystal Rapid	(5,7,14,15)
Aldridge	n.d.	2/06/1967	2/27/1993	2737	98.3	R, AC	Crystal Rapid	(5,14,15)
Reilly	L38-23	5/21/1958	8/10/1991	2347	98.3	R, UC	Crystal Creek	(7,15)
Butchart	2366	5/31/1966	2/01/1990	1466	98.3	R, DC	Crystal Creek	(5,7,14,15)
Butchart	2367	5/31/1966	4/03/1986	1268	98.3	R, DC	Crystal Creek	(5,7,14,15)
Litton	n.d.	1967	2/28/1995	2945a	98.3	R, US	Crystal Rapid	(2,5,7,8,13,17)
Litton	n.d.	1967	2/28/1995	2945b	98.3	R, US	Crystal Rapid	(2,5,7,8,13,17)
Litton	n.d.	1967	2/28/1995	2945c	98.3	R, US	Crystal Rapid	(2,5,7,8,13,17)
Weeden	II-43	1973	10/16/1991	2227	103.8	R, DS	104-Mile Rapid	(5,15,17)
Reilly	L69-37	5/07/1964	2/19/1992	2088	104.6	L, UC	Ruby Canyon	(7,15,17)
Reilly	L70-00	5/07/1964	2/19/1992	2607	106.0	L, AC	Serpentine Rapid	(5,14)
Carkhuff	A206	ca. 1901	2/28/1995	2947	107.2	L, DS	Above Bass Rapid	(5,14,17)
MNA	n.d.	1974	2/28/1995	2946	107.5	L, DS	Bass Canyon	(14,17)
James	n.d.	ca. 1900	3/07/1994	2903	107.7	L, DS	Bass Rapid	(7,14,17)
Euler	AZB:15:00.28	4/30/1975	3/07/1994	2904	107.7	L, US	Bass Rapid	(1,7,15)
James	n.d.	ca. 1900	3/07/1994	2904	107.8	R, US	Bass Rapid	(1,7,15
James	n.d.	ca. 1900	3/07/1994	2902	107.8	R, US	Bass Rapid	(5,7,14,17)

Appendix 6. List of the photographic views taken by other photographers of the Colorado River corridor in Grand Canyon that were replicated in this study—Continued

Photographer	Number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
Marston	576 108.11	6/15/1957	3/08/1994	2767	107.8	R, AC	Hotauta Canyon	(7)
Carkhuff	A32	ca. 1901	2/28/1995	2948	107.9	L, DS	Bass Rapid	(17)
James	n.d.	ca. 1900	3/07/1994	2905	108.0	R, US	Near Bass Camp	(5,7,14,17)
Clarkhuff	A58	1901	6/30/1972	688	108.0	L, AC	Shinumo Creek	(15,17)
			8/23/1972	688	108.0	L, AC	Shinumo Creek	
			9/22/1976	688	108.0	L, AC	Shinumo Creek	
			10/25/1983	688	108.0	L, AC	Shinumo Creek	
Marston	576 108.6	6/15/1957	3/07/1994	2766	108.0	R, US	Bass Camp	(7,14)
Maude	n.d.	ca. 1900	3/07/1994	2823	108.1	L, US	Bass Camp	(7)
James	P.44602	ca. 1900	3/07/1994	2765	108.3	R, DS	Bass Camp	(7,17)
Marston	576 108.11	6/15/1957	3/07/1994	2761	108.3	R, AC	Bass Camp	(1,7,14)
Euler	AZ B:15:1.25	7/?/1978	3/07/1994	2763	108.3	R, AC	Bass Camp	(1,7)
Euler	AZ B:15:1.34	9/?/1987	3/07/1994	2764	108.3	R, DS	Bass Camp	(1,7)
Balsam	AZ B:15:1.42	10/22/1988	3/07/1994	2762	108.3	R, AC	Bass Camp	(1,7)
Maude	n.d.	ca. 1900	3/07/1994	2822	108.4	L, DS	Bass Camp	(5,7,14,17)
James	P.44603	ca. 1900	3/08/1994	2824	108.4	R, US	Bass Camp	(17)
Euler	AZ B:15:1.1	6/?/1962	3/08/1994	2768a	108.4	R, US	Bass Camp	(1,7,15,17)
Euler	AZ B:15:1.16	7/14/1978	3/08/1994	2768b	108.4	R, US	Bass Camp	(1,7,15,17)
James	P.44060	ca. 1900	3/08/1994	2825	108.5	R, US	Shinumo Saddle	(7,17)
James	P.44063	ca. 1900	3/08/1994	2826	108.5	R, US	Shinumo Saddle	(7,17)
Clarkhuff	1	1901	3/08/1994	2827	108.5	R, US	Shinumo Saddle	(7,17)
Maude	n.d.	ca. 1900	3/07/1994	2819	108.6	L, AC	Shinumo Rapid	(7,5,14,15,17)
James	P.44828	ca. 1900	3/07/1994	2820	108.7	L, DS	Shinumo Rapid	(7,14,17)
James	n.d.	ca. 1900	3/07/1994	2906	108.7	R, US	Shinumo Rapid	(5,6,14,17)
James	n.d.	ca. 1900	3/07/1994	2821	108.8	L, DS	Shinumo Rapid	(7,14)
Cogswell	872	11/7/1909	9/14/1994	2866	112.2	L, DS	Waltenberg Rapid	(5,6,7,14)
Cogswell	873	11/7/1909	9/14/1994	2867	112.2	L, US	Waltenberg Rapid	(5,6,14,15)
Wilson	4:14:19	7/24/1942	3/01/1993	3003	112.2	L, DS	Waltenberg Rapid	(5,14)
Weeden	II-60	1973	10/17/1991	2231	112.2	R, DS	Waltenberg Rapid	(5,14,15,17)
Burg	n.d.	10/28/1938	3/01/1993	3004	112.3	L, US	Waltenberg Rapid	(5,14)
Hillers	875	9/04/1872	3/01/1993	2650	115.0	L, US	Obscure location	(7)
Weeden	II-72	1973	10/17/1991	2232	116.8	L, AC	Below Elves Chasm	(5,14,15,17)
Weeden	II-71	1973	10/17/1991	2233	117.0	L, AC	Below Elves Chasm	(5,14,15,17)
Weeden	II-112	1973	10/17/1993	2365	122.3	R, AC	122-Mile Canyon	(2,15,17)
new	n.d.	2/04/1990	2/04/1990	1487	122.8	L, US	Forster Canyon	(14,15,17)
new	n.d.	2/04/1990	2/04/1990	1488	122.8	L, DS	Forster Canyon	(5,15,17)
new	n.d.	2/04/1990	2/04/1990	1489	125.1	L, AC	Fossil Rapid	(5,15,17)
new	1490	2/05/1990	2/05/1990	1490	125.1	L, AC	Fossil Rapid	(5,14,15)
Hillers	879	9/5/1872	9/19/1968	2368	126.0	L, US	Obscure location	(5,15)
			7/31/1974	2368	126.0	L, US	Obscure location	
			9/15/1994	2368	126.0	L, US	Obscure location	
new	2094x	2/01/1992	3/02/1993	2094x	126.9	R, US	127-Mile Rapid	(5,6,14,17)

Appendix 6. List of the photographic views taken by other photographers of the Colorado River corridor in Grand Canyon that were replicated in this study—Continued

Photo-grapher	Number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
			3/09/1994	2094x	126.9	R, US	127-Mile Rapid	
new	2828	3/09/1994	3/1/1995	2828	127.3	R, AC	Obscure location	(5,6,14,17)
Beer	n.d.	4/28/1955	3/1/1995	2950	127.3	R, US	Obscure location	(5,6)
Beer	n.d.	4/28/1955	3/1/1995	2949	127.3	R, DS	Obscure location	(7,17)
new	2831	2/07/1990	3/09/1994	2831	127.6	R, UC	127.6 debris fan	(6,7)
			3/01/1995	2831	127.6	R, UC	127.6 debris fan	
new	2033	8/12/1991	3/02/1993	2033	127.6	L, DS	127.6 debris fan	(5,17)
			3/09/1994	2033	127.6	L, DS	127.6 debris fan	
			3/01/1995	2033	127.6	L, DS	127.6 debris fan	
new	1425	2/07/1990	3/02/1993	1425	127.6	L, AC	127.6 debris fan	(5,14,17)
			3/09/1994	1425	127.6	L, AC	127.6 debris fan	
			3/01/1995	1425	127.6	L, AC	127.6 debris fan	
Weeden	III-4	1973	10/19/1991	2335	127.6	L ,DS	127.6 debris fan	(5,15,17)
			3/10/1994	2335	127.6	L, DS	127.6 debris fan	
			3/01/1995	2335	127.6	L, DS	127.6 debris fan	
Weeden	III-3	1973	10/19/1991	2336	127.6	L, DS	127.6 debris fan	(5,15,17)
			3/10/1994	2336	127.6	L, DS	127.6 debris fan	
			3/01/1995	2336	127.6	L, DS	127.6 debris fan	
Crammond	n.d.	8/13/1991	3/10/1994	1792	127.6	L, US	127.6 debris fan	(5,6)
			3/01/1995	1792	127.6	L, US	127.6 debris fan	
Eddy	76	7/28/1927	9/25/1993	2624	129.0	L, AC	Specter Chasm	(6,14)
Clover	2:14:03	7/24/1938	3/02/1993	3005	130.5	R, US	Bedrock Rapid	(7)
Jones	2b	1954	3/01/1995	2951c	130.5	L, DS	Bedrock Rapid	(5)
Jones	n.d.	1954	3/01/1995	2951b	130.5	L, US	Bedrock Rapid	(7)
Jones	n.d.	1954	3/01/1995	2951a	130.5	L, US	Bedrock Rapid	(5,6,14,15,17)
Weeden	III-6	1973	10/19/1991	2519	131.1	R, US	Obscure location	(5,15,17)
Eddy	214	7/28/1927	2/07/1990	1496	131.9	R, US	Dubendorff Rapid	(2,13,14)
Hillers	876	9/06/1872	3/23/1968	1497	131.6	R, DS	Dubendorff Rapid	(5,7,14,15
			3/23/1974	1497	131.6	R, DS	Dubendorff Rapid	
			2/08/1990	1497	131.6	R, DS	Dubendorff Rapid	
			3/03/1993	1497	131.6	R, DS	Dubendorff Rapid	
Hillers	883	9/06/1872	9/20/1968	1498a	131.7	R, DS	Dubendorff Rapid	(5,7,14,15
			2/08/1990	1498a	131.7	R, DS	Dubendorff Rapid	
Hillers	892	9/06/1872	9/20/1968	1495	131.8	R, UC	Stone Creek	(15)
			2/07/1990	1495	131.8	R, UC	Stone Creek	
Hillers	891	9/06/1872	9/20/1968	1499	131.8	R, DC	Stone Creek	(15)
			2/08/1990	1499	131.8	R, DC	Stone Creek	
Reilly	L57-14	7/05/1962	8/13/1991	2035	131.9	R, UC	Stone Creek	(13,15,17)
Reilly	L16-05	6/28/1955	8/13/1991	2036	131.9	R, UC	Stone Creek	(15,17)
Goldwater	CR 150	8/15/1940	3/04/1993	2738	133.8	R, US	Tapeats Creek	(5,17)
Frost	n.d.	1952	3/01/1995	2676	133.9	R, DS	Tapeats Creek	(5,17)
Freeman	243	9/09/1923	10/28/1983	1095	134.0	R, DS	Tapeats Creek	(7,14,17)

Appendix 6. List of the photographic views taken by other photographers of the Colorado River corridor in Grand Canyon that were replicated in this study—Continued

Photo-grapher	Number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
			2/29/1992	1095	134.0	R, DS	Tapeats Creek	
Sharp	n.d.	11/?/1937	2/25/1992	2701	134.8	R, DS	Granite Narrows	(5,15,17)
Hillers	893	9/07/1872	9/22/1968	693	136.3	R, AC	Deer Creek Falls	(17)
			7/01/1972	693	136.3	R, AC	Deer Creek Falls	
			10/28/1983	693	136.3	R, AC	Deer Creek Falls	
			3/04/1993	693	136.3	R, AC	Deer Creek Falls	
Sharp	n.d.	11/?/1937	8/13/1991	2037	136.1	L, AC	Deer Creek Falls	(5,17)
Wilson	4:06:01	7/26/1942	3/04/1993	3006	136.3	R, UC	Deer Creek Falls	(5,17)
Beaman	399	1871	8/15/1991	1793	143.4	R, DS	Kanab Creek	(5,14,15)
Jones	7	1954	3/02/1995	2952	143.4	R, US	Kanab Creek	(7,17)
Hillers	529	9/10/1872	3/10/1994	2829	143.5	R, UC	Kanab Creek	(9,15)
Hillers	682	9/10/1872	3/02/1995	2956	143.4	R, UC	Kanab Creek	(6,16)
Hillers	692	9/10/1872	9/22/1968	695	143.6	R, US	Kanab Creek	(6,16)
			7/02/1972	695	143.6	R, US	Kanab Creek	
			3/25/1990	695	143.6	R, US	Kanab Creek	
			5/10/1964	2039	143.6	R, US	Kanab Creek	
			8/14/1991	2039	143.6	R, US	Kanab Creek	
Hillers	895	9/10/1872	10/01/1991	2098	143.6	R, US	Kanab Creek	(5,6,14)
			3/03/1993	2098	143.6	R, US	Kanab Creek	
Hillers	688	9/10/1872	7/02/1972	696	143.6	R, UC	Kanab Creek	(5,15
Hillers	529	9/10/1872	9/21/1985	1239	143.6	R, UC	Kanab Creek	(5,15)
Bell	225	1872	3/04/1993	2652	143.5	R, US	Kanab Creek	(5)
Bell	216	1872	3/04/1993	2653	143.5	R, DS	Kanab Creek	(5,14)
Bell	178	1872	3/04/1993	2654	143.5	R, UC	Kanab Creek	(5,9)
Bell	263	1872	3/02/1995	2953	143.4	R, UC	Kanab Creek	(7,16)
Bell	269	1872	3/02/1995	2954	143.4	R, DC	Kanab Creek	(7,16)
Bell	218	1872	3/02/1995	2955	143.4	R, DC	Kanab Creek	(16)
Bell	III-269	1872	8/14/1991	1792	143.6	R, UC	Kanab Creek	(15)
Bell	II-11	1872	3/24/1974	1096	143.6	R, DC	Kanab Creek	(5,15)
			10/29/1983	1096	143.6	R, DC	Kanab Creek	
			11/28/1990	1096	143.6	R, DC	Kanab Creek	
			8/15/1991	1096	143.6	R, DC	Kanab Creek	
Bell	II-5	1872	8/15/1991	1794	143.6	R, DS	Kanab Creek	(5,15)
Bell	V-5	1872	7/02/1972	694	143.6	R, DS	Kanab Creek	(5,15)
Wilson	4:08:21	7/26/1942	3/04/1993	2595	143.5	R, DS	Kanab Creek	(5.14)
Reilly	L70-24	5/10/1964	8/14/1991	2038	143.6	R, DC	Kanab Creek	(15)
Reilly	R42-7	7/06/1953	8/14/1991	2040	143.6	R, DC	Kanab Creek	(15)
Reilly	L70-19	5/10/1964	8/15/1991	2042	143.6	R, DC	Kanab Creek	(5,15,17)
Reilly	L70-17	5/10/1964	8/15/1991	2042b	143.6	R, DS	Kanab Creek	(5,15,17)
Cogswell	123A	11/09/1909	2/09/1990	1506	144.0	R, DS	Kanab Creek	(2,13,16)
Cogswell	123B	11/09/1909	2/09/1990	1505	144.0	R, US	Kanab Creek	(14,16)
Sharp	n.d.	11/?/1937	2/01/1992	2611	148.0	R, US	Matkatimiba Creek	(2,13,14,17)

Appendix 6. List of the photographic views taken by other photographers of the Colorado River corridor in Grand Canyon that were replicated in this study—Continued

Photo-grapher	Number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
Wittick	15501	6/?/1885	3/11/1994	2832	156.9	L, DS	Havasu Creek	(7,14)
Wittick	16099	6/?/1885	9/16/1994	2869	156.9	L, US	Havasu Creek	(5,7,14)
Marston	v. 80,166	7/25/1947	3/11/1994	2831	156.9	L, US	Havasu Creek	(7,14,17
Marshall	n.d.	1903	3/02/1995	1798	157.0	UC	Havasu Creek	(15)
Marshall	n.d.	1903	3/02/1995	1595	157.0	L, US	Havasu Creek	(5, 6)
Marshall	n.d.	1903	3/02/1995	2193	157.0	UC	Havasu Creek	(6,15, 16)
Kolb	3462/5815	12/30/1911	3/05/1993	2655	157.0	L, US	Havasu Creek	(5,7,14)
new	2675a	9/26/1993	3/11/1994	2675a	157.6	L, AC	First Chance Camp	(5,6,17)
			3/03/1995	2675a	157.6	L, AC	First Chance Camp	
new	2675b	9/26/1993	3/11/1994	2675b	157.6	L, AC	First Chance Camp	(5,6,17)
			3/03/1995	2675b	157.6	L, AC	First Chance Camp	
Kearsley	n.d.	1990	3/03/1995	1598	157.6	R, US	First Chance Camp	(5,6,17)
new	2676	9/27/1993	3/11/1994	2676	160.8	L, DS	Obscure location	(5,6,17)
			3/03/1995	2676	160.8	L, DS	Obscure location	
Kearsley	n.d.	1990	3/03/1995	1597	160.8	R, US	Obscure location	(5,6,14,17)
Fahrni	3-246	7/31/1934	3/05/1993	3009	164.5	R, UC	Tuckup Canyon	(7,16)
Fahrni	3-242	7/31/1934	3/05/1993	3008	164.5	R, UC	Tuckup Canyon	(7)
Fahrni	3-244	7/31/1934	3/05/1993	3007a	164.5	R, DS	Tuckup Canyon	(5,7,17)
Fahrni	3-243	7/31/1934	3/05/1993	3007b	164.5	R, US	Tuckup Canyon	(5,7,17)
Reilly	R01-7	7/24/1950	3/05/1993	2656	166.3	L, DS	National Canyon	(5,17)
Nichols	1	7/?/1957	9/17/1994	2931	171.4	L, DS	Mohawk Canyon	(5,15,17)
Weeden	III-107	5/27/1909	10/21/1991	1432	176.0	L, US	Red Slide	(15,17)
Freeman	346	9/18/1923	1974	1157	177.5	L, DS	Above Lava Falls	(7,15,17)
			8/25/1984	1157	177.5	L, DS	Above Lava Falls	
Hillers	431A	4/16/187	5/16/1995	2684	178.0	R, US	Toroweap Point	(5,15,17)
Hillers	434	4/16/1872	5/16/1995	2688	178.0	R, US	Toroweap Point	(5,15,17)
Hillers	66	4/16/1872	8/18/1992	966	178.0	R, US	Toroweap Point	(5,15)
Hillers	67	4/16/1872	8/18/1992	966	178.0	R, US	Toroweap Point	(5,15)
Eden	2089	9/?/1951	8/18/1992	966	178.0	R, US	Toroweap Point	
Eden	2068	9/?/1957	8/18/1992	966	178.0	R, US	Toroweap Point	
Dodge	8340	8/?/1959	8/18/1992	966	178.0	R, US	Toroweap Point	
Turner	966	6/10/1979	8/18/1992	966	178.0	R, US	Toroweap Point	
Bell	55	1872	5/16/1995	2975	178.0	R, US	Toroweap Point	(5,15,17)
Bell	284	1872	5/16/1995	2974	178.0	R, US	Toroweap Point	(5,15,17)
unknown	3862	1938	5/16/1995	2687	178.0	R, US	Toroweap Point	(5,15,17)
unknown	2357	unknown	5/16/1995	2686	178.0	R, US	Toroweap Point	(5,15,17)
Eden	2080	9/1951	5/16/1995	2685	178.0	R, US	Toroweap Point	(5,15,17)
Hillers	897	4/16/1872	5/15/1995	2683	178.0	R, DS	Toroweap Point	(4,5,7,15,17)
Hillers	905	4/16/1872	5/16/1995	2690	178.0	R, UC	Toroweap Point	(7)
Hillers	896	4/16/1872	5/16/1995	2689	178.0	R, AC	Toroweap Point	(5,6,7)
Hillers	62	4/16/1872	5/16/1995	967	178.0	R, DS	Toroweap Point	(5,6,14)
Hillers	620	4/19/1872	8/18/1992	967	178.0	R, DS	Toroweap Point	

Appendix 6. List of the photographic views taken by other photographers of the Colorado River corridor in Grand Canyon that were replicated in this study—Continued

Photo-grapher	Number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
Scoyen	6616	1929	8/18/1992	967	178.0	R, DS	Toroweap Point	
Fraser	307 GDCN 179.1	7/?/1930	8/18/1992	967	178.0	R, DS	Toroweap Point	
Litton	n.d.	7/?/1951	8/18/1992	967	178.0	R, DS	Toroweap Point	
Eden	2085	9/?/1951	8/18/1992	967	178.0	R, DS	Toroweap Point	
Eden	2087	9/?/1951	8/18/1992	967	178.0	R, DS	Toroweap Point	
Litton	n.d.	7/?/1952	8/18/1992	967	178.0	R, DS	Toroweap Point	
Reilly	L19-33	3/25/1956	8/18/1992	967	178.0	R, DS	Toroweap Point	
Reilly	L19-34	3/25/1956	8/18/1992	967	178.0	R, DS	Toroweap Point	
Reilly	L19-35	3/25/1956	8/18/1992	967	178.0	R, DS	Toroweap Point	
Reilly	G-164	4/16/1956	8/18/1992	967	178.0	R, DS	Toroweap Point	
Dodge	8346	8/21/1959	8/18/1992	967	178.0	R, DS	Toroweap Point	
Litton	n.d.	7/?/1951	5/15/1995	969	178.0	R, DS	Toroweap Point	(5,6,14,15,17)
Eden	2082	9/?/1951	5/15/1995	969	178.0	R, DS	Toroweap Point	
Leding	2359	10/22/1952	5/15/1995	969	178.0	R, DS	Toroweap Point	
Eden	2082	9/?/1951	5/15/1995	969	178.0	R, DS	Toroweap Point	
Hamilton	5605	10/?/1955	5/15/1995	969	178.0	R, DS	Toroweap Point	
Hamilton	8353	10/?/1955	5/15/1995	969	178.0	R, DS	Toroweap Point	
Reilly	L24-7	4/16/1956	5/15/1995	969	178.0	R, DS	Toroweap Point	
Reilly	G875	4/16/1956	5/15/1995	969	178.0	R, DS	Toroweap Point	
Marston	563 GDCN-179.8		3/25/1956	969	179.3	R, DS	Lava Falls Rapid	
Reilly	L40-8	6/1/1958	5/15/1995	969	178.0	R, DS	Toroweap Point	
Reilly	L40-10	6/1/1958	5/15/1995	969	178.0	R, DS	Toroweap Point	
Wieland	24	5/?/1963	5/15/1995	969	178.0	R, DS	Toroweap Point	
Hertzog	6525NA	5/19/1966	5/15/1995	969	178.0	R, DS	Toroweap Point	
Bell	243	1872	5/16/1995	2681	178.0	R, AC	Toroweap Point	(5,6,7)
Bell	235	1872	5/16/1995	2976	178.0	R, DS	Toroweap Point	(5,15,17)
Bell	241	1872	5/16/1995	2976	178.0	R, DS	Toroweap Point	(5,15,17)
Bell	44	1872	8/19/1992	2723a	178.0	R, DC	Toroweap Point	(7)
Bell	46	1872	8/19/1992	2723b	178.0	R, DC	Toroweap Point	(7)
Bell	45	1872	8/19/1992	2723c	178.0	R, DC	Toroweap Point	(7)
Litton	n.d.	1951	5/15/1995	2680	178.0	R, DC	Toroweap Point	(7)
Belknap	n.d.	8/?/1963	6/10/1979	968	178.0	R, AC	Vulcan's Anvil	(5,17)
new	2970	3/08/1995	3/08/1995	2970	179.0	R, DS	Lava Falls Rapid	(5,6,14)
Hillers	602	4/19/1872	3/11/1993	2613	179.3	R, US	Lava Falls Rapid	(5,6,14)
			2/26/1992	2613	179.3	R, US	Lava Falls Rapid	
			8/18/1992	2613	179.3	R, US	Lava Falls Rapid	
			3/13/1994	2613	179.3	R, US	Lava Falls Rapid	
Hillers	623	4/20/1872	3/11/1993	3055	179.3	R, AC	Lava Falls Rapid	(14)
Hillers	616	4/01/1872	3/08/1993	2598	179.3	R, US	Lava Falls Rapid	(5,14)
Hillers	597	4/16/1872	9/26/1968	2744	179.3	R, DS	Lava Falls Rapid	(5,14,15)

Appendix 6. List of the photographic views taken by other photographers of the Colorado River corridor in Grand Canyon that were replicated in this study—Continued

Photo-grapher	Number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
			3/09/1993	2744	179.3	R, DS	Lava Falls Rapid	
Hillers	905	4/16/1872	n.a.	n.m.	179.3	R, UC	Toroweap Point	(7)
Stanton	621	2/27/1890	2/20/1991	1510b	179.3	L, DS	Lava Falls Rapid	(5,6,14)
Cogswell	940	11/10/1909	2/11/1990	1511	179.3	L, US	Lava Falls Rapid	(5,6,14)
Cogswell	1161	11/11/1909	3/12/1994	2770	179.3	L, US	Lava Falls Rapid	(7)
Kolb	568-631	12/31/1911	3/11/1993	3052	179.5	R, US	Lava Falls Rapid	(5,6,14)
Kolb	568-5796	1/01/1912	3/11/1993	2662	179.4	R, US	Lava Falls Rapid	(5,6,14)
Kolb	568-632	12/31/1911	3/09/1993	2599	179.4	R, DS	Lava Falls Rapid	(5,6,14)
Kolb	568-633	12/31/1911	3/13/1994	2773	179.3	R, US	Lava Falls Rapid	(15,17)
Eddy	92	8/02/1927	2/11/1990	1512	179.3	L, AC	Lava Falls Rapid	(5,6,14)
Eddy	93	8/02/1927	3/13/1994	2771	179.3	L, US	Lava Falls Rapid	(5,6,14,15)
Weatherhead	172.8	8/02/1927	3/01/1993	2663	179.3	L, DS	Lava Falls Rapid	(14)
Fahrni	3-254	7/31/1934	3/09/1993	2658b	179.4	L, AC	Lava Falls Rapid	(5,6,14)
Fahrni	3-255	7/31/1934	3/09/1993	2658c	179.4	L, AC	Lava Falls Rapid	(5,6,14)
Fahrni	3-258	7/31/1934	3/09/1993	2658a	179.4	L, DS	Lava Falls Rapid	(5,6,14)
Fahrni	3-260	7/31/1934	3/08/1993	2743	179.4	L, US	Lava Falls Rapid	(5,6,14)
Sharp	n.d.	11/16/1937	8/16/1991	1795	179.3	L, US	Prospect Canyon	(7)
Sharp	n.d.	11/16/1937	8/16/1991	2045	179.3	L, AC	Lava Falls Rapid	(5,6,14)
Clover	3412:14:14	7/29/1938	3/14/1994	2838	179.3	L, US	Lava Falls Rapid	(7,14)
Goldwater	CR 24	8/17/1940	3/08/1993	2657	179.3	L, AC	Lava Falls Rapid	(5,6,14)
Goldwater	CR 57	8/17/1940	3/08/1993	2742	179.3	L, DS	Lava Falls Rapid	(5,6,14)
Goldwater	CR 34	8/17/1940	3/10/1993	2659	179.3	L, UC	Lava Falls Rapid	(5)
Heald	3:6:6	7/27/1941	7/26/1942	2741	179.4	L, DS	Lava Falls Rapid	(5,6,14)
			3/08/1993	2741	179.4	L, AC	Lava Falls Rapid	
Wilson	4:08:11	7/26/1942	3/10/1993	2660a	179.4	L, AC	Lava Falls Rapid	(5,6,14)
Wilson	4:06:08	7/26/1942	3/10/1993	2660b	179.4	L, AC	Lava Falls Rapid	(5,6,14)
Wilson	4:12:5	7/26/1942	3/13/1994	2834	179.3	L, AC	Lava Falls Rapid	(5,14)
Riffey	477 GDCN 179.444	7/27/1947	2/20/1991	1769	179.3	L, AC	Lava Falls Rapid	(5,6,14)
Marston	477 GDCN 179.2	7/27/1947	2/20/1991	1770	179.3	L, AC	Lava Falls Rapid	(5,6,14)
Marston	477 GDCN	7/27/1947	2/20/1991	1768	179.3	L, AC	Lava Falls Rapid	(5,6,14)
Nevills	5:12:01	7/27/1947	3/10/1993	2661	179.3	L, AC	Lava Falls Rapid	(5,6,14)
Anspach	497 GDCN 179.8	7/27/1949	2/20/1991	2004	179.3	L, AC	Lava Falls Rapid	(5,6,14)
Reilly	L6-35	7/27/1949	8/16/1991	2043	179.3	L, DS	Lava Falls Rapid	(5,6,14)
Belknap	48826	6/19/1950	3/13/1994	2772	179.3	L, DS	Lava Falls Rapid	(5,6,7,14,15)
Belknap	48841	6/19/1950	3/10/1993	803	179.3	R, AC	Lava Falls Rapid	(5,6,14)
			9/26/1976	803	179.3	R, AC	Lava Falls Rapid	
			3/25/1974	803	179.3	R, AC	Lava Falls Rapid	
			10/31/1983	803	179.3	R, AC	Lava Falls Rapid	
			8/24/1963	803	179.3	R, AC	Lava Falls Rapid	
Reilly	R01-11	7/25/1950	8/16/1991	2046	179.3	L, US	Lava Falls Rapid	(5,6,14)

Appendix 6. List of the photographic views taken by other photographers of the Colorado River corridor in Grand Canyon that were replicated in this study—Continued

Photo-grapher	Number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
Litton	n.d.	1951	3/05/1995	2959	179.3	R, DS	Lava Falls Rapid	(14)
Litton	n.d.	1951	3/05/1995	2960	179.3	R, US	Lava Falls Rapid	(5,6,14)
			3/06/1995	2960	179.3	R, US	Lava Falls Rapid	
Nichols	n.d.	1952	9/18/1994	2935	179.3	L, DS	Lava Falls Rapid	(5,6,14)
Nichols	n.d.	1952	3/04/1995	2957	179.3	L, DS	Lava Falls Rapid	(5,6,14)
			3/06/1995	2957	179.3	L, DS	Lava Falls Rapid	
			3/07/1995	2957	179.3	L, DS	Lava Falls Rapid	
			3/08/1995	2957	179.3	L, DS	Lava Falls Rapid	
			3/09/1995	2957	179.3	L, DS	Lava Falls Rapid	
Nichols	n.d.	1952	3/07/1995	2969	179.3	L, AC	Lava Falls Rapid	(2,5,6,13,14)
Litton	n.d.	1952	3/07/1995	2968	179.3	L, AC	Lava Falls Rapid	(2,5,6,13,14)
Nichols	n.d.	1953	9/18/1994	2933	179.3	L, UC	Lava Falls Rapid	(7)
Frost	n.d.	1953	3/08/1995	2971a	179.3	L, AC	Lava Falls Rapid	(14)
Frost	n.d.	1953	3/08/1995	2971b	179.3	L, AC	Lava Falls Rapid	(6,14)
Nichols	n.d.	1954	3/07/1995	2966	179.3	L, DS	Lava Falls Rapid	(5,15)
Beer	n.d.	5/1/1955	3/08/1995	2972	179.3	L, US	Lava Falls Rapid	(14)
Beer	n.d.	5/1/1955	9/18/1994	2934	179.3	L, US	Lava Falls Rapid	(5,6,14)
Nichols	n.d.	7/13/1957	9/18/1994	2932	179.3	L, DS	Lava Falls Rapid	(5,6,14)
Beckwith	II-17	7/13/1957	2/20/1991	1586	179.3	L, DS	Lava Falls Rapid	(5,6,14)
Staveley	n.d.	7/20/1958	2/20/1991	2002	179.3	L, DS	Lava Falls Rapid	(5,6,14)
Marston	606 GDCN 179.2.19	6/23/1960	2/20/1991	1585	179.3	L, DS	Lava Falls Rapid	(5,6,14)
Marston	48832	6/23/1960	2/20/1991	1587b	179.3	L, DS	Lava Falls Rapid	(5,6,14)
Marston	606 GDCN 179.18.10	6/23/1960	2/20/1991	1588	179.3	L, DS	Lava Falls Rapid	(5,6,14)
Marston	606 GCN 179.2.14	6/23/1960	2/20/1991	1587a	179.3	L, DS	Lava Falls Rapid	(5,6,14)
Jones	n.d.	1961	3/07/1995	2967	179.3	L, AC	Lava Falls Rapid	(5,6,7,13, 14)
Reilly	L58-3	7/10/1962	2/20/1991	2003	179.3	L, AC	Lava Falls Rapid	(5,6,14)
Reilly	L58-4	7/10/1962	3/13/1994	2834	179.3	L, DS	Lava Falls Rapid	(5,6,14)
Belknap	48858	8/24/1963	3/09/1993	2746	179.3	R, AC	Lava Falls Rapid	(5,6,14)
Belknap	48865	8/24/1963	3/09/1993	2746	179.3	R, AC	Lava Falls Rapid	(5,6,14)
n.d.	63-9-25	9/25/1963	2/21/1991	1589	179.3	R, DS	Lava Falls Rapid	(5,6,14)
	GDCN 179- 25		3/09/1993	1589	179.3	R, DS	Lava Falls Rapid	
n.d.	63-9-25 GDCN 179-28	9/25/1963	3/10/1993	2005	179.4	R, US	Lava Falls Rapid	(5,6,14)
Reilly	L70-32	5/12/1964	8/16/1991	2044	179.3	L, AC	Lava Falls Rapid	(5,6,14)
Visbak	16	2/21/1965	2/20/1991	1592	179.3	R, DS	Lava Falls Rapid	(5,6,14)
			3/12/1994	1592	179.3	R, DS	Lava Falls Rapid	
			3/06/1995	1592x	179.3	R, DS	Lava Falls Rapid	
			3/07/1995	1592x	179.3	R, DS	Lava Falls Rapid	
			3/08/1995	1592x	179.3	R, DS	Lava Falls Rapid	
Visbak	24	2/21/1965	3/09/1993	3050	179.4	R, US	Lava Falls Rapid	(5,6,14)

Appendix 6. List of the photographic views taken by other photographers of the Colorado River corridor in Grand Canyon that were replicated in this study—Continued

Photo-grapher	Number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
Harris	2	5/21/1965	3/10/1993	3010	179.3	L, DS	Lava Falls Rapid	(5,6,14)
Harris	3	5/21/1965	3/13/1994	2836	179.3	L, AC	Lava Falls Rapid	(5,14,15)
Harris	896	4/30/1967	3/08/1993	2739	179.3	L, AC	Lava Falls Rapid	(5,6,14)
Harris	4	7/?/1969	3/08/1993	2740b	179.3	L, AC	Lava Falls Rapid	(14)
Harris	1	7/?/1969	3/08/1993	2740a	179.3	L, AC	Lava Falls Rapid	(14)
Litton	n.d.	1972	3/08/1995	2977	179.3	R, US	Lava Falls Rapid	(2,5,6,13,14)
Litton	n.d.	ca. 1973	3/05/1995	2962	179.3	L, US	Lava Falls Rapid	(5,14,15)
			3/06/1995	2962	179.3	L, US	Lava Falls Rapid	
Litton	n.d.	ca. 1973	3/05/1995	2963	179.3	L, US	Lava Falls Rapid	(5,15)
			3/06/1995	2963	179.3	L, US	Lava Falls Rapid	
Brown	n.d.	1977	3/12/1994	2907	179.3	R, US	Lava Falls Rapid	(5,14)
Brown	n.d.	1977	3/14/1994	2837	179.3	R, US	Lava Falls Rapid	(5,14)
Belknap	48866	8/25/1963	9/26/1976	803	179.3	R, AC	Lava Falls Rapid	(5,6,14)
Turner	803	9/26/1976	10/31/1983	803	179.3	R, AC	Lava Falls Rapid	(5,6,14)
Visbak	n.d.	6/14/1954	3/5/1995	2961	179.3	R, DS	Lava Falls Rapid	(5,14,15)
new	2891	3/06/1995	3/06/1995	2891	179.3	R, AC	Lava Falls Rapid	(5,6,14)
new	2964a	3/06/1995	3/06/1995	2964a	179.3	L, UC	Lava Falls Rapid	(5,6,14)
new	2964b	3/06/1995	3/07/1995	2964b	179.3	L, DS	Lava Falls Rapid	(6)
new	2965	3/06/1995	3/06/1995	1965	179.3	L, UC	Lava Falls Rapid	(5,6,14)
new	2958	3/05/1995	3/06/1995	2958	179.3	R, DS	Lava Falls Rapid	(5)
Hillers	616	4/19/1872	3/08/1993	2598	179.4	R, US	Lava Falls Rapid	(14)
Kolb	88	9/18/1923	7/03/1972	698	179.5	L, DS	Below Lava Falls	(15)
new	2890	3/06/1995	3/06/1995	2890	179.6	R, US	Below Lava Falls	(5,6,14)
Brown	70k-cfs	6/21/1983	11/01/1983	1097a	198.6	R, US	Parashant Wash	(15)
Brown	28k-cfs	4/25/1983	11/01/1983	1097b	198.6	R, DS	Parashant Wash	(15)
Brown	70k-cfs	6/21/1983	11/01/1983	1098	198.6	R, DS	Parashant Wash	(5,15,17)
			8/26/1984	1098	198.6	R, DS	Parashant Wash	
MNA	PS-59	1974	8/17/1991	1797	204.4	R, DS	Spring Canyon	(7,15,17)
Sharp	n.d.	11/?/1937	3/12/1993	2747	205.5	L, US	205-Mile Rapid	(5,14,15)
Litton	n.d.	ca. 1973	3/09/1995	2678	205.4	R, DS	205-Mile Rapid	(2,5,7,13,14,15)
Brown	21/22	1983	11/01/1983	1099	208.9	L, DS	Granite Park	(4,15,17)
			8/26/1984	1099	208.9	L, DS	Granite Park	
MNA	PS-370	1974	1/11/1983	1100	208.9	L, US	Granite Park	(15,17)
Wilson	4:07:06	7/28/1942	3/13/1993	2748a	209.0	L, AC	Granite Park	(2,13,14)
Wilson	4:15:22	7/28/1942	3/13/1993	2748b	209.0	L, US	Granite Park	(14,17)
Cogswell	1211	11/11/1909	2/14/1990	1518	212.2	L, DS	Li'l Bastard Rapid	(5,15)
Cogswell	1228	11/12/1909	2/14/1990	1519	217.0	L, AC	217-Mile Rapid	(5,14)
Cogswell	1240	11/12/1909	9/20/1994	2936	222.5	MS, DS	Obscure location	(15,17)
Cogswell	1245	11/12/1909	3/10/1995	2679	223.5	L, DS	224-Mile Rapid	(5,14,15,17)
Wittick	15501	4/?/1883	3/20/1994	2784	225.1	L, US	Obscure location	(7)
Wittick	15502	4/?/1883	9/20/1994	2937	225.1	L, DS	Obscure location	(7)
Wittick	15495	4/?/1883	3/20/1994	2785	225.1	L, DS	Obscure location	(5,17)

Appendix 6. List of the photographic views taken by other photographers of the Colorado River corridor in Grand Canyon that were replicated in this study—Continued

Photo-grapher	Number	Date of original	Date of repeat	Stake number	River mile	Side, direction	Location	Subject(s)
Wittick	15466	4/?/1883	3/15/1994	2839	225.2	R, DS	Obscure location	(15)
Wittick	n.d.	4/?/1883	3/16/1994	2482	225.5	L, US	Diamond Creek	(15,17)
Darton	910	1902	8/25/1972	723a	225.5	L, DS	Diamond Creek	(2,15,17)
Darton	911	1902	8/25/1972	723b	225.5	L, US	Diamond Creek	(15,17)
Wittick	n.d.	4/?/1883	3/16/1994	2841	225.6	L, US	Diamond Creek	(15,17)
Wittick	n.d.	4/?/1883	3/17/1994	2779	225.7	UC	Diamond Creek	(7)
Wittick	n.d.	4/?/1883	3/17/1994	2780	225.7	UC	Diamond Creek	(6,7)
Wittick	n.d.	4/?/1883	3/17/1994	2781	225.7	UC	Diamond Creek	(6,15)
Wittick	15498	4/?/1883	3/21/1994	2786	225.7	UC	Peach Springs Wash	(6,7,13)
Wittick	15490	4/?/1883	3/20/1994	2782	225.7	L, AC	Diamond Creek	(7,13)
Wittick	J-10	4/?/1883	3/21/1994	2787	225.7	UC	Peach Springs Wash	(7)
Wittick	15445	4/?/1883	3/21/1994	2789	225.7	UC	Peach Springs Wash	(6,7,13)
Darton	909	1902	3/21/1994	2788	225.7	UC	Peach Springs Wash	(7)
James	P04940	ca. 1900	3/16/1994	2778	225.7	UC	Diamond Creek	(6)
Jackson	74712	ca. 1883	3/10/1995	2973	225.7	L, US	Diamond Creek	(5,6,14,15,17)
Wittick	15467	4/?/1883	3/16/1994	2776a	226.0	L, US	Diamond Creek Rapid	(5,6,7,15)
Wittick	15500	4/?/1883	3/20/1994	2783	226.0	L, DS	Diamond Creek Rapid	(4,5,6,14,15,17)
Wittick	n.d.	4/?/1883	3/16/1994	2776b	226.0	L, US	Diamond Creek Rapid	(5,6,14,15)
Wittick	n.d.	4/?/1883	3/16/1994	2776c	226.0	L, DS	Diamond Creek Rapid	(4,5,6,14,15,17)
Wittick	n.d.	4/?/1883	3/16/1994	2777	226.0	L, DS	Diamond Creek Rapid	(4,5,6,14,15,17)
Wittick	n.d.	4/?/1883	3/15/1994	2840	226.1	L, US, AC	Diamond Creek Rapid	(5,14,17)

[1]Archaeology, the view contained an archaeological site.

[2]Boats, one or more boats appear in the view.

[3]Cryptobiotic soils, the view contains a significant amount of cryptobiotic soils.

[4]Debris bar, a debris bar in the Colorado River appears in the view.

[5]Debris fan, a debris fan appears in the view, but not all views with debris fans are listed.

[6]Debris flow, a debris flow has occurred during the last century in the view.

[7]Desert, the view contained desert vegetation.

[8]Driftwood, the view contains driftwood at or near the highest flood stage of the Colorado River during the last century.

[9]Eolian sand, the view contains eolian sand.

[10]Grazing, desert vegetation in the view was grazed by domestic livestock (at or upstream of Lees Ferry), heavily grazed by deer, or heavily grazed by burros.

[11]New desert, the view contains significant amounts of desert vegetation that has invaded the new high-water zone.

[12]Old high-water line, the view contained vegetation of the old high-water zone, but not all views could be interpreted for change.

[13]People, member(s) of various river parties appear in the view.

[14]Rapid, the view contains a rapid.

[15]Riparian, the view contained riparian vegetation that could be interpreted for change.

[16]Rockfall, a rockfall has occurred in the view during the last century.
[17]Sand bars, the view contains sand bars.
[18]Lake, matched views show Lake Mead.

Appendix 7. List of radiocarbon dates determined from organic samples collected from tributaries in Grand Canyon

[Radiometric dates were obtained from analyses of samples of organic matter consisting mainly of twigs preserved within debris-flow mudcoats, larger pieces of wood (driftwood) deposited by debris flows and, less commonly, charcoal buried by debris flow sediments. Radiocarbon date, values are in years before present (yrs BP) except otherwise specified. Laboratory number, (GX) -- Geochron Laboratories; (A) -- University of Arizona laboratories; (AA) -- University of Arizona tandem mass accelerator laboratories. Calendric date, converted from radiocarbon date using a computer program developed by Stuiver and Reimer (1986). We report a range at one standard deviation. Post-1950 dates were converted using the post-bomb 14C relation (e.g., Ely and others, 1992)]

River mile	River side	Tributary name	Radio-carbon date	Laboratory number	Calendric date (AD)	Provenance
2.8	R	Cathedral Wash	[1]106.2±1.2	GX-18492	AD 1957 or 1989	wood in mudcoat
16.8	R	House Rock Canyon	[1]122.7±2.1	GX-19329	AD 1959 or 1982	driftwood
30.5	R	Unnamed canyon	[1]103.4±1.3	GX-18491	AD 1956 or 1989	wood in mudcoat
62.6	R	"Crash Canyon"	[1]118.4±1.4	GX-17584	AD 1958 or 1984	twigs in mudcoat
63.3	R	Unnamed canyon	5,410±175	GX-17583	BC 4458-4006	twigs in mudcoat
65.5	R	Lava Canyon	250±80	2A-4543	AD 1520-1955	driftwood
			625±65	2AA-1787	AD 1281-1405	wood in deposit
			1,460±60	2AA-1788	AD 540-644	wood in deposit
66.8	L	Espejo Creek	305±60	GX-17577	AD 1488-1652	twigs in mudcoat
			315±110	GX-17578	Ad 1440-1660	twigs in mudcoat
			340±60	GX-17579 Average =	AD 1450-1642 AD 1490-1642	twigs in mudcoat
			1,565±110	GX-17581	AD 360-636	charcoal in deposit
			2,410±125	GX-17580	BC 770-390	charcoal in deposit
72.1	R	Unnamed canyon	[1]130.6±1.3	GX-17586	AD 1959 or 1976	twigs in mudcoat
93.5	L	Monument Creek	170±90	2A-4542	AD 1647-1955	wood in deposit
96.7	L	Boucher Creek	375±75	GX-19924	AD 1436-1638	wood in boulder levee
			560±90	GX-19923	AD 1295-1432	wood in deposit
98.2	R	Crystal Creek	"modern"	2A-4541	AD 1679-1955	bark on buried tree
			130±50	2AA-1785	AD 1671-1955	organics in deposit
			180±70	2AA-1784	AD 1650-1955	wood in deposit
			355±70	2AA-1786	AD 1442-1641	wood in deposit
119.0	R	119-Mile Creek	420±80	GX-18357	AD 1421-1619	wood in mudcoat
			485±105	GX-18356 Average =	AD 1327-1479 AD 1418-1480	wood in mudcoat

Appendix 7. List of radiocarbon dates determined from organic samples collected from tributaries in Grand Canyon—Continued

River mile	River side	Tributary name	Radio-carbon date	Laboratory number	Calendric date (AD)	Provenance
			1,032±64	[3]GX-18350	AD 912-1027	twig in mudcoat
125.0	L	Fossil Canyon	240±100	GX-18352	AD 1516-1955	driftwood on deposit
			380±100	GX-18355	AD 1430-1640	wood in deposit
			395±80	GX-18354	AD 1430-1632	wood in deposit
			410±100	GX-18353	AD 1420-1635	wood in deposit
				Average =	AD 1437-1618	
			865±60	GX-18351	AD 1041-1255	wood in deposit
127.3	L	Unnamed canyon	2,685±150	GX-17587	BC 1010-664	packrat midden
			2,945±130	GX-17588	BC 1387-943	packrat midden
			3,050±130	GX-17589	BC 1488-1110	packrat midden
127.6	L	"127.6-Mile"	[1]109.2±1.4	GX-17582	AD 1957 or 1988	twigs in mudcoat
			[1]108.2±0.8	GX-17585	AD 1957 or 1988	twigs in mudcoat
139.9	L	140-Mile Canyon	255±100	GX-18349	AD 1490-1955	twigs in mudcoat
157.6	R	Unnamed tributary	[1]116.8±1.2	GX-19922	AD 1958 or 1993	wood in 1993 deposit
160.8	R	Unnamed tributary	[1]116.2±1.5	GX-19926	AD 1958 or 1993	wood in 1993 deposit
179.4	L	Prospect Canyon	365±90	GX-19320	AD 1436-1644	1955 deposit
			[1]153.8±1.5	GX-19321	AD 1963 or 1969	1963 driftwood
			[1]141.1±1.1	GX-19322	AD 1962 or 1974	1993 driftwood
			[1]127.7±1.3	GX-19323	AD 1959, 1961, or 1981	1963 driftwood
			190±95	GX-19324	AD 1640-1955	1955 driftwood
			635±80	GX-19325	AD 1279-1406	1955 driftwood
			460±75	GX-19326	AD 1410-1473	1940 driftwood
			485±90	GX-19925	AD 1330-1454	Surface F driftwood
208.6	R	209-Mile Canyon	285±60	GX-18035	AD 1513-1658	wood, age unknown

[1]Indicates a radiocarbon date of post-1950 and units of percent modern carbon (PMC).

[2]Radiocarbon dates previously reported in Webb and others (1989).

[3]AMS, Accelerator/mass spectrometer-derived dates.

Appendix 8. Characteristics of boulders transported by recent debris flows in tributaries of Marble and Grand Canyons

[Lithology of boulder, for descriptions of Grand Canyon stratigraphy, see Huntoon and others (1986). Boulder-axes lengths: a-axis, the longest dimension of the boulder; b-axis, the intermediate dimension of the boulder; and c-axis, the shortest dimension of the boulder. In most cases only the ten largest boulders transported during recent debris flows are included. Boulder volumes were determined by assigning an idealized geometric shape to each particle (i.e., rectangular solid, cube, right-cylindrical solid, sphere, ellipsoid, etc. Weight, determined by multiplying the calculated volume by an average density of 2.6 Mg/m3. Site, refers to specific locations within drainages or on debris fans that are referred to in the report's text. For purposes of calculating boulder volumes; a, b, and c equal axis lengths, and A, B, and C equal semi-axis lengths. (n.d.), indicates that no specific date could be established for the debris flow, however, the debris flow occurred between 1890 and 1965]

River mile	Side	Date of debris flow	Lithologic source of boulder	a-axis diameter (m)	b-axis diameter (m)	c-axis diameter (m)	Estimated volume (m^3)	Estimated weight (Mg)	Site
18.0	L	1987	Supai	1.9	0.9	0.9	[1]1.5	4.1	Fan
			Supai	1.2	1.2	0.7	[1]1.0	2.6	Fan
			Coconino	1.4	1.3	1.1	[1]2.0	5.2	Fan
			Coconino	1.8	1.3	1.1	[1]2.6	6.7	Fan
			Supai	2.1	2.0	0.3	[1]1.3	3.4	Fan
			Supai	1.8	1.7	0.5	[2]0.8	2.1	Fan
			Kaibab	1.0	0.9	0.7	[1]0.6	1.6	Fan
			Kaibab	1.1	0.9	0.8	[1]0.8	2.1	Fan
			Kaibab	1.3	0.8	0.6	[1]0.6	1.6	Fan
			Kaibab	1.3	0.7	0.6	[1]0.5	1.3	Fan
42.9	L	1983	Supai	2.4	2.2	1.9	1.1	26.0	Fan
			Supai	4.4	4.2	2.4	[2]22.0	57.0	Fan
			Supai	2.6	2.2	1.6	[1]9.2	24.0	Fan
			Supai	2.0	2.0	1.3	[1]5.2	13.0	Fan
			Supai	1.7	1.1	0.8	[1]1.5	3.9	Fan
			Supai	1.4	1.2	1.1	[1]1.8	4.7	Fan
			Muav	2.1	1.2	0.8	[1]2.0	5.2	Fan
42.9	L	1983	Supai	2.6	2.0	1.1	[2]2.9	7.5	Fan
			Supai	2.6	1.0	1.0	[1]2.6	6.8	Fan
			Supai	3.2	3.0	2.5	[1]24.0	62.0	Fan
43.2	L	1983	Redwall	4.2	3.2	2.1	[1]28.0	73.0	Fan
			Supai	2.6	2.6	0.8	[1]5.4	14.0	Fan
			Redwall	2.1	2.0	1.5	[1]6.3	16.0	Fan
			Redwall	2.3	1.6	1.2	[1]4.4	11.0	Fan
			Supai	2.7	1.5	1.3	[1]5.3	14.0	Fan
			Redwall	3.2	2.1	1.4	[1]9.4	24.0	Fan
			Redwall	2.2	1.7	1.2	[1]4.5	12.0	Fan
			Redwall	2.9	2.4	1.3	[1]9.0	23.0	Fan
			Redwall	3.5	2.2	1.6	[1]12.0	31.0	Fan
			Redwall	3.0	1.9	1.0	[1]5.7	15.0	Fan

Appendix 8. Characteristics of boulders transported by recent debris flows in tributaries of Marble and Grand Canyons—Continued

River mile	Side	Date of debris flow	Lithologic source of boulder	a-axis diameter (m)	b-axis diameter (m)	c-axis diameter (m)	Estimated volume (m^3)	Estimated weight (Mg)	Site
62.5	R	190.9	Redwall	6.1	5.6	4.4	[1]1.5	30.9	Fan
			Redwall	4.0	3.1	2.3	[1]28.0	73.0	Fan
			Redwall	4.0	2.3	2.2	1.2	52.0	River
			Redwall	3.8	3.3	1.3	[1]16.0	42.0	River
			Redwall	3.0	2.3	2.3	[4]12	31.0	Fan
			Muav	2.6	2.4	1.0	[1]6.2	16.0	Fan
			Supai	2.6	1.3	1.1	[1]3.7	9.6	Fan
			Redwall	3.3	2.1	2.1	[5]7.6	20.0	River
			Muav	2.2	2.1	0.9	[1]4.1	11.0	Fan
62.5	R	190.9	Muav	2.4	1.3	0.9	[1]2.8	7.3	Fan
62.6	R	190.9	Muav	5.0	4.9	1.8	[2]22.0	57.0	Fan
			Redwall	2.6	1.5	1.1	[1]4.3	11.0	Fan
			Redwall	4.1	2.7	1.6	[5]9.3	24.0	Fan
			Supai	1.9	1.5	0.2	[2]0.3	0.8	Fan
			Redwall	1.8	1.6	1.3	[1]3.7	9.6	Fan
			Redwall	1.5	1.4	1.3	[1]2.7	7.0	Fan
			Muav	2.4	1.4	0.9	[1]3.0	7.8	Fan
			Redwall	2.0	1.9	1.9	[4]5.7	15.0	Fan
68.5	L	1993	Redwall	1.9	1.7	1.1	[1]3.5	9.1	Fan
			Redwall	1.5	1.3	1.1	[1]2.1	5.5	Fan
			Redwall	2.0	1.2	0.8	[1]1.9	4.9	Fan
			Redwall	1.8	1.5	1.5	[1]4.0	10.0	Fan
			Supai	1.8	1.1	1.1	[1]2.2	5.7	Fan
			Tapeats	2.6	1.5	1.5	[1]5.8	15.0	Fan
			Redwall	2.2	1.6	1.5	[1]5.3	14.0	Fan
			Redwall	2.8	2.2	1.0	[1]6.2	16.0	Fan
			Redwall	2.5	1.6	1.6	[1]6.4	17.0	Fan
			Redwall	2.7	2.1	1.5	[1]8.5	22.0	Fan
0.7.9	L	1993	Redwall	0.8	0.8	0.8	[3]0.3	0.8	Fan
			Tapeats	1.6	1.1	1.1	[5]1.0	2.6	Fan
			Redwall	2.0	1.5	1.5	[4]3.5	9.1	Fan
0.7.9	L	1993	Redwall	1.5	1.2	1.1	[1]2.0	5.2	Fan
			Redwall	1.3	1.2	0.7	[1]1.1	2.9	Fan
			Redwall	1.5	0.9	0.8	[2]0.5	1.3	Fan
			Supai	2.3	1.9	0.5	[1]2.2	5.7	Fan
			Tapeats	1.2	0.9	0.8	[1]0.9	2.3	Fan
			Tapeats	0.9	0.8	0.9	[1]0.6	1.6	Fan
			Tapeats	0.8	0.7	0.6	[1]0.3	0.8	Fan

Appendix 8. Characteristics of boulders transported by recent debris flows in tributaries of Marble and Grand Canyons—Continued

River mile	Side	Date of debris flow	Lithologic source of boulder	a-axis diameter (m)	b-axis diameter (m)	c-axis diameter (m)	Estimated volume (m^3)	Estimated weight (Mg)	Site
71.2	R	1984	Tapeats	0.7	0.5	0.2	[1]0.1	0.2	Fan
			Tapeats	0.6	0.4	0.2	[1]0.1	0.1	Fan
			Tapeats	0.5	0.4	0.4	[1]0.1	0.2	Fan
			Tapeats	0.5	0.4	0.3	[1]0.1	0.2	Fan
			Tapeats	4.0	2.1	1.3	[1]11.0	29.0	Fan
			Tapeats	0.5	0.4	0.4	[1]0.1	0.2	Fan
			Tapeats	0.7	0.3	0.3	[1]0.1	0.2	Fan
			Tapeats	0.6	0.4	0.2	[1]0.1	0.1	Fan
			Tapeats	0.7	0.4	0.4	[1]0.1	0.3	Fan
			Tapeats	0.5	0.4	0.3	[1]0.1	0.2	Fan
72.1	R	1984	Dox	2.2	1.7	1.0	[1]3.7	9.6	Fan
			Dox	3.5	1.8	1.5	[1]9.5	25.0	Fan
			Dox	2.6	1.5	0.7	[1]2.7	7.0	Fan
			Dox	2.3	1.7	1.0	[1]3.9	10.0	Fan
			Dox	3.0	2.2	0.4	[1]2.6	6.8	Fan
			Dox	2.2	1.7	1.0	[1]3.7	9.6	Fan
72.1	R	1984	Dox	3.5	1.8	1.5	[1]9.4	24.0	Fan
			Dox	2.7	2.6	1.1	[1]7.7	20.0	Fan
			Dox	2.8	1.7	1.6	[1]7.6	20.0	Fan
			Dox	2.1	1.5	0.9	[1]2.8	7.3	Fan
75.5	L	1987	Kaibab	1.1	0.8	0.8	[1]0.7	1.8	Site F
			Redwall	1.1	1.0	0.5	[1]0.5	1.3	Site F
			Tapeats	2.0	1.0	1.0	[1]2.0	5.2	Site F
			Tapeats	2.5	1.8	0.6	[1]2.7	7.0	Site F
			Tapeats	1.8	1.2	0.5	[1]1.1	2.9	Site F
			Tapeats	1.5	0.9	0.9	[1]1.2	3.1	Site F
			Tapeats	2.8	1.8	1.4	[1]7.0	18.0	Site F
			Redwall	3.0	1.5	1.0	[1]4.5	12.0	Site F
			Tapeats	1.8	1.6	0.9	[1]2.6	6.8	Site F
			Supai	0.8	0.7	0.5	[1]0.3	0.7	Site F
			Coconino	0.9	0.6	0.39	[2]0.1	0.3	Site C
			Tapeats	0.95	0.7	0.5	[1]0.3	0.8	Site C
			Tapeats	0.85	0.7	0.53	[1]0.3	0.8	Site C
			Kaibab	0.85	0.55	0.5	[1]0.2	0.5	Site C
			Tapeats	0.65	0.6	0.4	[1]0.1	0.3	Site C
			Dox	1.1	0.75	0.3	[1]0.2	0.5	Site C
			Tapeats	1.3	1.0	0.85	[2]0.5	1.3	Site C
			Tapeats	1.55	1.4	0.65	[2]0.7	1.8	Site C
			Tapeats	0.9	0.65	0.65	[1]0.4	1.1	Site C

Appendix 8. Characteristics of boulders transported by recent debris flows in tributaries of Marble and Grand Canyons—Continued

River mile	Side	Date of debris flow	Lithologic source of boulder	a-axis diameter (m)	b-axis diameter (m)	c-axis diameter (m)	Estimated volume (m^3)	Estimated weight (Mg)	Site
75.5	L	1987	Supai	1.0	0.65	0.35	[1]0.2	0.5	Site C
75.5	L	190.9	Supai	1.3	1.3	1.3	[3]1.1	2.9	Fan
			Shinumo	1.8	1.5	1.05	[1]2.8	7.4	Fan
			Supai	1.85	0.95	0.75	[1]1.3	3.4	Fan
			Shinumo	2.4	1.7	0.95	[1]3.9	10.0	Fan
			Shinumo	1.3	1.1	0.95	[1]1.3	3.4	Fan
			Tapeats	2.2	1.25	0.95	[1]2.6	6.9	Fan
			Supai	1.2	0.8	0.8	[1]0.8	2.1	Fan
			Dox	1.65	0.55	0.45	[1]0.4	1.1	Fan
			Supai	1.2	1.0	1.0	[1]1.2	3.2	Fan
			Tapeats	1.9	1.15	0.5	[1]1.1	2.9	Fan
125.0	L	1989	Redwall	1.98	1.66	1.22	[2]2.0	5.3	Fan
			Muav	2.47	1.6	1.0	[2]2.0	5.3	Fan
			Supai	1.6	1.23	0.6	[1]1.2	3.2	Fan
			Supai	2.28	1.35	1.35	[4]3.3	8.7	Fan
			Muav	1.91	1.8	1.38	[1]4.6	12.0	Fan
			Muav	2.63	1.9	1.14	[2]2.8	7.4	Fan
			Muav	3.8	1.58	1.55	[1]9.3	25.0	Fan
			Redwall	2.32	1.4	1.3	[5]2.2	5.8	Fan
			Muav	2.62	1.63	0.85	[1]3.6	9.5	Fan
			Muav	1.85	1.28	0.85	[1]2.0	5.3	Fan
126.9	L	1989	Redwall	2.4	2.14	0.98	[1]5.0	13.0	Fan
126.9	L	1989	Muav	3.0	1.5	1.0	[1]4.5	12.0	Fan
			Tapeats	3.4	2.45	1.1	[1]9.2	24.0	Fan
			Muav	2.25	1.23	0.65	[1]1.8	4.8	Fan
			Supai	2.45	2.25	1.4	[5]4.0	11.0	Fan
			Muav	1.3	1.0	0.85	[1]1.1	2.9	Fan
			Supai	1.3	1.3	1.3	[6]2.2	5.8	Fan
			Redwall	2.1	1.5	1.0	[1]3.2	8.5	Fan
			Supai	1.9	1.6	1.2	[5]1.9	5.0	Fan
			Supai	1.2	1.2	0.75	[1]1.1	2.9	Fan
127.3	L	1989	Redwall	1.5	1.2	0.9	[1]1.6	4.2	Fan
			Redwall	2.8	2.3	1.4	[1]9.0	23.0	Fan
			Redwall	1.7	1.5	0.4	[1]1.0	2.6	Fan
			Redwall	1.3	1.0	0.9	[1]1.2	3.1	Fan
			Redwall	1.5	1.2	0.6	[1]1.1	2.9	Fan
127.6	L	1989	Redwall	4.0	2.8	2.5	[1]25.0	66.0	([7])

Appendix 8. Characteristics of boulders transported by recent debris flows in tributaries of Marble and Grand Canyons—Continued

River mile	Side	Date of debris flow	Lithologic source of boulder	a-axis diameter (m)	b-axis diameter (m)	c-axis diameter (m)	Estimated volume (m^3)	Estimated weight (Mg)	Site
			Redwall	2.5	1.5	1.15	[1]4.3	11.0	([7])
			Redwall	2.5	2.5	2.5	[3]8.2	22.0	([7])
			Redwall	2.5	2.0	2.0	[4]7.9	21.0	([7])
			Redwall	3.65	3.4	2.85	[1]35.0	94.0	([7])
			Redwall	4.5	3.5	2.65	[1]42.0	111.0	([7])
			Redwall	3.6	3.2	2.9	[1]33.0	88.0	([7])
			Redwall	3.0	2.5	1.4	[2]5.3	14.0	([7])
			Redwall	3.0	2.4	1.4	1.1	27.0	([7])
127.6	L	1989	Redwall	3.85	2.55	1.35	[1]13.0	35.0	([7])
157.6	R	1993	Muav	1.5	1.5	0.9	[2]1.0	2.6	Fan
			Muav	1.8	1.7	0.4	[1]2.9	7.5	Fan
			Muav	1.5	1.1	0.6	[1]1.0	2.6	Fan
			Muav	1.5	0.9	0.6	[1]0.8	2.1	Fan
			Redwall	1.5	0.9	0.9	0.5.6	1.6	Fan
			Muav	1.4	0.6	0.6	[1]0.5	1.3	Fan
			Muav	1.2	1.1	0.7	[2]0.5	1.3	Fan
			Muav	1.3	1.1	0.5	[2]0.3	0.8	Fan
			Muav	1.2	1.2	0.6	[2]0.4	1.0	Fan
			Muav	1.5	0.7	0.4	[1]0.4	1.0	Fan
160.8	R	1993	Muav	2.5	2.0	1.3	[1]6.5	17.0	Fan
			Muav	3.2	2.0	1.6	1.1	26.0	Fan
			Muav	2.0	1.9	1.5	[2]2.8	7.3	Fan
			Muav	1.8	1.7	1.5	[1]4.6	12.0	Fan
			Redwall	2.5	1.7	1.3	[5]2.9	7.5	Fan
			Muav	2.7	1.5	1.1	[2]2.2	5.7	Fan
			Redwall	1.7	1.4	1.1	[5]1.4	3.6	Fan
			Muav	3.1	2.2	0.8	[2]5.4	14.0	Fan
			Redwall	2.1	1.6	0.6	[5]1.0	2.6	Fan
			Redwall	1.5	1.2	1.1	[5]1.0	2.6	Fan
179.4	L	1939	Basalt	2.4	1.7	1.6	[5]3.4	8.8	Fan
			Basalt	2.4	1.2	0.8	[2]11.0	29.0	Fan
			Basalt	2.0	1.7	1.4	[5]2.5	6.5	Fan
			Basalt	2.8	1.7	1.6	[2]3.8	9.9	Fan
			Basalt	2.5	1.4	0.9	[5]1.6	4.2	Fan
			Basalt	3.9	2.2	1.6	[5]7.2	19.0	Fan
			Basalt	3.7	1.9	0.9	[5]3.3	8.6	Fan
			Basalt	3.2	3.0	1.6	[5]8.2	21.0	Fan
			Basalt	3.9	1.8	1.7	[5]6.2	16.0	Fan
			Basalt	2.9	1.8	1.4	[5]3.8	9.9	Fan

Appendix 8. Characteristics of boulders transported by recent debris flows in tributaries of Marble and Grand Canyons—Continued

River mile	Side	Date of debris flow	Lithologic source of boulder	a-axis diameter (m)	b-axis diameter (m)	c-axis diameter (m)	Estimated volume (m^3)	Estimated weight (Mg)	Site
		1939	Basalt	2.9	2.3	1.8	[5]8.4	22.0	Levee
			Basalt	3.6	1.5	1.4	[5]3.9	10.0	Levee
			Basalt	3.3	2.6	2.5	[5]11.0	29.0	Levee
			Redwall	1.8	1.3	1.0	[5]1.2	3.1	Levee
			Redwall	2.3	2.0	1.6	[5]3.8	9.9	Levee
			Basalt	1.8	1.8	1.6	[5]2.7	7.0	Levee
			Basalt	1.7	1.3	1.0	[5]1.1	2.9	Levee
			Basalt	3.2	2.7	1.9	[5]8.6	22.0	Levee
			Basalt	1.6	1.2	1.2	[5]1.2	3.1	Levee
			Basalt	2.4	2.0	1.6	[5]4.0	10.0	Levee

[1]Volume determined for a rectangular solid; V = a x b x c.

[2]Volume determined for a right-triangular solid; V = (((a x b)/2) x c).

[3]Volume determined for a spherical solid; V = 4.189(R3), where R = (0.5 x (b axis)) when b = c.

[4]Volume determined for a right-circular cylinder; V = p x R2 x h, where R = (b/2) when b = c, and h = a-axis.

[5]Volume determined for an ellipsoid, where A, B and C are equal to the semi-axes of the boulder (A = a/2, B = b/2 and C = c/2); V = ((4/3p(A x B x C))).

[6]Volume determined for a cubic solid; V = a x b x c, where all axes are equal.

[7]Boulder was transported by debris flow but was deposited in the channel of the tributary before reaching the Colorado River; therefore, it was deposited between the head of the drainage and the confluence.