Late Holocene Debris Fans and Alluvial Chronology of the Colorado River, Eastern Grand Canyon, Arizona

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Downstream view of Colorado River in eastern Grand Canyon from Peshlaki Point on the Palisades of the Desert. In lower center, Lava Canyon Rapids is between Palisades Creek on the left bank of the river and mouth of Lava Canyon on the right. Palisades Creek debris fan is bisected by active debris-flow channel of Palisades Creek. In upper-left corner upstream of bend in river, are the debris fans of Espejo and Comanche Creeks. Light-colored areas with dark vegetation on left and right banks are alluvial deposits of the Colorado River.

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Abstract

Bouldery debris fans and sandy alluvial terraces of the Colorado River developed contemporaneously during the late Holocene at the mouths of nine major tributaries in eastern Grand Canyon. Aside from interest in tributary debris flows and river hydraulics, interest in debris fans and terraces also stems from their connection with human activity along the river, which has been concentrated on these surfaces for 2-3 millennia. Poorly sorted, coarse-grained debris-flow deposits of several ages are interbedded with, overlie, or are overlapped by three terrace-forming alluviums. The deposits are the striped alluvium, deposited from somewhat before 770 B.C. to about A.D. 300; the alluvium of Pueblo-II age, which is characterized by Pueblo-II remains (A.D. 1000-1150) but was deposited from about A.D. 700 to 1200; and the alluvium of the upper mesquite terrace, deposited from about A.D. 1400 to 1880. The geomorphology of the debris fans is broadly similar. Two elements define the geomorphology of the typical fan: the large, inactive surface of the fan itself with median area of 45,900 m^2 and a smaller, entrenched, and active debris-flow channel and fan with median area of 12,030 m^2. The inactive fan is segmented into at least three surfaces with distinctive weathering characteristics. These surfaces are conformable with underlying debris-flow deposits that date from around 770 B.C. to before A.D. 660, A.D. 660 to before A.D. 1200, and from A.D. 1200 to slightly before 1890, respectively, based on late-19th century photographs, radiocarbon and archeologic dating of the three stratigraphically related alluviums, and radiocarbon dating of fine-grained debris-flow deposits. These debris flows aggraded the fans in at least three stages beginning about 2.8 ka, if not somewhat earlier. Several mainstem floods eroded the margin of the segmented fans, reducing fan symmetry. The entrenched, active debris-flow channel contains deposits less than 100 years old, which form a debris fan at the mouth of the channel adjacent to the river. Early and middle Holocene debris-flow and alluvial deposits have not been recognized, as they were evidently not preserved adjacent to the river or are buried by younger deposits.

Introduction

Debris fans and related alluvial terraces are among the largest and possibly the most important geomorphic features along the Colorado River in Grand Canyon (Hamblin and Rigby, 1968; Howard and Dolan, 1981). The fans develop at the mouths of tributary streams where large boulders of locally derived bedrock are deposited in the channel of the Colorado River by debris flow (Webb and others, 1989; Melis and Webb, 1993). The river is unable to move the large boulders except during relatively infrequent, large floods. As a result, the course of the river between bedrock walls, the presence and severity of rapids, and the location of Colorado River terraces are controlled by the coarse-grained deposits (Graf, 1979; Howard and Dolan, 1981; Kieffer, 1985; Webb and others, 1988; Schmidt and Graf, 1990).

Interest in debris fans and alluvial terraces of the Colorado River stems partly from the close association of fans and terraces with human activity in Grand Canyon. Archeologic sites are abundant along the Colorado River in the study area (fig. 1), averaging more than 12 per km (Fairley and others, 1994). The sites are closely associated with terraces and debris fans that prehistoric people used for many purposes, including camp sites, agriculture, and construction of masonry structures (Hereford and others, 1993). Most sites are affiliated with the Pueblo-II Anasazi, dating between A.D. 1000-1150 (Euler and Taylor, 1966), although sites range in age from about 800 B.C. to the early 20th century (Jones, 1985; Altschul and Fairley, 1989). Modern man uses these same deposits for recreational purposes while hiking or rafting through Grand Canyon. The whitewater rapids at the distal margin of many fans as well as the spectacular scenery of Grand Canyon attract 22,000 rafters annually who experience firsthand the powerful waves and swift currents (Stevens, 1990). In addition, most of the alluvial sand deposited by the Colorado River accumulates near the debris fans (Schmidt and Graf, 1990); these deposits form the substrate for riparian vegetation, which in turn supports the diverse riparian ecosystem of the Colorado River (Carothers and Brown, 1991, p. 111-167).

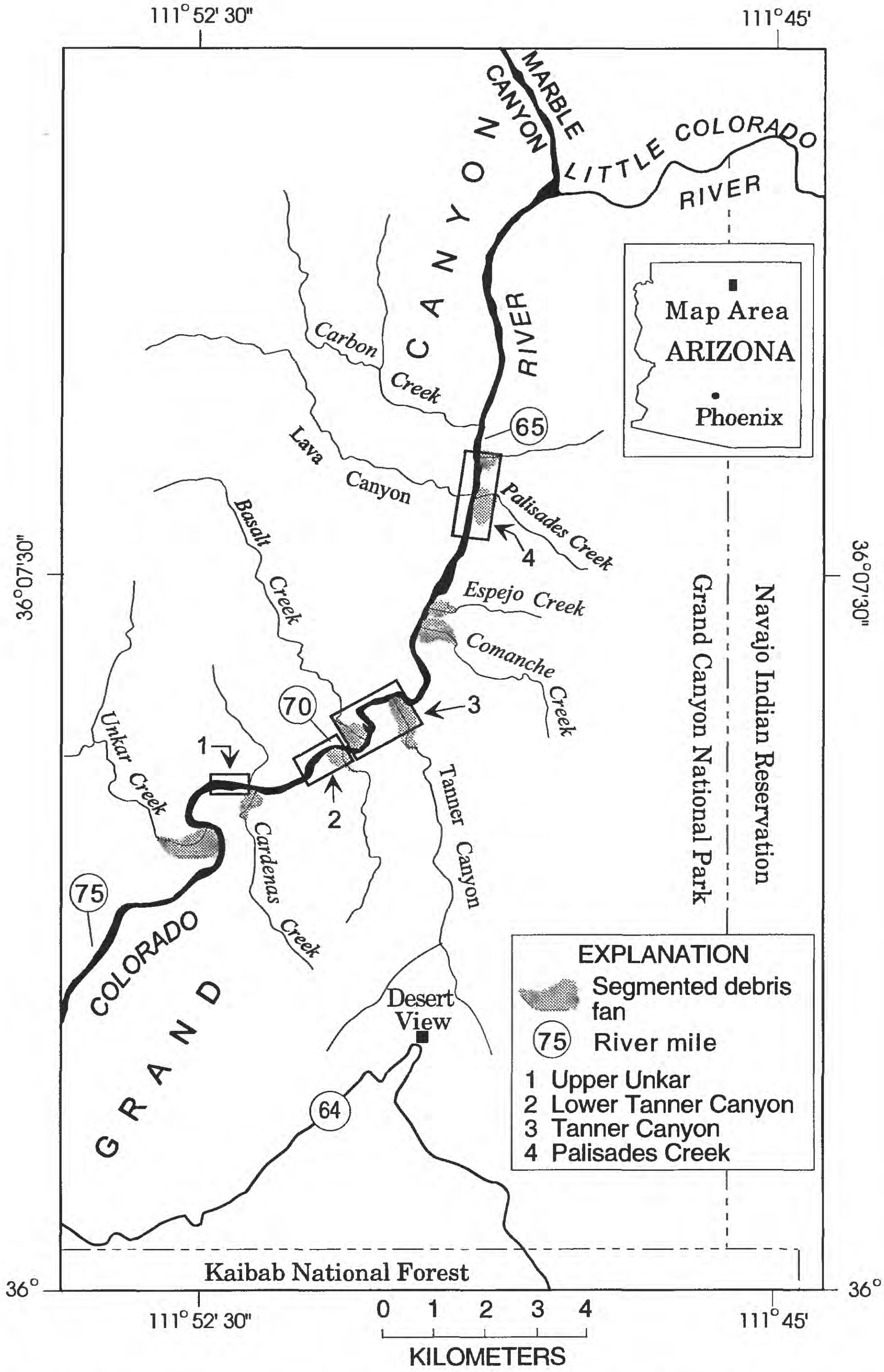


Figure 1. Study area in eastern Grand Canyon. Pattern shows segmented fans; boxes show areas mapped on large-scale topographic maps.

The study area borders the Colorado River in eastern Grand Canyon, Arizona (fig. 1). The area lies entirely within the "Furnace Flats" geomorphic reach defined by Schmidt and Graf (1990, table 1), which extends from River mile 61.6 to 77.4, which is 61.6 to 77.4 miles downstream of the Compact Point near Lees Ferry, Arizona. This reach is characterized by a relatively wide, shallow channel with slope of 0.0021.

Bedrock at river level is mainly the Dox Formation of Huntoon and others (1986) with minor outcrops of the Cardenas Lavas of Hendricks and Stevenson (1990), which are both Middle Proterozoic. The Dox is relatively nonresistant and easily eroded, as a result Grand Canyon is unusually wide in the Furnace Flats reach, although channel width and slope are similar to several other geomorphic reaches.

Debris fans of eastern Grand Canyon are segmented into surfaces of different ages; segmentation as used in this report is discussed by Cooke and others (1993, p. 179-184). The debris fans are evidently similar to Type IB alluvial fans of Blair and McPherson (1994, p. 394-395), except that fan margins are extensively eroded by the Colorado River. This type of fan, like those of eastern Grand Canyon, has a stratigraphic record dominated by clast-rich debris flows with minor interbedded fluvial gravels.

Previous Studies

Previous geomorphic studies have concentrated on the relation of alluvial deposits of the Colorado River to debris fans, the hydraulics of the rapids and flood-related geomorphic evolution of debris fans, and the processes and frequency of debris-flow sediment transport. These studies dealt primarily with active debris fans and alluvial deposits that are younger than the debris fans and terraces discussed in this report. A flood history of the Colorado River was developed by O'Connor and others (1994), who found that at least 15 floods with peak discharge greater than 5,500 m^3/s occurred in the past 4,500 years. For comparison, before closure of Glen Canyon Dam in 1963, the largest flood of the gaged record near Lees Ferry was 6,200 $m^3\backslash s$ and the mean annual flood was 2,200 m^3/s. Regulated streamflow reduced the mean annal flood to 800 m^3/s (Williams and Wolman, 1984, p. 10-11) and the largest flood since 1963 has been 2,800 m^3/s.

The close association between alluvial terraces and debris fans was described by Howard and Dolan (1981). They found that fine-grained sand deposits form terraces of pre- and post-dam age adjacent to debris fans throughout Grand Canyon. Alluvial deposits of post-dam age were mapped, classified, and related to hydraulic conditions at rapids and debris fans by Schmidt and Graf (1990). They found that most of the alluvial deposits in Grand Canyon are in recirculation zones, or eddies, that form upstream and downstream of channel constrictions near active debris fans. Schmidt (1990) found that the alluvial depositional sites increase in size as discharge increases. These two studies show that channel hydraulics along the margin of a fan affect sedimentation through a wide range of discharge. Hence, development of segmented debris fans and accumulation of Colorado River alluvium are closely linked, as emplacement of the fans formed alluvial depositional sites.

Erosion of debris fans by the Colorado River was studied by Kieffer (1985), who developed a model describing the coevolution of debris fans and rapids. Initially, the fan is enlarged by deposition of coarse debris-flow sediment that constricts the river channel, which is subsequently eroded by mainstem floods. Fan erosion and channel widening begins shortly after emplacement, the result of supercritical flow conditions in the newly constricted channel. Eventually, a large flood widens the channel substantially, producing subcritical flow conditions and establishing a stable channel configuration for that discharge level. Kieffer (1985) showed that the margins of the debris fans are erodible and that substantial erosion takes place at flow rates that have occurred historically. Erosional modification of fans, therefore, does not require extremely large floods.

Studies of tributary streams demonstrate that debris flow is the principal means of sediment transport to the Colorado River throughout Grand Canyon (Webb and others, 1989; Melis and Webb, 1993). Debris flows originate in the steep headwaters of tributaries following prolonged or intense rainfall. In places, repeated photographs show the effects of debris-flow sedimentation in the river channel. Generally, deposition of the coarse sediment forms a debris fan that narrows the channel forming a rapid where none existed or causing an existing rapid to become rockier and steeper (Cooley and others, 1977; Webb and others, 1988). These studies of active processes show that debris flows are relatively frequent, forming debris fans in the channel and maintaining the rapids.

Briefly, the ongoing processes of debris-flow sediment transport and the relation of active debris fans to river hydraulics are reasonably well understood. However, the older debris fans and the chronology of interbedded mainstem alluvium have been studied only recently (Hereford and others, 1993; Hereford, 1993). In this report, we discuss the general geomorphology, surficial geology, and age of nine tributary fans in eastern Grand Canyon (fig. 1), as well as the late Holocene alluvial chronology of the Colorado River. Ongoing studies indicate that segmented fans of similar size, age, and morphology are present elsewhere in Grand Canyon where the bedrock channel is wide enough for accumulation and preservation of sediment.

Methods

The largest debris fans and terraces in Grand Canyon are too small to show adequately on 1:24,000-scale topographic maps. This limitation was overcome by producing large-scale base maps of the four areas shown in figure 1. These maps range in scale from 1:1,000 to 1:2,000 and have a l-meter contour interval; they were produced photogrammetrically using low-altitude aerial photographs (Hereford and others, 1993). On these maps, portrayal of fan topography and related geomorphic features is adequate for surficial geologic mapping (for example see Hereford, 1993). The surficial deposits were classified by type, mapped, and dated where possible. The fans outside the mapped areas (fig. 1) were studied in the field using low-altitude aerial photographs and 1:5,000 scale topographic maps (Lucchitta, 1991).

Poor exposure and lack of organic material preclude direct dating of the coarse-grained debris-flow sediment. For this reason, qualitative and quantitative analysis of surface weathering was used to distinguish fan surfaces (or segments) at the nine debris fans (fig. 1), thereby establishing the relative age and correlation of surfaces in the study area. The minimum date of the youngest surfaces was established from historic photographs taken in 1890, which were supplied by Robert H. Webb (U.S. Geological Survey, Tucson, Arizona). The absolute age of a surface was then inferred from radiometric and archeologic dating of alluvium associated with the debris fans as well as by dating of fine-grained debris-flow sediment interbedded with the alluvium. The stratigraphic relations demonstrate that the ages of the terrace-forming deposits brackets the ages of the debris-fan segments.

The age of the deposits as determined by radiocarbon assays is reported in calendar years to emphasize the close association between the surficial deposits and archeologic remains. Calibration of radiocarbon years to calendar years was done with the Gronigen Radiocarbon Calibration Program (version of June 1991) using data current through 1989; the program was furnished by the U.S. Geological Survey Radiocarbon Laboratory (Reston, Virginia). In the calibration procedure, multiple dates are possible for a single sample because of secular radiocarbon fluctuations (Klein and others, 1982).

Segmented Debris Fans of the Eastern Grand Canyon

Geomorphology

The geomorphology of debris fans in eastern Grand Canyon consists of two major elements. The larger element is the broad surface of the fan itself, which is segmented into at least three surfaces of different ages. More than three surfaces are present locally, although we are unable to map them separately on 1:2,000 scale maps. The deposits underlying the surfaces are referred to as the fan-forming debris-flow deposits, because the primary fan surfaces are developed on these deposits. The smaller element is an active debris-flow channel entrenched 2-5 m below the segmented surface that is partly filled with debris-flow deposits. These deposits form a small debris fan at the mouth of the channel. The deposits of the fan and entrenched channel are referred to as the channelized debris-flow deposits.

In eastern Grand Canyon, the preserved area of the fan-forming deposits is substantially larger than the area of the entrenched channel and its associated fan (fig. 2). Typically, the area of the segmented fan surfaces is about 6 times larger than the area of the active debris-flow channels and related fans, based on the median ratio of fan to channel area. In certain cases, the subaerial extent of these channelized deposits may not coincide with the full extent of the debris flow, as much of the sediment can be deposited subaqueously in the channel (Melis and Webb, 1993; Melis and others, 1993). The smallest of the debris fans is upper Palisades Creek with total area of 10,100 m^2; the largest is Unkar Creek with total area of 220,000 m^2 (upc and uc, respectively, fig. 2).

Debris fans larger than about 10,000 m^2 with segmented surfaces are widespread in Grand Canyon wherever the bedrock channel is sufficiently wide, although the scarcity of large-scale maps precludes area measurements canyon-wide. Large-scale topographic maps (Hereford and Thompson, 1994a, b) show that debris fans at Nankoweap Creek and Little Nankoweap Creek in Marble Canyon and Granite Park Wash and 209 Mile Canyon in western Grand Canyon (River mile 52 and 209, respectively) have segmented surfaces and active channels. The location of late Holocene fans in Grand Canyon and the surfaces identified on them are listed in table 1.

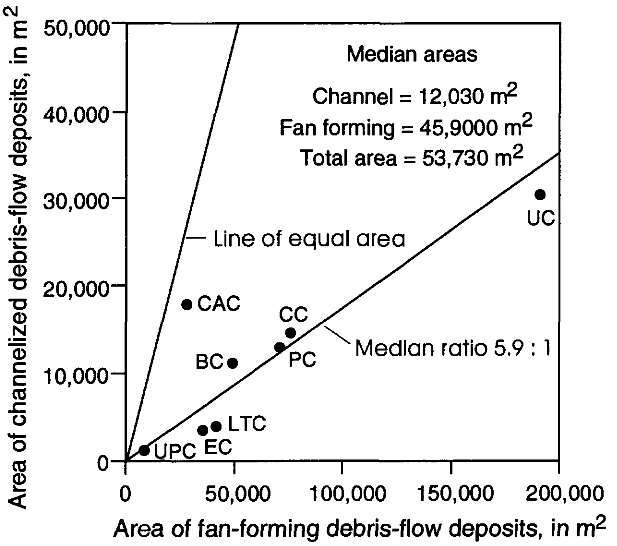


Figure 2. Area of debris fan and entrenched channel for selected tributaries in the study area (fig. 1). Topographic boundary of the fans was identified on low-altitude aerial photographs. Area was measured on 1:5,000 scale topographic maps of Lucchitta (1991). BC = Basalt Canyon; CAC = Cardenas Creek; CC = Comanche Creek; LTC = lower Tanner Canyon; PC = Palisades Creek; UC = Unkar Creek; UPC = upper Palisades Creek.

The shape of debris fans is reach dependent (Melis and Webb, 1993); deep, narrow reaches such as upper Granite Gorge between River mile 77.5-117.8 (Schmidt and Graf, 1990) have insufficient space to accommodate large debris fans. At Crystal Creek fan in the upper Granite Gorge, the active channel is substantially larger than the older fan, as inferred from the large-scale map of Kieffer (1988). This geomorphology differs from the fans of eastern Grand Canyon and resulted from extensive erosion by the Colorado River that mostly removed the older fan surfaces.

In eastern Grand Canyon, the channelized and fan-forming debris-flow deposits are further subdivided according to age and topographic expression. The channelized debris-flow deposits consist of a younger unit that forms the active debris-flow channel and an older unit that forms one or more poorly to well-developed terraces in the entrenched channel. Both units were deposited by at least two debris flows in the past 100 years, based on the relation of the deposits to Colorado River alluvium of known age (Hereford and others, 1993).

At least three fan-forming debris-flow deposits form the surface of segmented fans in the study area (fig. 1) and other debris fans in Grand Canyon (table 1). These surfaces parallel the underlying deposits and are contemporaneous with deposition; the deposits are referred to as the older, intermediate, and younger fan-forming debris flows or deposits, respectively. The surfaces are distinguished from each other by relative topographic position and surface-weathering characteristics. Generally, the older surfaces have the highest elevation and are farthest from the river. The degree of surface weathering differs among the three surfaces, as shown in table 2. The stage of development of the characteristics listed in table 2 is generally time dependent (Smith, 1994), which suggests that the three surfaces are of different relative ages.

Characteristics typical of the surfaces are illustrated in figure 3. The younger surface has weakly developed or no discernable rock varnish and the limestone clasts appear fresh with little surface roughness (fig. 3a; table 2). On the intermediate-age surface, rock varnish is on 50-100 percent of the sandstone clasts and limestone clasts are distinctly roughened with solution pits (fig. 3b; table 2). The undersides of clasts on the surface typically have a thin, very light-gray to white discontinuous coating of calcium carbonate. On the older surface, up to 100 percent of the clasts have well-developed rock varnish; limestone clasts are distinctly and deeply pitted (fig. 3c); and the undersides of clasts have a thin, mostly continuous coating of calcium carbonate. Sandstone clasts locally have honeycomb-like or cavernous weathering resembling tafoni (fig. 3d). On the oldest surfaces, rillenkarren is on up to 5 percent of the clasts (fig. 3e).

Solution pits on carbonate clasts, which are prominent on intermediate-age and older surfaces of Grand Canyon (fig. 3; tables 1, 2), are thought to result mainly from biogenic weathering and solution by acidified rainfall. The metabolic activity of endolithic cyanobacteria, or blue-greenalgae, is probably the major cause of solution pits (Danin, 1983; Danin and Garty, 1983), although some controversy surrounds the significance of biogenic weathering (Cooke and others, 1993, p. 44). We have not tested for the presence of bacteria in eastern Grand Canyon, however, biogenic solution is reported from similar arid environments (Smith, 1988). The bacteria remain dormant while dry, but moisture from rainfall or dew causes photosynthetic activity that consumes CO_2 during the day; the excess is then released at night to the wet surface of the clast. This release of CO_2 plus water forms carbonic acid that slowly etches the surface of the clast.

The depth of solution pits is a quantitative method of distinguishing among the intermediate-age and older

Figure 3. Photographs showing weathering of fan surfaces, all scales 10 cm long. A-D Palisades Creek fan. **(a)** Younger debris-flow surface with light-colored clasts without surface pitting.

Figure 3b. Intermediate-age surface with rock varnish and pitted-limestone clast above scale.

Figure 3c. Older surface with well-developed rock varnish, pitting of limestone clast (below scale), and granular disintegration of light-colored sandstone clast (right of scale).

Figure 3d. Sandstone clast with tafoni weathering on older surface.

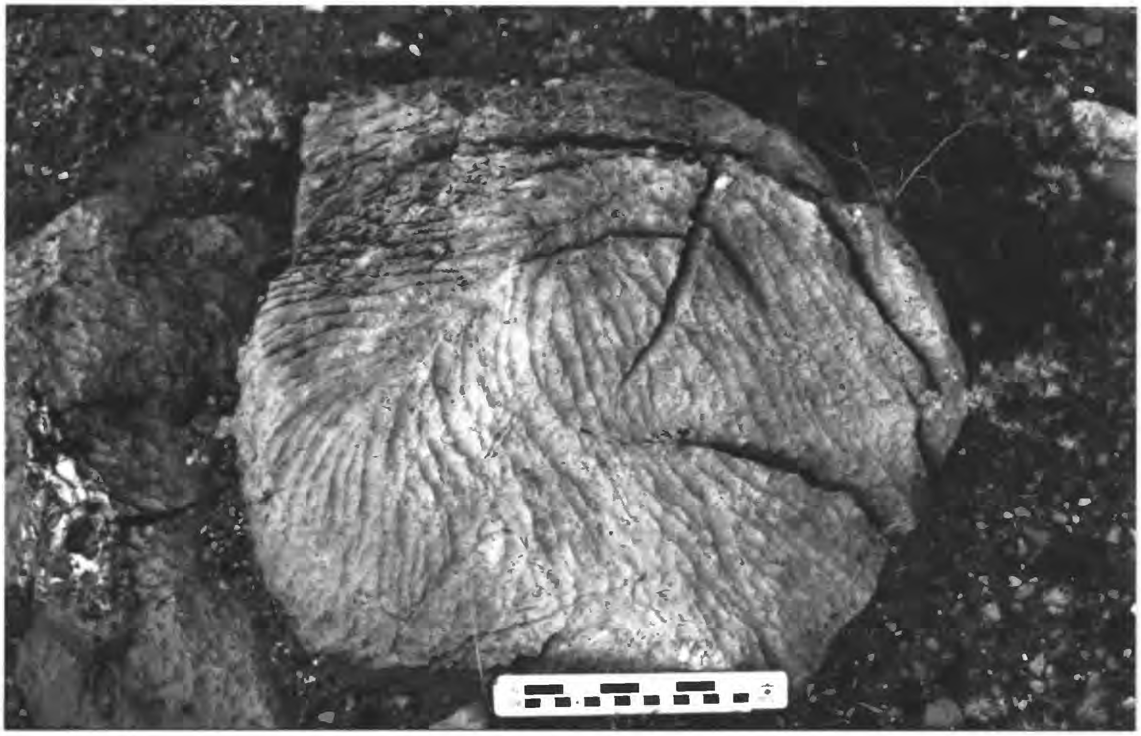


Figure 3e. Limestone clast with rillenkarren, older surface Cardenas Creek.

surfaces. A depth micrometer was used to measure the depth of several thousand solution pits on 149 intermediate-age and 96 older clasts (table 2) distributed among the nine debris fans. Previously discussed topographic relations and surface weathering were used initially to identify the surfaces. Fifteen traverses were made on intermediate-age surfaces and 14 on the older surfaces. The number of clasts examined in a traverse ranged from 2-10 and from 2-9 in the intermediate-age and older categories, respectively. Average pit depth of all pits on the intermediate-age surfaces is 3.23 mm, and all pits measured on the older surfaces average 5.76 mm (fig. 4a). These average depth measurements show a clear distinction between intermediate-age and older surfaces (fig. 4b). Average pit depth of the intermediate-age surfaces was shallower than 4 mm in 95 percent of the cases; whereas pit depth of the older-surface was deeper than about 4.5 mm in 95 percent of the cases. Finally, maximum depth per traverse also shows a clear distinction between the surfaces (fig. 4c). Ninety-five percent of intermediate-age surfaces have maximum pit depth shallower than about 7.5 mm, while maximum depth on the older surfaces is deeper than about 7.5 mm in 95 percent of the cases.

The rate of pit deepening was estimated from pit depths on limestone boulders used to construct an ancient check dam in the Nankoweap Creek area of Marble Canyon. Based on dated ceramics, this small dam was built by the Kayenta Anasazi in Pueblo-II time (A.D. 1000-1150). Using A.D. 1075 as the construction date, the dam is 0.915 ka. Maximum pit depth is 3.58 mm and average depth is 1.93 mm. The rate of deepening is about 4 (3.91) and 2 (2.11) mm/ka for maximum and average depth, respectively. The less deeply pitted intermediate-age fan surfaces of eastern Grand Canyon (fig. 4) are contemporaneous with the dam.

An earlier study estimated rate of pit deepening using maximum depth measured on the surface of limestone used to construct dated archeologic structures in Israel (Danin, 1983; Klein, 1984). These studies found that average maximum depth increases by 5 mm/ka, which is less than the 4 mm/ka estimated for eastern Grand Canyon. This reduced rate probably results from climate and different lithology. Grand Canyon is warmer and drier than Israel, which should reduce the rate substantially. Average annual temperature at Phantom Ranch in eastern Grand Canyon is 21^0 C and average rainfall is 211 mm, whereas at the Middle East archeologic sites, annual temperature is $17\text{-}18^0$ C and annual rainfall is 611 mm (Danin, 1983; Sellers and

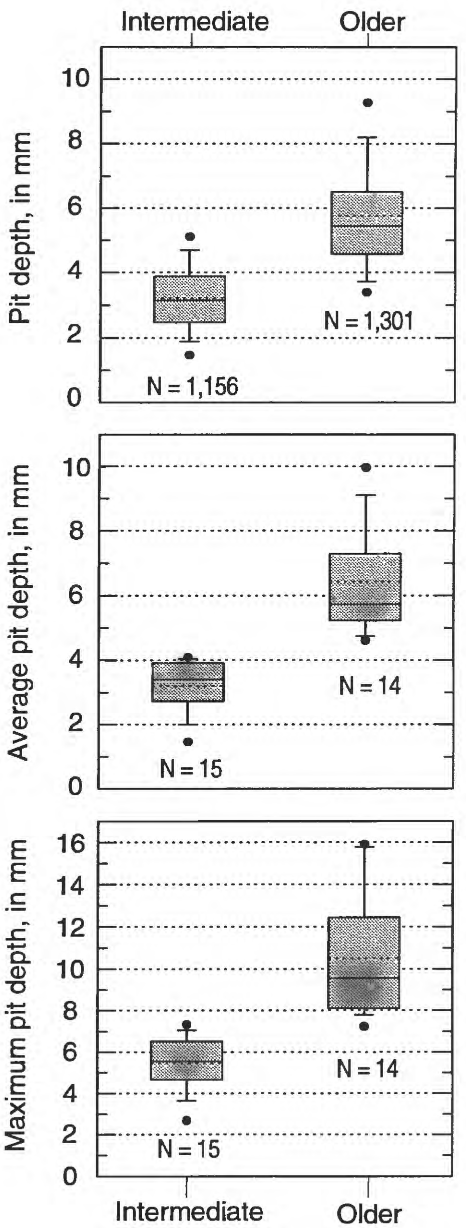


Figure 4. Box-plot statistical summaries of pit-depth measurements of intermediate-age and older surfaces. Shaded box is 25-75th percentile, median shown with solid line and average shown with dotted line, capped-vertical bar is range of 5-90th percentile, and solid circles are the 5th and 95th percentiles, respectively. (a) All measurements, (b) average pit depth by traverse, and (c) maximum depth by traverse.

Hill, 1974, p. 372-373). Lithologically, the limestone clasts used in the check dam are heterogenous compared with the relatively pure limestones used in the tombstones and large archeologic structures studied by Danin (1983) and Klein (1984).

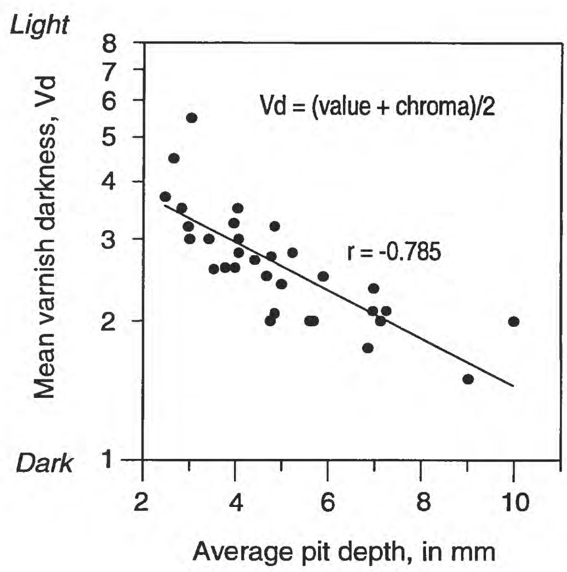


Figure 5. Darkness of varnish on sandstone clasts as a function of pit depth. Darkest clasts are associated with deeply pitted limestone clasts.

We are reluctant to calculate the age of the surfaces using the 2 or 4 mm/ka rate, as the functional relation between time and average or maximum pit depth is unknown in eastern Grand Canyon. Nevertheless, debris fans with limestone clasts having pit depth similar to the check dam are about 1 ka. Most of the intermediate-age surfaces probably predate Pueblo-II time, or A.D. 1000-1150 (fig. 4).

Degree of patination expressed by the darkness of sandstone clasts is related to limestone-clast pit depth (fig. 5). Varnish darkness (Bull, 1991, p. 63-64), the mean of value and chroma, of sandstone clasts decreases with increasing average pit depth. Surfaces with deeply pitted limestone clasts have the darkest sandstone clasts, which is also indicated in table 2. The patination on these surfaces (figs. 3, 5; table 2) developed between Pueblo-II time and somewhat before 2.8 ka, which is the likely maximum age of the fans as discussed in a following section of the report.

This rate of patination and weathering is difficult to compare with other desert areas because of different clast lithology, local climate effects peculiar to eastern Grand Canyon, and regional climate differences. The patinated clasts examined here are sandstone; whereas alluvial fans of the deserts in the nearby southern Basin and Range province are primarily volcanic, plutonic, and metamorphic (Wells and others, 1987; McFadden and others, 1989; Bull, 1991, p. 86; Reheis and others, 1993). These indurated rocks probably weather slowly compared with the sandstones and limestones of debris fans in eastern Grand Canyon. The microclimate of the river corridor as it relates to weathering and varnish formation is affected by close proximity of the Colorado River, which increases humidity locally.

Regional climate of eastern Grand Canyon differs from climate of southern Basin and Range. Although temperature is similar to low elevation sites in the Basin and Range, annual rainfall of Grand Canyon is nearly twice that of Baker, California in the eastern Mojave Desert and Yuma, Arizona in the Sonoran Desert (National Climate Data Center, and Sellers and Hill, 1974, p. 584-585). High elevation sites in the southern Great Basin are also drier and cooler than eastern Grand Canyon. For example, Beatty, Nevada receives 155 mm/yr and average annual temperature is 15^{0} C; Tonopah, Nevada averages 136 mm/yr and average temperature is only 11^{0} C.

Fan Morphology

The distribution of the fan-forming deposits has considerable variation that affects the shape of the fans in eastern Grand Canyon. Figure 6 illustrates the two main types of fan morphology. At the Palisades Creek fan (fig. 1), the older fan-forming deposits are preserved at the apex and near the eroded distal margin close to the river (fig. 6a). Intermediate-age deposits form most of the fan surface. Below the apex of the fan, intermediate-age deposits cover older deposits; whereas the intermediate deposits are inset below the older deposits at the fan apex. The younger debris-flow deposits occur mainly on the south side of the fan, where the fine-grained distal facies of the intermediate-age and younger debris flows are interbedded with Colorado River alluvium. Older and younger channelized deposits are in the relatively deep main channel of Palisades Creek and in the smaller channel north of the creek, respectively.

The surficial geology of the lower Tanner Canyon debris fan is illustrated in figure 6b. This fan lacks the distinctive radial shape of the Palisades Creek fan. The older debris-flow deposits are at the west and east margins of the fan and in the central portion where they form a ridge in a broad channel-like depression. This channel, which is 110 m wide and 2-3 m below the surface of the older debris flow, contains the intermediate-age and younger fan forming-deposits and the channelized deposits. The younger fan-forming deposit crops out on the west side of the fan, where it forms a low ridge between topographically higher outcrops of older and intermediate-age deposits. On the west side of the outcrop, the younger debris-flow sediment flowed across an alluvial terrace that is extensively covered with sand dunes. Subsequent eolian activity has partly covered the deposit, producing the outlier at the westernmost outcrop. The older and younger channelized deposits occupy relatively narrow and deep channels entrenched into the intermediate and younger surfaces. The older channelized debris flow is interbedded with alluvium that dates from A.D. 1922-1958, indicating the debris flow occurred during this period. The younger channelized debris flow was deposited in A.D. 1983 or 1984, based on aerial photographs taken in 1984 and the relation of the deposits to alluvial sand deposited in summer 1983.

Sand at lower Tanner Canyon and Palisades Creek forms several discontinuous terraces around the distal margins of the fans that ranges in age from prehistoric to post-dam. The sand is extensively reworked by eolian activity, forming coppice dunes that cover a large part of the underlying alluvium. The dunes are not indicated in figure 6, as they obscure the relation between the alluvial sand and the debris-flow deposits. The irregular, digitate contact between terrace-forming alluvium and the older and intermediate-age debris-flow surfaces results largely from onlap; whereas the contact with the younger deposits results from deposition of the debris flow on alluvium.

Stratigraphy

The channelized and fan-forming debris-flow deposits are broadly similar in composition. Both units consist primarily of clast-supported angular and subangular to subrounded clasts of local bedrock ranging in size from granules to boulders that are up to 3-5 m on an edge. The clasts are a mixture of resistant Paleozoic sandstone, limestone, and dolomite, which are present in the walls of the canyon and steep talus slopes beneath the cliffs. Listed in order of increasing relative abundance, the clasts are Kaibab Limestone and Coconino Sandstone (Permian), Supai Formation (Pennsylvanian and Permian), Tapeats Sandstone (Cambrian), and Redwall Limestone (Mississippian). The debris-flow matrix is a poorly sorted mixture of clay to coarse sand and granule gravel. Large boulders up to 1-3 m on an edge occur near the apex of the fans, although boulders this large are also present at the margin of the fans. Fluvial gravel of tributary origin is locally interbedded with the debris-flow sediment. The fluvial gravel typically consists of subrounded weakly imbricated pebble to small boulder-size clasts with minor coarse sand matrix; these gravels are distinctly finer grained and relatively well-sorted compared with debris-flow gravel.

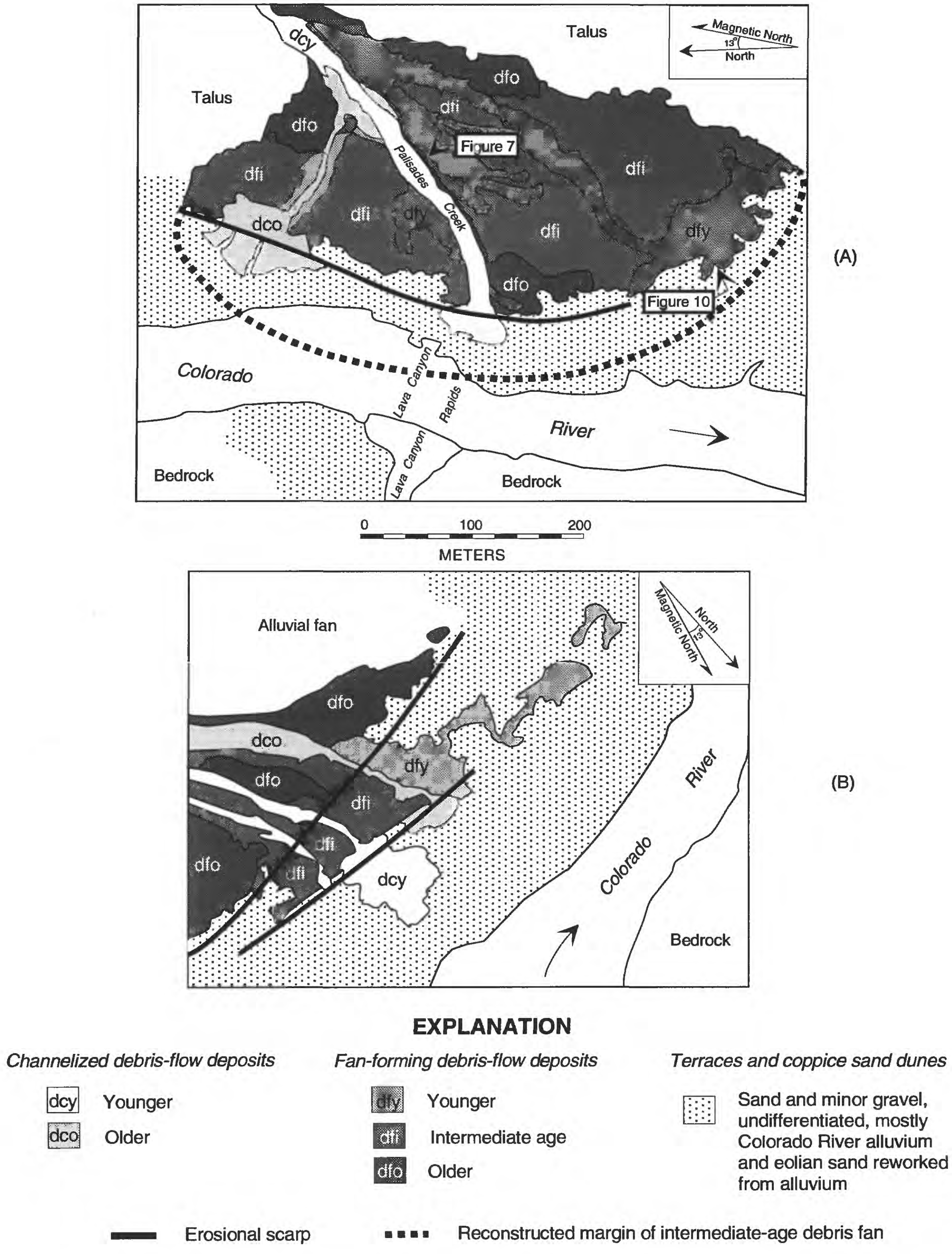
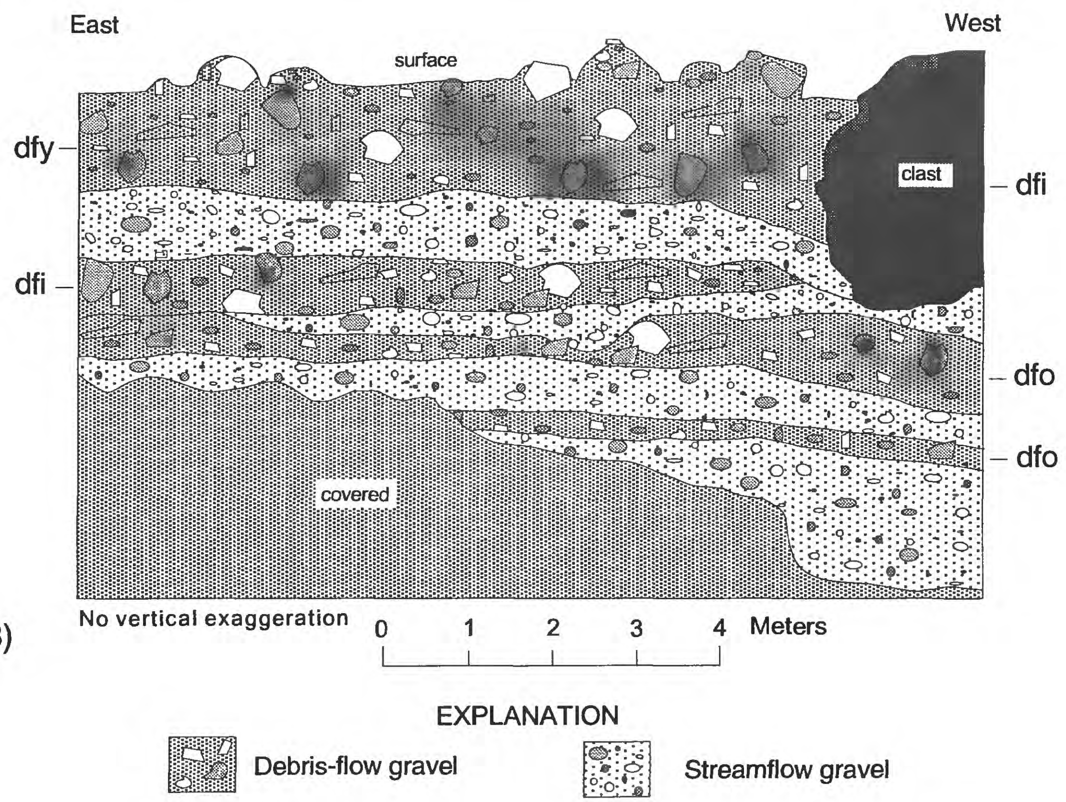


Figure 6. Surficial geologic maps of segmented debris fans. (a) Moderately truncated Palisades Creek fan showing radiating pattern of fan-forming debris-flow deposits, reconstructed outline of intermediate-age debris-flow deposits, and trace of erosional scarp at base of fan. (b) Severely truncated lower Tanner Canyon fan showing two erosional scarps at margin of older and intermediate-age deposits, respectively.

(A)



(B)

Figure 7. Interbedded debris-flow and fluvial gravel, south side of Palisades Creek. (a) Photograph of the deposits, scale is 1.4 m long with 20 cm divisions, and (b) measured stratigraphic section. Older, intermediate age, and younger deposits labelled dfo, dfi, and dfy, respectively. See figure 6a for location of section.

Fan-forming debris-flow deposits are exposed in the south side of the active debris-flow channel of Palisades Creek (fig. 1). This section of the proximal to medial portion of the fan (fig. 7a) is unusually well exposed and shows the stratigraphic relations among the deposits; the location of the section on the debris fan is shown in figure 6a. Figure 7b is a stratigraphic section of the older through younger fan-forming deposits. The deposits consist of four beds of gravelly debris-flow sediment interbedded with four beds of fluvial gravel derived from Palisades Creek. The composition and texture of these beds are similar to the debris-flow and fluvial gravels described above. The fluvial beds are probably contemporaneous with the debris-flow beds. Historic debris flows are typically preceded or followed by streamflow, according to Webb and others (1988, p. 12; 1989) and Cooley and others (1977, p. 12).

The basal and upper contacts of the debris-flow beds occur over 1-5 cm and are sharp and scoured. Evidence of weathering and soil development is lacking along each of the seven bedding planes; evidence of long-term exposure and weathering at the surface of the younger debris flow (dfy, fig. 7b) is also absent, probably because it was deposited only slightly more than 100 years ago. The large clast (dfi, fig. 7b) is part of the intermediate-age deposit, as shown by field relations immediately west of the cross-section. The clast is patinated at the surface and has a thin, discontinuous coating of light-colored calcium carbonate extending 5-10 cm beneath the surface (fig. 7a). Weathering of this clast, which happened after deposition, was preserved because the upper portion of the clast was above the abrasive effects of subsequent debris-flow and streamflow activity.

The absence of buried soils or evidence of long-term exposure is not expected given the age of the deposits, which is discussed in a following section of the report. The intermediate-age bed is about 1,300 years older than the younger deposit, and the older debris-flow beds are possibly 1,000 years older than the intermediate-age bed. (fig. 7b). This lack of soil development implies that deposition of the debris-flow beds was accompanied by erosion of the underlying bed, which removed evidence of weathering and exposure. This conclusion is supported by evidence that debris flows in steep channels can be erosive, exerting six times more shear stress than streamflow (Costa, 1984). Moreover, evidence from historic debris flows in Grand Canyon shows that passage of the flood wave was locally erosive (Cooley and others, 1977; Webb and others, 1988, 1989).

The stratigraphy of the Palisades Creek fan indicates that the fan resulted from at least four fan-forming debris flows. Three of these are distributed across the medial to distal surface of the fan (fig. 6a), where the surfaces have the distinctive weathering characteristics listed in table 2. The older debris flow consists of two beds (fig. 7b) that are indistinguishable on the surface. Either the two beds are closely related in time or the older bed is not exposed at the surface. Three temporally distinct surfaces are also present on debris fans elsewhere in eastern Grand Canyon. These surfaces are equivalent to those at Palisades Creek based on the degree of surface weathering, although deposition of the younger, intermediate, and older debris-flow deposits, respectively, probably did not occur at the same time throughout eastern Grand Canyon.

Erosional Truncation of Debris Fans

Geologic and topographic maps of the debris fans reveal the extent of erosion by the Colorado River, which in turn affects how the fans aggraded. The distribution of the fan-forming deposits and the shape of the upper part of the Palisades Creek fan resemble the radiating pattern typically associated with alluvial fans (Hooke, 1987). An erosional scarp at the toe of the fan (fig. 6a), however, is evidence that the Colorado River eroded and partly truncated the fan. The height of the scarp ranges from 2-3 m; elevation ranges from 822-825 m at the upstream end of the fan and from 820-823 m at the rapid. Reconstruction of the intermediate-age deposit suggests that the near-channel margin of the fan was eroded 50-60 m to the east, forming the scarp (fig. 6a). The reconstruction is based on the assumption that the intermediate-age debris flow initially extended across the entire radius of the fan. The scarp truncates the older and intermediate-age debris-flow deposits, and it is overlapped by alluvium that is younger than A.D. 1200. Therefore, erosion of the scarp occurred between A.D. 660-1200. Most of this fan lies above the level of prehistoric and historic floods. Prehistoric alluvial deposits range in elevation from 823-825 m around the margin of the fan, which is well below the fan apex at 845 m. In addition, the fan lacks well developed inset relations among the surfaces, and it appears to have aggraded vertically (figs. 6a and 7).

The size of the flood that eroded the scarp and widened the channel is uncertain, but it was probably large because (1) the top of the scarp is 5 m above present post-dam high-water level (2,800 m^3/s), (2) channel width at the rapid measured to the base of the scarp is 155 m compared with 120 m at the present high-flow level, and (3) the deposits contain clasts up to 2-3 m in diameter. An alluvial terrace that postdates both the scarp and debris flow overlaps the scarp locally. This terrace is above the level of a still younger terrace that was probably deposited by the largest flood of the historic period in July 1884 with peak flow rate of 8,500 m^3/s (Hereford, 1993). Thus, the flood that initially eroded the scarp was probably somewhat larger than 8,500 m^3/s. According to Kieffer (1985), flow rates between 8,500 to 11,300 m^3/s are necessary to widen the channel substantially and to erode the margin of a typical debris fan.

Unlike the Palisades Creek fan, the lower Tanner Canyon fan is severely truncated and retains little of the fan shape (fig. 6b). Most of the lower Tanner Canyon fan lies within the range of prehistoric floods. Prehistoric flood-related alluvial deposits are downstream of the fan at elevations of 808-812 m; the elevations of the two fan segments range from 810-815 m, which is well within the range of prehistoric Colorado River floods. The intermediate and older debris-flow deposits are both truncated along two distinct west-trending scarps that have maximum relief of 3 and 5 m, respectively (fig. 6b). The scarps were produced by at least two mainstem floods; the first flood or floods occurred after deposition of the older debris flow. Truncation of the fan margin steepened the overall fan gradient, causing entrenchment of a channel in the central portion of the fan. The intermediate-age flow was subsequently deposited in a channel position 2-3 m below the surface of the older deposit. The intermediate-age flow partly filled the channel and extended the fan beyond the eroded margin of the older deposits. The second flood truncated the fan margin formed by the intermediate-age deposits (fig. 6b). Finally, the fan has not aggraded vertically, rather it has developed mainly by aggradation of inset segments. The inset segments result from one or more floods that cut into the medial portion of the fan. This lowered the baselevel of the fan leading to entrenchment of the surface and emplacement of subsequent debris flows at a lower level.

The topographic maps of Lucchitta (1991) and Hereford and others (1993) show that the Unkar Creek, Cardenas Creek, Comanche Creek, Espejo Creek, and upper Palisades Creek fans (fig. 1) are moderately truncated, as they have an approximate fan-like shape that broadly resembles the Palisades Creek fan. In contrast, the Basalt Creek and Tanner Canyon fans are severely truncated, as indicated by steep scarps, with up to 5 m of relief, that surround the margin of each fan. These different morphologies are related to the age of the fan, the course of the river around the fan, and the elevation of the fan relative to flood level.

A severely truncated fan could be older than a moderately truncated fan, as the older fan has been subjected to a larger number of mainstem floods. The fans of eastern Grand Canyon, however, are of broadly similar age as indicated by similar weathering characteristics (table 2). The course of the river channel relative to the debris fan differs between the moderately and severely truncated fans. At moderately truncated fans, the river is relatively straight and essentially parallel with the distal-fan margin. Whereas, at the severely truncated fans, the river flows into and around the fan margin (lower Tanner and Tanner Canyon) or it flows entirely around the fan margin (Basalt Creek; figs. 1 and 6). In these situations, the river is particularly effective at eroding the fan because it flows directly into the upstream margin of the fan, or the river channel completely surrounds the fan margin.

Finally, the elevation of the fan relative to the river also controls the extent of erosional modification, at least in the case of the Palisades Creek and lower Tanner Canyon fans. The apex of the moderately truncated Palisades Creek fan lies well above flood levels, suggesting that the volume of sediment was larger than the river was able to remove during recent millennia. On the other hand, most of the severely truncated lower Tanner Canyon fan lies within the level of prehistoric floods, and the fan was relatively low and easily eroded. This difference between high and low elevation fans is evidently related to the slope or gradient of the fan, which in turn is a function of basin relief, lithology, and area (Cooke and others, 1993, p. 177-178).

Alluvial Chronology and Age of the Segmented Debris Fans

Abundant radiocarbon assays and archeologic remains date the late Holocene alluvial deposits of the Colorado River. However, direct dating of the coarse-grained debris-flow deposits forming the segmented fans has not been possible because of poor exposure and lack of organic material. Nevertheless, the fan-forming debris-flow deposits are inferred to be late Holocene, based on radiocarbon dating of fine-grained debris-flow deposits, the relation to dated Colorado River alluvium, and the association with dated archeologic remains. Generally, the debris fans are younger than Pleistocene, as inferred from their topographic position below terrace-forming river gravel of known late Pleistocene age (Hereford, 1993). Calcic soils on the terraces were dated in eastern Grand Canyon by Machette and Rosholt (1991) using the uranium-trend disequilibrium method. These minimum dates suggest that the two lowest gravel terraces are 15±5 and 40±24 ka, respectively, which is latest Pleistocene. Moreover, the debris fans occupy a bedrock channel that is lower, narrower, and of different alignment than the channel with late Pleistocene deposits. This suggests that the bedrock channel was downcut and widened substantially after deposition of the terrace-forming gravels and before accumulation of the debris fans and associated alluvium.

Alluvial Chronology

Three late Holocene terraces and related alluvial deposits are stratigraphically related to the segmented debris fans of eastern Grand Canyon. From oldest to youngest, these deposits are referred to as the striped alluvium, the alluvium of Pueblo-II age, and the alluvium of the upper mesquite terrace. The alluvial deposits form discontinuous, poorly preserved terraces and terrace-like features bordering the debris fans as well as upstream and downstream of the fans. The observed stratigraphic relations between the debris-flow deposits and the alluvial terraces are summarized in table 3. Basically, the debris-flow deposits are interbedded with, overlie, or are overlapped by the alluviums.

Figure 8 illustrates schematically the geomorphology and geology of the three terraces, the height of the terraces above the river, and the position of the terraces relative to recently regulated streamflow levels. This figure is a composite developed from exposures in eastern Grand Canyon. Each terrace occupies a distinctive position along the river with the oldest terrace highest and farthest from the river. The full suite of terraces is not present at any single cross-section nor are the terraces paired. The terraces have inset geomorphic relations such that younger terraces are topographically lower than older terraces; however, the stratigraphic relations among the deposits indicates that the units partly overlap, as shown in figure 8.

The physical and time stratigraphy of the alluviums, the age of the debris-flow deposits, and the archeologic chronology of eastern Grand Canyon are shown in figure 9. The radiocarbon dates shown in figure 9 are listed in table 4, which gives the location, sample material, stratigraphic context of the samples, and calibrated dates. Several of the dates in figure 9 overlap between the striped alluvium and alluvium of Pueblo-II age and between the alluvium of the upper mesquite terrace and the alluvium of Pueblo-II age, respectively. This overlap suggests that the units are not clearly separated in time. Inset topographic relations and related stratigraphic discontinuities, however, demonstrate that the units are separated by erosional unconformities (fig. 8; Hereford and others, 1993; Hereford, 1993). These physical relations were used to identify the stratigraphic unit from which the carbon samples were collected; thus each unit should yield temporally distinct dates. The overlapping dates, therefore, result largely from limitations of the ^{14}C dating method; specifically, secular variation of ^{14}C fluctuations, the inherent precision of ^{14}C measurements, and uncertainties regarding sample provenance (Taylor, 1987).

Geologic and archeologic evidence suggests that the duration of each hiatus was up to several centuries. Substantial realignment of the alluvial channel by widening and deepening suggests that erosion continued for a significant amount of time. However, the absence of buried soils indicates that the interval of nondeposition was brief relative to the time needed for soil development. The archeologic record shows that major cultural adjustments occurred during the two periods of erosion and nondeposition, suggesting that substantial time elapsed in each case. The striped alluvium is aceramic and lacks any structures more complex than simple hearths. In contrast, complex dwelling structures and a wide variety of ceramic material are associated with the alluvium of Pueblo-II age. The alluvium of the upper mesquite terrace does not contain material of Anasazi affiliation, indicating that the Anasazi abandoned the Grand Canyon before deposition of the alluvium.

Briefly, the radiocarbon dates, stratigraphic relations, and archeologic information suggest the following sequence of alluvial events between 770 B.C. to A.D. 1880: 1) deposition of the striped alluvium beginning about 770 B.C. until about A.D. 300 followed by erosion of the alluvium and nondeposition until about A.D. 700, 2) deposition of alluvium of Pueblo-II age from A.D. 700 until 1200 with erosion occurring from A.D. 1200 until about 1400, 3) deposition of the alluvium of upper mesquite terrace until about A.D. 1880.

Age of Debris-fan Surfaces as Inferred from Age of Late Holocene Terraces

The older debris-flow deposits of eastern Grand Canyon are partly equivalent to the striped alluvium. This alluvium consists of light-colored sand of Colorado River origin interbedded with pebble to small-cobble gravel of red Dox Sandstone near the channel margin. The gravel beds form the distinctive red stripes that are characteristic of the unit. The alluvium is in the Tanner Canyon and lower Tanner Canyon areas (fig. 1) where eight radiocarbon dates suggest that deposition occurred from about 770 B.C. until around A.D. 300 (fig. 9, table 4). These are the oldest dates reported from fine-grained Colorado River alluvium in Grand

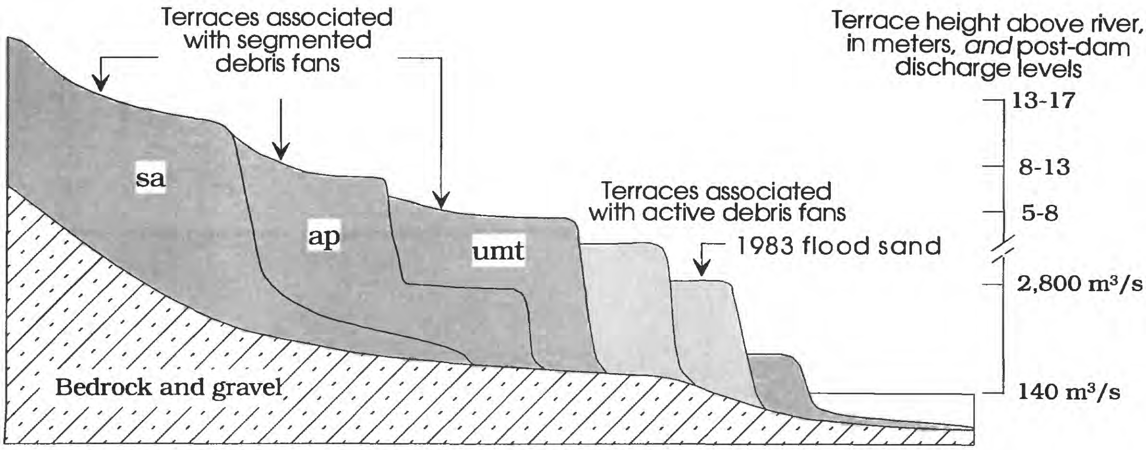


Figure 8. Generalized cross-section showing geomorphic and geologic relations of late Holocene terrace-forming alluvium and positions of terraces relative to regulated streamflow levels, eastern Grand Canyon. Alluvium and terraces associated with segmented debris fans: sa = striped alluvium, ap = alluvium of Pueblo-II age, umt = upper mesquite terrace.

Canyon, although a date of 2570-2290 B.C. was reported from alluvium in upper Marble Canyon by O'Connor and others (1994). Five of the samples (2, 3, 4, 7, and 8, table 4) were obtained from near the base of the exposed striped alluvium, although the base of the unit is not exposed. The alluvium began to accumulate before 400 B.C. (samples 4, 7, and 8), or even before 770 B.C., as suggested by sample 2. The older debris-flow deposit is interbedded with the striped alluvium at an outcrop near the extreme west end of the lower Tanner Canyon area. Thirty meters south of this outcrop, the deposit forms the surface of a debris fan that has weathering characteristics similar to the older fan surface elsewhere in eastern Grand Canyon (table 2). These relations indicate that the older debris-flow deposits in this area, and presumably elsewhere in eastern Grand Canyon, are as old as the striped alluvium.

In eastern Grand Canyon, deposits with intermediate-age surface characteristics are interbedded with and overlapped by alluvium of Pueblo-II age (table 3), which is present at or near the large debris fans (fig. 1). This suggests that the intermediate-age deposits in this region are somewhat older than to partly contemporaneous with the alluvium. The alluvium is named for the abundant Anasazi cultural remains of the Pueblo-II period (A.D. 1000-1150), although material of the Pueblo-I period (A.D. 800-1000) is present locally near the base of the alluvium and early Pueblo III (A.D. 1150-1200) material is on the surface (Hereford and others, 1993). Based on archeologic remains and 10 radiocarbon dates (fig. 9, table 4), this alluvium accumulated between about A.D. 700-1200.

Additional dates were obtained from intermediate-age surfaces at Tanner Canyon and lower Tanner Canyon (fig. 1). These minimum dates are from two hearths constructed in reworked alluvial sand deposited on the surface of the debris flow and from the inner rings of a mesquite tree rooted on the surface (table 4, samples 31 and 32, and 30, respectively). At lower Tanner Canyon, the intermediate-age surface is older than A.D. 1040-1380, and at Tanner Canyon the surface predates A.D. 1180-1400 based on the date of the hearths.

The younger debris-flow deposits postdate the alluvium of Pueblo-II age, as they are graded to a lower topographic level. Moreover, the debris-flow deposits do not contain Anasazi cultural remains, indicating that the younger deposits postdate A.D. 1200, which is the terminal date of Anasazi occupation of eastern Grand Canyon (Jones, 1985; Altschul and Fairley, 1989). The younger deposits are mostly equivalent to the alluvium of the upper mesquite terrace, which is present discontinuously throughout eastern Grand Canyon. This alluvium dates from about A.D. 1400-1880, based on nine radiocarbon dates (fig. 9, table 4). At Palisades Creek, the younger debris-flow deposit overlies the upper mesquite terrace, suggesting that it postdates A.D. 1880. The debris-flow deposits are probably not younger than A.D. 1890, as shown by historic photographs taken in January 1890 by Robert B. Stanton during an expedition to map a railroad in Grand Canyon (Smith and Crampton, 1987). These photographs show portions of the Palisades Creek and Basalt Creek fans (fig. 1; Robert H. Webb Stanton numbers 385 and 394). The fan surface in each case is smooth and fresh appearing, suggesting that a debris flow had occurred recently.

Age of the Debris-flow Distal Facies

At the southern margin of the Palisades Creek fan, the thin bedded, relatively fine-grained distal facies of the intermediate-age and younger fan-forming deposits

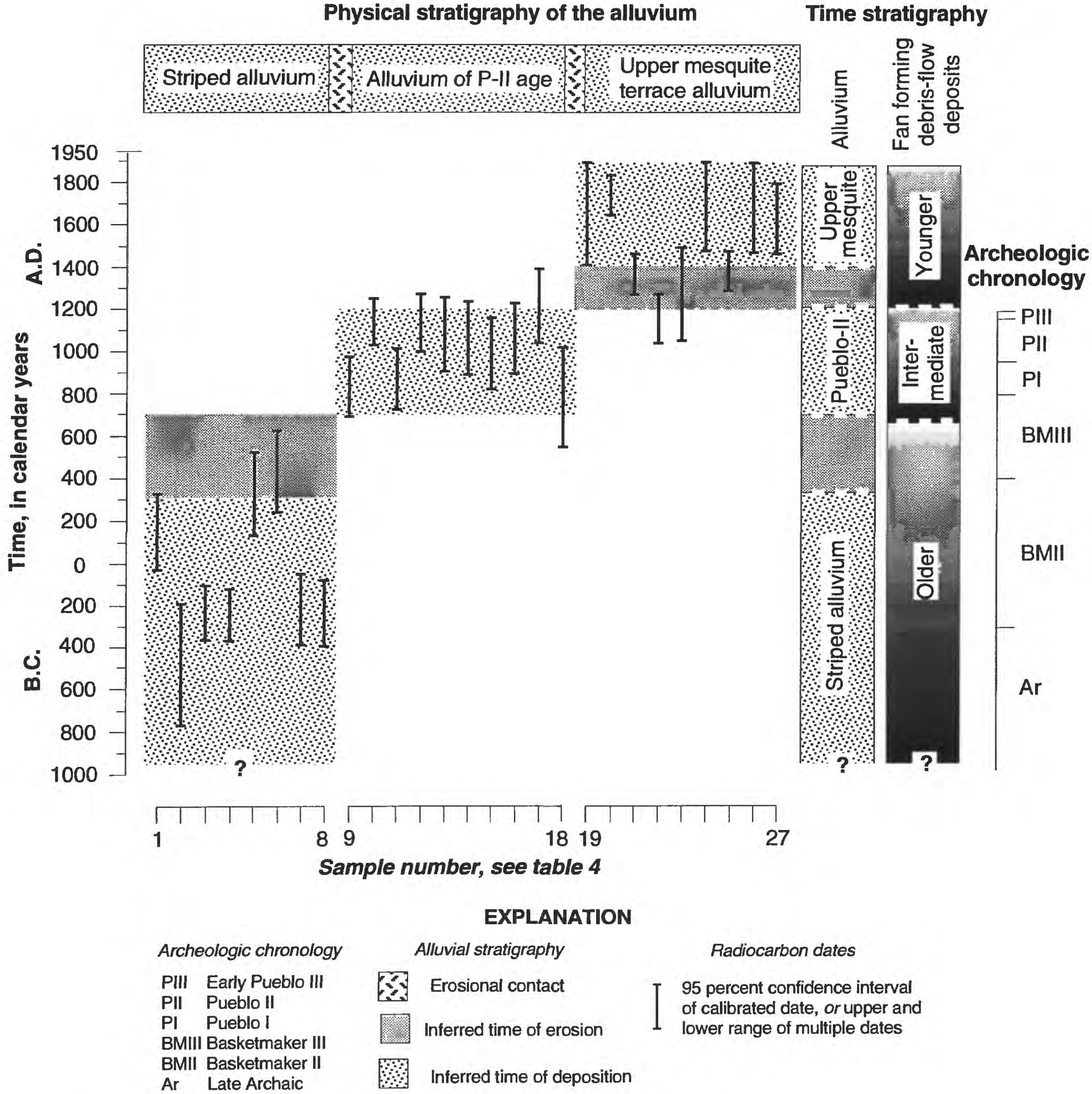


Figure 9. Radiocarbon dates calibrated to calendar years arranged by stratigraphic unit showing relations among physical stratigraphy of late Holocene alluvium, archeologic chronology, and time stratigraphy of alluvium and debris-flow deposits. Archeologic chronology of Altschul and Fairley (1989).

were dated radiometrically. The stratigraphy at this locality consists of four beds of alluvial sand interbedded with the distal facies of three debris flows, as shown in figure 10. The debris-flow deposits are a distinctive moderate orange pink and moderate reddish orange, the colors typical of debris-flow matrix exposed in Palisades Creek. From oldest to youngest, gravel content is 29, 45, and 2 percent, respectively. With exception of widely scattered small boulders, the gravels are typically granule to small-cobble size and the gravel is matrix supported. The matrix is very poorly sorted medium sand with average silt and clay content of 25 percent.

Although they differ substantially in grain size and thickness, these fine-grained deposits are equivalent to the previously discussed debris-flow gravel beds exposed in Palisades Creek (fig. 7). The distal facies of the younger debris flow traces continuously up the fan surface to the medial portion of the fan at the outcrop in Palisades Creek, as shown in figure 6a. The size of clasts in the deposit becomes progressively larger and thickness increases substantially in the upslope direction. The intermediate-age and older distal facies undergo the same transition in grain size and thickness, although the transition is not exposed continuously on the surface.

Dateable material was found at the base and top of the intermediate-age debris-flow bed and in the two overlying alluvial sand units. Results of radiocarbon dating indicate that the intermediate-age debris flow occurred about A.D. 660, which is the median date of the two samples bracketing the deposit (fig. 10; samples 28 and 29, table 4). Deposition occurred before A.D. 1000, as the bed is the occupation surface of an early Pueblo-II site. The sand overlying the intermediate-age bed yielded dates typical of the alluvium of Pueblo-II age, that is about A.D. 700-1200. The upper alluvial sand bed (umt, fig. 10) contains a limb or trunk of pine driftwood that was fresh appearing and fragrant when sampled. The outermost 5-10 growth rings of the driftwood were dated radiometrically (table 4, sample 20), yielding three calibrated dates of A.D. 1540-1700, 1720-1830, and 1840-1880. Thus, radiocarbon dates show that the younger debris-flow deposit at this locality postdates A.D. 1540-1880, and the Stanton photographs show that it is older than A.D.1890.

In short, although the coarse-grained fan-forming debris-flow deposits of eastern Grand Canyon could not be dated directly, the relation of the deposits to dated alluvium suggests that the debris-flow deposits began to accumulate from about 770 B.C. until shortly before A.D. 1890. The debris fans, therefore, have been in place for at least 2.8 ka. The older deposits date from 770 B.C. until sometime before A.D. 660, assuming that the dates from lower Tanner Canyon and Palisades Creek are representative. These older deposits coincide with the late Archaic through Basketmaker-II periods of Southwest archeology. Deposits of intermediate age date from A.D. 660 to as late as 1200, which is coincident with the Basketmaker III through early Pueblo-III periods. The younger deposits postdate A.D.1200 and predate A.D. 1890. Based on the lack of well- developed surface weathering (table 2), the younger deposits in eastern Grand Canyon probably occurred in the later part of the interval A.D. 1200-1890.

Discussion and Conclusions

Late Holocene bouldery debris fans and sandy alluvial terraces of the Colorado River are the principal geomorphic features along the river in eastern Grand Canyon. The terraces and fans are a locus of human activity for the past 2-3 millennia. Archeologic sites are relatively abundant on these surfaces, consisting

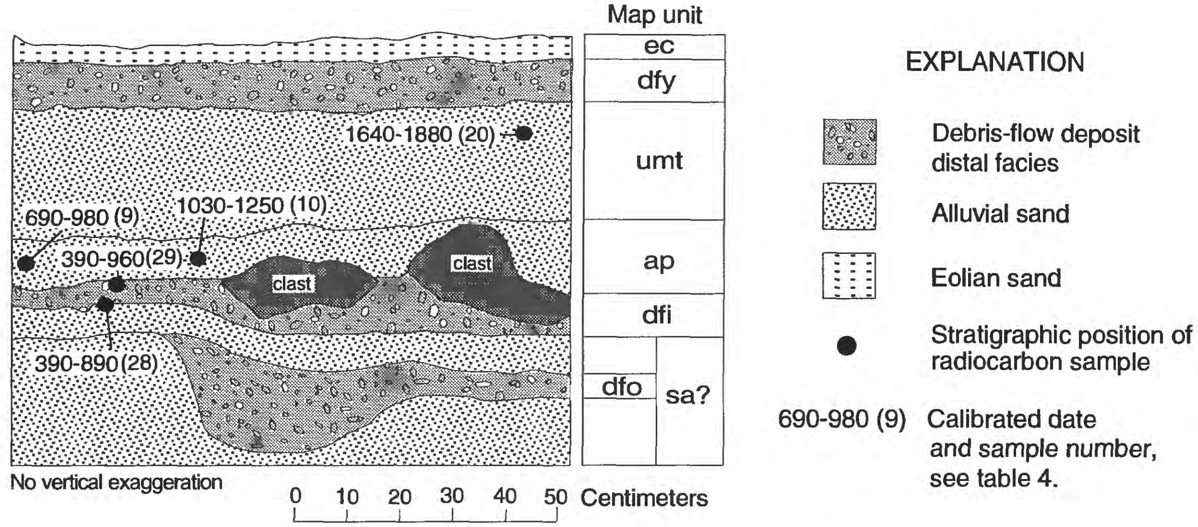


Figure 10. Cross-section at southern margin of Palisades debris fan showing stratigraphic position of radiocarbon samples and alluvium interbedded with debris-flow deposit distal facies. Map units: ec = eolian deposit; umt = upper mesquite terrace; ap = alluvium of Pueblo-II age; dfi = intermediate-age debris-flow deposit; dfo = older debris-flow deposit; sa? = striped alluvium. See figure 6a for location of section.

mainly of long abandoned camp sites and masonry structures. Debris fans are the more prominent geomorphic feature, as the terraces have substantially less topographic relief and are heavily reworked by wind. Debris fans range in size from about 10,000 to slightly more than 220,000 m^2; median area of the debris fans is 53,730 m^2. The fans consist of two elements; the active, entrenched channel and the broad surface of the fan itself, whose area is typically 6 times larger than the active channel. Fans of similar age, size, and morphology are present throughout Grand Canyon wherever the bedrock channel is wide enough for deposition and preservation of sediment.

The inactive fan surface has three topographically and temporally distinct segments that are identified and correlated in eastern Grand Canyon by relative topographic relief and degree of surface weathering. These surfaces are conformable with underlying debris-flow deposits, whose ages are contemporaneous with the ages of the surfaces. Topographically, the older surfaces are typically above younger surfaces. Weathering of younger fan surfaces is slight; they have little or no rock varnish on sandstone clasts and limestone clasts are fresh with little surface roughness. Intermediate-age surfaces have weak stage-I carbonate morphology, rock varnish on 50-100 percent of the clasts, and distinctly pitted-limestone clasts, the result of prolonged exposure to acidified rainfall and biogenic activity. Older surfaces have stage-I carbonate morphology, somewhat darker rock varnish on most clasts, and deeply pitted-limestone clasts.

The depth of weathering pits is used to distinguish between the intermediate-age and older-fan surfaces. Average depth is 3.22 mm on the intermediate-age surfaces and 5.76 mm on the older surfaces ($N = 1,156$ and 1,301, respectively). An archeologic structure dated between A.D. 1000-1150 and constructed with limestone has average pit depth of 1.93 mm; this is an average deepening rate of 2.11 mm/ka, using the median date of the structure. Therefore, most of the intermediate-age surfaces and all of the older surfaces are older than 1 ka, based on pit depth of limestone clasts.

Three terrace-forming alluviums of the Colorado River are stratigraphically related to the debris-fan surfaces and deposits. These are referred to informally as the striped alluvium, named for distinctive, thin interbeds of reddish hillslope sediment; the alluvium of Pueblo-II age, which is characterized by abundant archeologic remains of the Kayenta Anasazi; and the alluvium of the upper mesquite terrace. The terraces were mapped on large-scale topographic maps and dated using radiocarbon methods and archeologic remains.

Stratigraphic information and 27-radiocarbon dates suggest the following late Holocene alluvial chronology of the Colorado River in eastern Grand Canyon: 1) deposition of the striped alluvium beginning somewhat before 770 B.C. and lasting until about A.D. 300; 2) erosion and nondeposition between about A.D. 300-700; 3) deposition of the alluvium of Pueblo-II age at a lower position in the channel from about A.D. 700-1200; 4) another episode of downcutting and nondeposition from about A.D. 1200-1400; and 5) deposition of the upper mesquite terrace alluvium from about A.D. 1400-1880.

The causes of this alternating fluvial deposition and erosion are not well understood in eastern Grand Canyon. Water in the Colorado River is derived from snowmelt in the headwaters of the Rocky Mountains, whereas the sediment load is mainly from tributaries of the Colorado Plateau (Andrews, 1991). Thus, climate of either region could influence alluviation in Grand Canyon in ways that are not immediately apparent. Nevertheless, the alluvial chronology of the Colorado River in eastern Grand Canyon correlates broadly with a late Holocene chronology of the southern Colorado Plateau developed by Karlstrom (1988) and elaborated by Dean (1988, p. 129). The alluvium of Pueblo-II age probably correlates with the upper Tsegi Formation and the upper mesquite terrace alluvium correlates roughly with the Naha Formation, both of northeast Arizona and southern Utah (Hack, 1942; Cooley, 1962). Erosion in Grand Canyon around A.D. 1200-1400 correlates with widespread stream entrenchment on the southern Colorado Plateau at about this time.

Stratigraphic relations between the terraces and debris fans, radiocarbon dating of fine-grained distal facies of debris-flow deposits, and historic photographs resolve the ages of the debris-flow surfaces and deposits. The older surface dates from before about 770 B.C. until A.D. 660, although the maximum age is not well constrained. The intermediate-age surface dates from after A.D. 660 until 1200, and the younger surface dates from after A.D. 1200 until shortly before 1890. Most of the younger surfaces in eastern Grand Canyon are probably closer to the latter part of this interval, based on weakly developed surface weathering, historic photographs, and radiocarbon dates.

We think the maximum age of the debris fans is probably late Holocene. An absolute age of 2.8 ka is indicated for the striped alluvium, based on the oldest of several radiometric dates from near the base of the alluvium. The alluvium is interbedded with a debris-flow deposit that elsewhere has surface-weathering characteristics similar to the older fan; thus we correlate the striped alluvium with the older debris-flow deposits. Furthermore, the position of the alluvium in the channel is related to the present elevation and course of the river. Deposits older than the striped alluvium are gravelly and occur in a bedrock channel of different alignment and higher elevation than the present channel.

Nevertheless, the maximum age of the striped alluvium and related debris-flow deposits is not well constrained, as the basal contact of the alluvium is not exposed and is undated. Linear extrapolation of the 4 mm/ka rate of maximum pit deepening suggests the oldest surfaces with pits up to 16 mm deep might be 4 ka. This age, however, could be overestimated substantially, depending on the relation between time and maximum pit depth. Early to middle Holocene debris fans and alluvium were not found and are evidently not present, which probably results from non-preservation or burial by younger deposits.

Because debris flows are instantaneous events, the deposits of a particular fan will probably not correlate exactly with the deposits of any other fan. Nevertheless, the three-age categories are broadly defined periods of late Holocene debris-flow activity in eastern Grand Canyon. Too little is known presently about the correlation and specific dates of the fan-forming debris flows to offer more than speculation about their relation to late Holocene climate change. Moreover, late Holocene climate of the southern Colorado Plateau is poorly known, and the biseasonal precipitation pattern makes comparison with other regions difficult. Historic debris flows have occurred in summer from thunderstorms and in late fall from winter-frontal systems (Webb and others, 1989). If sediment supply was adequate, it seems likely that a long-term shift to frequent, intense rainfall in summer or late fall would increase debris-flow activity, thereby aggrading the fans.

Finally, conditions leading to deposition outside of the entrenched channel and aggradation of the fans do not occur often in eastern Grand Canyon. Indeed, deposition on the fan surfaces may have occurred only three times in 2.8 ka. Although further work will be necessary to subdivide the three surfaces, it seems likely that the number of fan-forming debris flows on a particular fan is small.

Assuming that the entrenched configuration of the fans is typical, then aggradation of the fan surface requires the debris-flow channel to be overtopped, spreading sediment across the fan. This type of aggradation was reported by Osterkamp and others (1986) from late Holocene debris flows on the flanks of Mt. Shasta in northern California. They recognized relatively small and frequent in-channel debris flows and large, relatively infrequent out-of-channel debris flows. In-channel debris flows correspond with the channelized debris-flow deposits of the present study. Out-of-channel flows are those of sufficient size to overtop a channel confinement, producing a mappable deposit on the fan surface; these correspond with the fan-forming debris flows.

Aggradation of segmented debris fans in eastern Grand Canyon probably results from changes of local baselevel and changes in frequency or magnitude of debris flow. The channel could be overtopped either by an increase in the frequency of channelized-debris flows that eventually fill the channel, or by one or more relatively large debris flows that fill the channel and deposit sediment on the fan simultaneously. In either case, substantial, rapid deposition of tributary debris in the river channel would raise baselevel locally, reducing gradient of the debris-flow channel, causing it to aggrade. Entrenchment of the debris-flow channel probably results from lower baselevel following erosion of debris in the river channel. This causes local steepening of fan gradient and incision of a new debris-flow channel.

Acknowledgments

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Table 1. Name, location by river mile of late Holocene debris fans in Grand Canyon National Park, surfaces present, and limestone clast solution-pit measurement sites. Debris fans discussed in this report are from River mile 65.1-72.5

Tributary	Colorado River mile (km)	Surface identified dfy	dfi	dfo	Pit-depth measurements
Soap Creek	11.2 (18.0)	x	x	x	
24.5 Mile Canyon	24.5 (39.4)	x	x	x	x
Buck Farm Canyon	41.0 (66.0)	x	x		
Little Nankoweap Creek	51.8 (83.3)	x	x	x	x
Nankoweap Creek	52.1 (83.8)	x	x	x	x
Unnamed	53.1 (85.4)	x	x	x	x
Kwagunt Creek	56.0 (90.1)	x	x	x	x
Upper Palisades Creek, Unnamed	65.1 (104.4)	x	x	x	x
Palisades Creek	65.4 (105.2)	x	x	x	x
Espejo Creek	66.8 (107.5)	x	x	x	x
Comanche Creek	67.2 (108.1)	x	x	x	x
Tanner Canyon	68.4 (110.1)	x	x	x	x
Basalt Creek	69.7 (112.1)	x	x	x	x
Lower Tanner Canyon, Unnamed	70.1 (112.8)	x	x	x	x
Cardenas Creek	71.0 (114.2)	x	x	x	x
Unkar Creek	72.5 (116.7)	x	x	x	x
75 Mile Creek	75.2 (121.0)	x		x	
Monument Creek	93.4 (150.3)	x	x		x
Crystal Creek	98.0 (157.7)	x		x	x
Unnamed	122.3 (196.8)	x	x	x	x
Unnamed	122.7 (197.4)	x	x	x	x
Forster Canyon	122.7 (197.4)	x	x		
Unnamed	124.4 (200.2)	x	x	x	x
Fossil Canyon	125.0 (201.1)	x	x	x	x
Unnamed	140.0 (225.3)	x	x	x	
Prospect Canyon	179.0 (288.0)	x	x	x	x
Unnamed	194.6 (313.1)	x	x	x	x
Unnamed	194.7 (313.3)	x	x	x	x
Unnamed	196.1 (315.5)	x	x	x	
205 Mile Creek	205.2 (330.2)	x	x		
Unnamed	208.5 (335.4)	x	x	x	x
209 Mile Canyon	208.7 (335.8)	x	x	x	x
Granite Park Canyon	208.9 (336.1)	x	x	x	x
Fall Canyon	211.5 (340.3)	x		x	
217 Mile Canyon	217.3 (349.6)	x		x	
220 Mile Canyon	220.0 (354.0)	x	x	x	x

Table 2. Surface-weathering characteristics of fan-forming debris flows, eastern Grand Canyon, Arizona

Characteristic	**Debris-flow age category**		
	Younger	Intermediate	Older
Carbonate coatings, undersides of clasts	None	Stage I, discontinuous, thin, < 0.1 mm	Stage I, discontinuous to continuous, thin < 0.5 mm
Splitting, spalling, and granular disintegration of sandstone clasts	None	Slight	Common
Tafoni	None	Present	Present and well developed
Limestone-clast pitting[a]	None to incipient, < 1 mm	Present, 1.47 to 4.04 mm	Present, 4.74 to 9.97 mm
Rilling of limestone clasts	None	None	Present on 5 percent of clasts
Rock varnish, sandstone clasts	Absent to incipient on 50 percent of clasts	Present on all 50-100 percent of clasts, brown to dark brown	Well developed on all clasts, dark brown to black

[a] Average depth of solution pits measured with a depth micrometer, number of individual measurements = 1,156 and 1,301 of intermediate-age and older, respectively. Measurements made on the surfaces of 149 and 96 intermediate-age and older clasts.

Table 3. Observed and possible stratigraphic relations between debris-flow deposits and surfaces with terrace-forming alluvium, eastern Grand Canyon

Debris-flow age category	**Stratigraphic relation**		
	Interbedded	Alluvium overlaps debris flow	Debris flow overlies alluvium
Younger	[umt][1]	[umt]	umt
Intermediate	ap[2]	ap [umt]	sa
Older	sa	[sa, ap, umt]	[sa]

sa = striped alluvium; ap = alluvium of Pueblo II age; umt = upper mesquite terrace
[1][--] Stratigraphic relation possible, but not observed
[2]ap Observed stratigraphic relation

Table 4. Radiocarbon dates of alluvium and of debris-flow related deposits and archeologic features, eastern Grand Canyon, Arizona

Sample number			Location[3]		Material	Date, in years B.P.	Calendar date[5]	Description
No	Field[1] number	Lab. number[2]	Latitude DMS[4]	Longitude DMS[4]				
				Striped alluvium				
1	TWRC 2	AA-5781	35 05 55	111 50 10	Charcoal	1870±70	30 B.C.-A.D. 260 A.D. 290-330	Striped unit
2	TWRC 14	β-51480	ibid.	ibid.	Charcoal	2330±100	770-190 B.C..	Flake zone, base of exposure
3	TWRC 3	W-5285	35 05 57	111 50 10	Charcoal	2160±40	370-280 B.C. 260-110 B.C.	Hearth, base of exposure
4	TWRC 4	W-5287	ibid.	ibid.	Charcoal	2150±30	360-290 B.C. 250-110 B.C.	Hearth, base of exposure
5	TWRC 8	AA-5785	ibid.	ibid.	Charcoal	1710±70	A.D. 130-450 A.D. 490-500 A.D. 510-530	Hearth, top of unit
6	TWRC 15	AA-9527	35 05 05	111 49 55	Charcoal	1610±90	A.D. 240-620	Top of unit
7	TWRC 15-1	β-35125	35 05 05	111 50 05	Charcoal	2170±70	390-90 B.C. 70-50 B.C.	Base of exposure
8	BCRC 1	AA-5789	35 05 28	111 50 59	Charcoal	2120±110	400 B.C.-A.D. 80	Base of exposure
				Alluvium of Pueblo-II age				
9	PCRC 5	W-5289	35 08 11	111 48 55	Charcoal	1170±60	A.D. 690-700 A.D. 710-750 A.D. 760-980	PII unit
10	PCRC 14	W-5373	ibid.	ibid.	Driftwood, outer rings	880±50	A.D. 1030-1250	Wood associated with structure in PII unit
11	PCRC 6	W-5291	35 08 28	111 48 52	Charcoal	1140±60	A.D. 720-730 A.D. 770-1010	Covered by slopewash
12	LCRC 1	W-5308	37 08 21	111 49 05	Charcoal	900±80	A.D. 1000-1270	Base of hearth
13	LCRC 2	W-5309	ibid.	ibid.	Charcoal	950±80	A.D. 900-910 A.D. 950-1250	Top of hearth
14	ECRC 1	AA-5785	37 07 15	111 49 23	Charcoal	970±90	A.D. 890-1240	Cultural horizon
15	ECRC 2	AA-5787	ibid.	ibid.	Charcoal	1050±60	A.D. 820-830 A.D. 860-1050 A.D. 1080-1120 A.D. 1140-1160	Cultural horizon

Table 4 (continued)

16	ECRC 3	W-5443	35 07 05	111 49 30	Charcoal	970±80	A.D. 890-930 A.D. 930-1230	Cultural horizon
17	TWRC 5	AA-5782	35 05 58	111 50 10	Charcoal	770±90	A.D. 1040-1320 A.D. 1350-1390	PII? unit
18	TWRC 6	AA-5783	ibid.	ibid.	Charcoal	1250±130	A.D. 550-1020	PII? unit

Upper mesquite terrace alluvium

19	PCRC 3	W-5255	35 08 29	111 48 52	Mesquite pith	310±150	A.D. 1410-1890	Bush rooted on PII unit covered by sand
20	PCRC 4	W-5288	35 08 11	111 48 55	Driftwood, outer rings	190±40	A.D. 1640-1700 A.D. 1720-1830 A.D. 1830-1880	Sand on PII unit, pre-dates 1890
21	LCRC 3	W-5310	37 08 21	111 49 05	Charcoal	560±80	A.D. 1270-1460	Hearth
22	LCRC 7	W-5404	ibid.	ibid.	Charcoal	840±70	A.D. 1040-1270	Middle of unit
23	LCRC 9	W-5371	ibid.	ibid.	Charcoal	630±120	A.D. 1050-1080 A.D. 1120-1140 A.D. 1160-1510	Cultural horizon
24	LCRC 10	AA-9525	ibid.	ibid.	Charcoal	240±90	A.D. 1470-1890	Base of debris flow, upper part of unit
25	LCRC 11	W-5372	ibid.	ibid.	Mesquite pith	550±80	A.D. 1280-1470	Plant rooted on contact with PII unit
25	C:13:10 M1	W-5259	35 05 23	111 52 15	Mesquite pith	250±100	A.D. 1460-1890	Umt unit
27	C:13:10 M2	W-5251	ibid.	ibid.	Mesquite pith	300±50	A.D. 1460-1670 A.D. 1780-1790	Umt unit

Intermediate-age debris-flow related deposits and archeologic features

28	PCRC 11	β-51470	35 08 11	111 48 55	Charcoal	1410±120	A.D. 390-890	Base of debris- flow distal facies
29	PCRC 12	β-51470	ibid.	ibid.	Charcoal	1380±140	A.D. 390-960	Top of debris- flow distal facies
30	TWRC 16	W-5440	35 05 03	111 49 45	Mesquite pith	570±50	A.D. 1290-1430	Tree rooted on debris-flow surface, minimum date

Table 4 (continued)

31	TWRC 17	W-5442	35 05 09	111 49 48	Charcoal	700±70	A.D. 1180-1190 A.D. 1210-1400	Hearth in sand deposited on debris flow, minimum date
32	LTWRC 1	W-5438	35 05 33	111 50 39	Charcoal	770±70	A.D. 1040-1100 A.D. 1110-1150 A.D. 1150-1300 A.D 1350-1380	Hearth in sand deposited on debris flow, minimum date

(1) TW = Tanner Canyon; BC and LTW = lower Tanner Canyon; PC = Palisades Creek; LC = Lava Canyon; EC = Espejo Creek; C:13:10 = upper Unkar; also see figure 1

(2) AA = Accelerator mass spectrometry method done at the National Science Foundation Accelerator Facility, University of Arizona by Meyer Rubin; β = Beta Analytical, Inc., Miami, Florida; WW = U.S. Geological Survey Radiocarbon Laboratory, Reston, Virginia

(3) Latitude and longitude from Lucchitta (1991); Hereford and others (1993), and Hereford (1993)

(4) DMS = Degrees, minutes, seconds

(5) 95 percent confidence interval in calendar years of the radiocarbon date, which was calibrated to calendar years using relations developed through measurement of ^{14}C activity of dendrochronologically dated wood (Klein and others, 1982). Multiple dates are possible because of atmospheric ^{14}C fluctuations