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Dating Prehistoric Tributary Debris Fans, Colorado River, Grand Canyon National Park, Arizona, with Implications for Channel Evolution and River Navigability

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Frontispiece

View upstream of the Colorado River in eastern Grand Canyon. Distant skyline in upper right is Palisades of the Desert. Vegetated area in lower right is the prehistoric debris fan of Comanche Creek and Espejo Creek.

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Dating Prehistoric Tributary Debris Fans, Colorado River, Grand Canyon National Park, Arizona, with Implications for Channel Evolution and River Navigability

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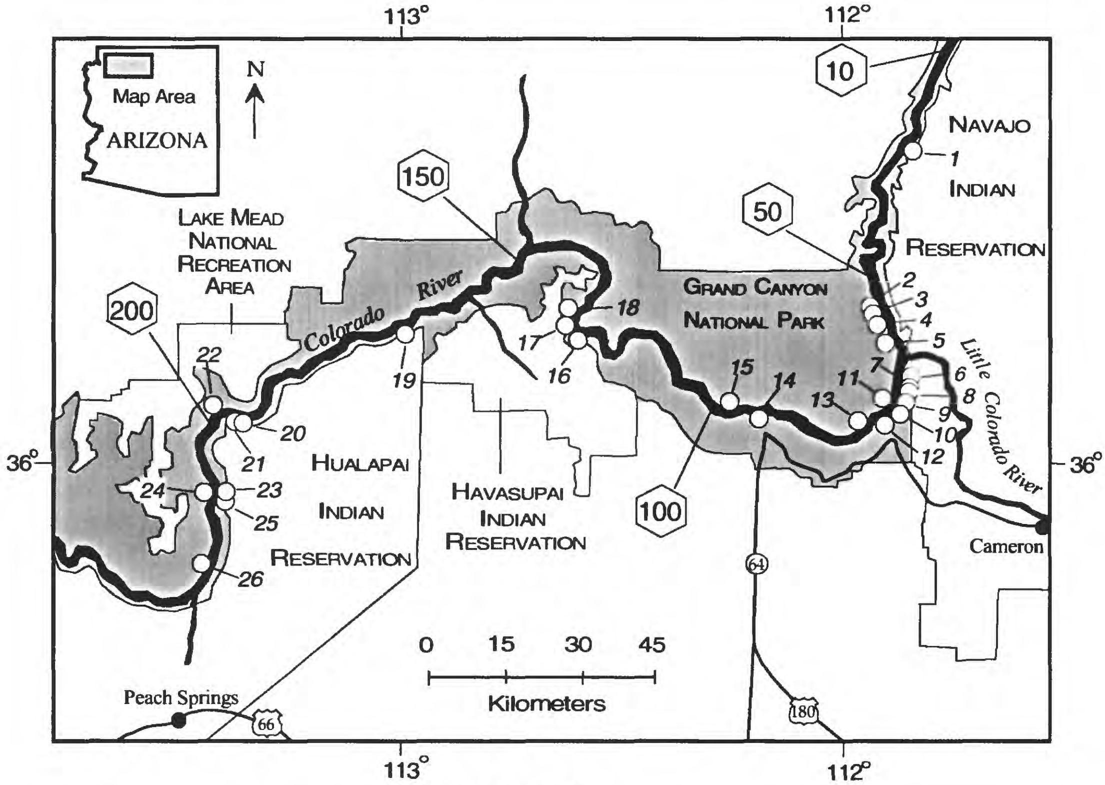
Abstract

The ages of prehistoric debris-fan surfaces and related debris fans are relevant to long-term channel management of the Colorado River in Grand Canyon National Park, Arizona. The debris fans formed by deposition of coarse-grained sediment in the river channel by fan-forming debris flows, which were substantially larger than most recent debris flows. These large debris flows were capable of severely constricting the mainstem channel, resulting in rapids that would probably have been unnavigable or waterfalls in extreme cases. There is no reason to believe that debris flows of this size will not occur in the future. At any particular tributary, fan-forming debris flows tend to happen every 850 years on average. The last canyon-wide episode of fan-forming debris flows was around 790 cal yr B.P. Thus, it is possible that another episode of increased debris-flow activity will ensue within 60 years. The age of debris-fan surfaces in Grand Canyon can be determined only rarely by conventional methods. For this reason, we developed a technique for dating surfaces based on the time-calibrated dissolution of carbonate boulders, which are abundant in debris-flow sediment. Weakly acidified rainfall and the metabolic activity of blue-green algae form small, roughly hemispheric dissolution pits on the initially smooth, exposed surfaces of carbonate boulders. The average depth of dissolution pits increases systematically with relative age of fan surfaces. The deepening rate, as measured by the depth of pitting, averages 2.54 ± 0.40 mm/ka (n = 7; ka = 1,000 years), which was calculated from several radiometrically dated surfaces and an archeologic structure. The calculated rate is a linear function of time over at least the past 3 ka, consistent with the process of carbonate dissolution and with dissolution rates determined from carbonate tombstones and other archeologic structures. Measurements (n = 6,973) of pit depth were made on 617 boulders on 71 fan surfaces at the 26 largest debris fans in Grand Canyon. Average pit depth for all surfaces ranges from 1.2 to 17.42 mm, which indicates that surfaces in Grand Canyon range in age from 500 to 7,000 cal yr B.P. Most fan surfaces (75 percent) are younger than 2.8 ka, probably reflecting removal of older debris fans by the Colorado River. The distribution of calculated ages throughout Grand Canyon has five clusters: 790, 1460, 2360, 2950, and 3820 cal yr B.P. These clusters may coincide with periods of increased debris-flow activity.

Introduction

This report addresses the ages of prehistoric (or late Holocene) debris fans along the Colorado River in Grand Canyon (fig. 1). The results of this study have implications for long-term channel management and navigability of the river. Composed of poorly sorted, bouldery sediment, segmented debris fans with multiple, mostly prehistoric, surfaces (Hereford and others, 1996a) are ubiquitous in Grand Canyon at the mouths of tributary streams (Hamblin and Rigby, 1968). We estimate the ages of these prehistoric surfaces and correlate debris-flow deposits using a quantitative dating technique based on time-calibrated dissolution of carbonate boulders.

Correlation of debris-fan surfaces along the Colorado River in Grand Canyon is important for identifying periods of increased debris-flow activity. Increased activity may correspond with unusual climate conditions, particularly increased precipitation. In addition, the age distribution of fans is important for understanding erosional removal of debris fans by the Colorado River in the natural discharge regimen. The age distribution of prehistoric fans in Grand Canyon partly reflects the long-term interaction between the Colorado River and the sediment output of tributary streams. The long-term effect of the river is to erode, reshape, and remove debris fans from the channel. This erosion was severely reduced by virtual elimination of natural floods with closure of Glen Canyon Dam in 1963. Thus, while geomorphically significant mainstem floods have been eliminated tributary debris flows continue unabated.



Explanation

○ Tributary debris fan study sites

(100) River mile, starting at Lees Ferry, Arizona

1 24.5 Left
2 Little Nankoweap Creek
3 Nankoweap Creek
4 53.1 Left
5 Kwagunt Creek
6 Palisades Creek
7 Espejo Creek
8 Comanche Creek
9 Tanner Creek
10 69.6 Left
11 Basalt Canyon
12 Cardenas Creek
13 Unkar Creek
14 Monument Creek
15 Crystal Creek
16 Forster Canyon
17 124.2 Left
18 Fossil Canyon
19 Prospect Canyon
20 195 Left
21 195.5 Left
22 196 Right
23 208.7 Left
24 209 Mile Canyon
25 Granite Park Canyon
26 220 Mile Canyon

Figure 1. Study area, Grand Canyon National Park, Arizona.

Fans are the largest and perhaps most important depositional feature along the floor of the Grand Canyon. The size and shape of the fans control the course of the river between bedrock walls and the location and severity of whitewater rapids (fig. 2; Stevens, 1990). In addition, important sites of fluvial deposition develop in zones of low current velocity upstream, downstream, and along the margins of debris fans (Howard and Dolan, 1981; Schmidt, 1990; Schmidt and Graf, 1990). The fluvial deposits form terraces that were farmed and occupied prehistorically by the Anasazi, ancestors of the Hopi Indians of northern Arizona. The debris fans were also used by the Anasazi (Fairley and others, 1994), and the largest archeologic site in Grand Canyon is on the Unkar Creek debris fan (fig. 1; Schwartz and others, 1980).

Although widely recognized as important geomorphic elements of the river system, the age and correlation of prehistoric debris fans have not been studied on a canyon-wide basis. Fan surfaces and deposits are difficult to date because organic material is rare in the coarse-grained deposits. Dated archeologic sites are

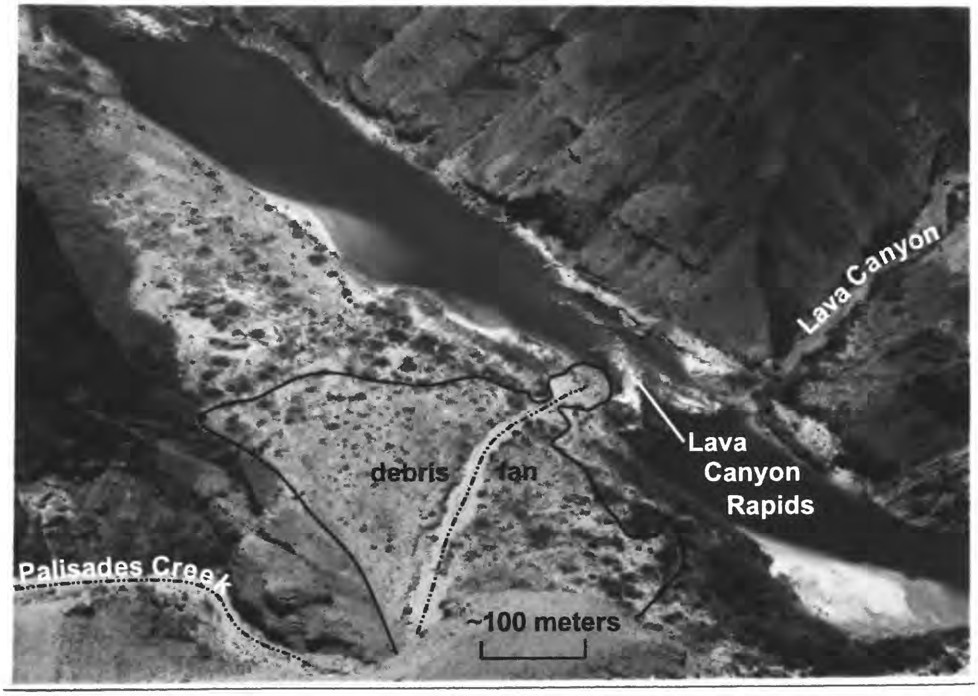


Figure 2. Photograph of Palisades Creek debris fan, a typical late Holocene fan in eastern Grand Canyon. Fan is bisected by entrenched, historically active channel with channelized debris-flow deposits; relatively dark area is the inactive, primary fan surface consisting of younger, intermediate-age, and older fan-forming surfaces discussed in text. Position of Colorado River against right side of canyon and location of Lava Canyon Rapids are controlled by bouldery sediment of debris fan.

present on fan surfaces locally, but sites provide only minimum ages. The relation of debris fans to dated fluvial deposits, however, constrains the age of the fans along the river to the late Holocene (Hereford and others, 1996a).

In this report, the ages of debris-fan surfaces are estimated using a simple calibration function that relates surface age to the average depth of dissolution pits on carbonate boulders; the estimated ages are mostly less than 2.8 ka. Dissolution pits result from weakly acidified rainfall and the metabolic activity of endolithic cyanobacteria. Although some controversy surrounds the significance of biogenic weathering (Cooke and others, 1993, p. 44), a major cause of dissolution pits may be the release of excess CO_2 following rainfall-induced photosynthesis (Danin, 1983; Danin and Garty, 1983). Regardless, atmospheric or metabolic CO_2 combines with water to form carbonic acid (H_2CO_3) that slowly etches the surfaces of carbonate boulders.

The depth of dissolution pits was time-calibrated using several dated fan surfaces. A deepening rate of 2.54 ± 0.40 mm/ka was calculated from the average depth of dissolution pits on carbonate boulders on the dated fan surfaces. Using this calibration, the age of any weathered fan surface in Grand Canyon can be estimated. In addition, the age of walls and other structures built of carbonate stones by prehistoric people can be estimated in the absence of temporally diagnostic potsherds. Generally, the surface exposure age of any mid- to late Holocene deposit with unmetamorphosed carbonate boulders can be estimated by this method if the local carbonate dissolution rate is known.

Previous studies of Grand Canyon debris flows and debris fans

Studies of modern depositional activity demonstrate that debris flow is the main process of sediment transport in tributaries of the Colorado River in Grand Canyon (Webb and others, 1989; Melis and Webb, 1993; Melis and others, 1995). Debris flows originate in the steep headwaters of tributaries following prolonged or intense rainfall. Failure of partly saturated, talus covered slopes initiates debris flows. The poorly rounded, bouldery sediment is moved downstream in a gravity-driven slurry where it is deposited on a debris fan in the channel of the Colorado River.

Prehistoric debris fans in eastern Grand Canyon were studied by Hereford (1996) and Hereford and others (1996a). The typical debris fan has two geomorphic elements: the relatively large surface of the fan itself which is inactive and mostly of prehistoric age, and the historically (post-A.D. 1890) active debris-flow channel which is substantially smaller and entrenched into the fan surface. The inactive surface of any particular fan is about 6 times larger than the active channel. Median area of the inactive fan and active channels is 4.6 and 1.2 ha, respectively. The median total area of the two elements for all fans in eastern Grand Canyon is 5.4 ha; individual fans range from 1 to 22.1 ha. This range of fan sizes is typical of the debris fans studied in this report, although the lack of large-scale topographic maps precludes area measurements canyon-wide.

The typical fan in eastern Grand Canyon (fig. 2) and elsewhere is segmented into several surfaces of different ages distinguished by relative topographic position and degree of weathering (see fig. 3 in Hereford and others, 1996a; and figs. 2-5 in Hereford and others, 1996b). The surfaces parallel the underlying deposits and are contemporaneous with deposition; we informally refer to these as the older, intermediate, and younger fan-forming surfaces or deposits. The relative age of fan surfaces corresponds to topographic position with the most elevated surface being the oldest. The younger fan-forming surfaces occupy the lowest position on the fans and are only slightly weathered in most cases. These surfaces were not differentiated from intermediate-age surfaces for this study. Only the oldest of the younger surfaces have carbonate boulders with shallow dissolution pits. Extremely young (between 75-500 cal yr B.P.) fan-forming surfaces without dissolution pits are uncommon, but we have mapped them at Nankoweap Rapids, Palisades Creek (fig. 1; Hereford and others 1996b; Hereford, 1996), and Granite Park. The intermediate-age and older surfaces are distinctly weathered with carbonate boulders having well-developed dissolution pits.

Clasts in the debris-flow deposits are derived from the more competent units of the Paleozoic and Proterozoic rocks exposed in the walls of Grand Canyon (Hereford and others, 1996a, b). For the most part, the clasts are composed of limestone, dolomitic limestone, and sandstone. These rocks are unmetamorphosed and lack penetrating fractures or shears. For estimating the age of fan surfaces, we used carbonate boulders derived from the Kaibab Formation (Permian) and Redwall Limestone (Mississippian). These boulders are abundant in the debris-flow deposits, and their relative abundance is a function of drainage basin size and relief (Melis and others, 1995). Redwall Limestone is typically the most abundant lithology because the unit is thicker and closer to the river than the Kaibab Formation, which crops out on the rim of Grand Canyon (Huntoon and others, 1986).

Methods

Twenty-six tributary debris fans were studied along the Colorado River from River mile 24.5 to 220, almost the entire length of the river in Grand Canyon (fig. 1). The studied fans are only a small sample of the 529 tributaries (Melis and others, 1995) in Grand Canyon, but those studied are among the largest in terms of contributing basin area and area of the debris fan. Median basin area of the 26 tributaries is 35 km^2; interquartile range is 3.7 to 37.3 km^2; and range of basin size is 0.4 to 257 km^2 according to the morphometric data in Melis and others (1995, appendices 2, 3).

Low-altitude color aerial photographs (approximate scale 1:4,800) of the river corridor flown in 1993 were used to select debris fans for study. The fans typically have one or more elevated segments with relatively low albedo indicating rock varnish. The spatial distribution of the studied fans is not random. These large fans tend to occur where the canyon at river level is relatively wide. The sampled fans are probably representative of debris fans in the size range 1 to 22 ha, which is approximately the same size as those in eastern Grand Canyon.

At each fan, the number of fan segments was determined by examining the degree of weathering and subsurface soil development. Surfaces were mapped on the aerial photographs to delineate their spatial distribution and to locate measurement transects. The youngest of the fan-forming surfaces (mostly younger than about 500 cal yr B.P.) were not studied, as surface weathering is virtually absent and carbonate clasts are unpitted. intermediate-age and older fan-forming surfaces were identified on the presence of Stage I soil-carbonate morphology (Machette, 1985), which is slightly deeper and more fully developed on the older surfaces (see fig. 2 in Hereford and others, 1996b). In addition, the relative abundance and degree of disintegration of sandstone and siltstone clasts increases between the intermediate-age and older surfaces. Darkness of rock varnish on sandstone boulders also increases with age, and darkness correlates well with depth of dissolution pits (Hereford and others, 1996a). One or more transects were made on each fan surface.

Surfaces were studied above the height of mainstem floods to eliminate erosional alteration of the surface. The preferred sample locality is usually upstream of the medial portion of the fan. A few sites, however, are debris-flow levees upstream of the fan head in the mouth of the tributary canyon. As discussed in a following section, surfaces in this setting are the oldest known to us. Small- to medium-size boulders (256-1012 mm) were measured. Boulders of this size are probably large enough to have been at the surface of the debris flow at the time of deposition. Weathering of the boulders began immediately after deposition rather than during subsequent erosional lowering of the surface.

The depth of dissolution pits on carbonate boulders was measured with a machinists depth micrometer with resolution of ±2.5 μm (±0.001 in). Ideally, the pit is a half-sphere, and the depth of the pit is essentially the radius of the sphere. The rock area or septa between the pits is assumed to be the initial, unweathered level of the surface of the boulder. The depth of individual pits on a single boulder varies considerably, particularly on the older surfaces. For this reason, the entire upper surface of the boulder was sampled with the number of measurements per boulder averaging 11.

Analysis of variance (ANOVA) was used to test homogeneity of pit depth among boulders in each transect. If the analysis showed that boulders of a particular transect were samples from the same population, then measurements from individual boulders were combined. The average depth and standard deviation of the combined data were assumed to be representative of the surface.

A number of transects, however, had one or more boulders with average depth that was significantly shallower or deeper than other boulders in the transect. Mixed populations of pit depths on a surface are possible and are expected in certain situations related to local contamination of the surface and from lithologic variation of carbonate boulders. A surface will locally have boulders of two ages

Table 1. Statistics of pit-depth data showing changes after analysis of variance (ANOVA)

	Total n before ANOVA		**Total n retained after ANOVA**	
	dfy & dfi	dfo	dfi (%)	dfo (%)
Transects	53	61	53 (100)	61 (100)
Boulders	299	318	258 (86)	248 (78)
Depth	3,322	3,651	2,730 (82)	2,670 (73)
Average depth (mm)	3.11	6.54	2.96	6.30
Standard deviation of depth (mm)	1.41	2.70	1.28	2.33

where a younger debris flow overtops an older surface adjacent to the debris-flow channel. Large boulders of the older debris flow remain above the surface of the younger flow. These older boulders have been exposed longer and have slightly deeper average pit depth than the boulders of the younger debris flow.

In addition, the lithology of carbonate clasts may control weathering rate to some extent. We were not able to identify subtle differences in carbonate lithology because examination of fresh surfaces was not practical or appropriate in a National Park given the fragile character of debris-fan surfaces. For this reason, sampled boulders were not broken, overturned, or removed. This practice minimized damage to the fan surfaces, which are essentially pristine. Thus, boulders of dolomitic limestone, dolomite, and sandy dolomitic limestone were sampled inadvertently. These rocks probably have slightly different weathering rates than relatively pure limestone. Presence of such boulders on the fans is related to the source of the debris-flow sediment, which in turn is related to diagenetic and facies changes in the bedrock unit.

If ANOVA revealed mixed populations of measurements within a transect for reasons discussed above, then boulders with anomalous measurements were eliminated one-at-a time by repeated application of multiple-comparison ANOVA until a homogeneous group of boulders with statistically indistinguishable mean and variance was attained. Measurements from the remaining boulders were combined to form a single sample of the surface. This procedure simplifies further statistical analysis and comparison with other surfaces as the resulting data are normally distributed. In practical application, this data manipulation has little influence on conclusions regarding age and correlation of debris fans. The affect of dropping anomalous boulders from transects is summarized in Table 1. Overall, the average was mostly unaffected, but the standard deviation decreased.

Summary of Depth Measurements

The pit-depth data are summarized by surface age in figure 3. All individual measurements from the combined younger and intermediate-age category and from the older surfaces are shown in figure 3a. Pit depths on younger and intermediate-age surfaces range from 0.36 to 11.94 mm with average depth of 2.96 ± 1.28 mm. On the older surfaces, depths range from 0.71 to 24.13 mm and average depth is 6.3 ± 2.33 mm. The substantial overlap of pit depth between the age categories shows that the two surfaces cannot be separated with only a few measurements. Individ-

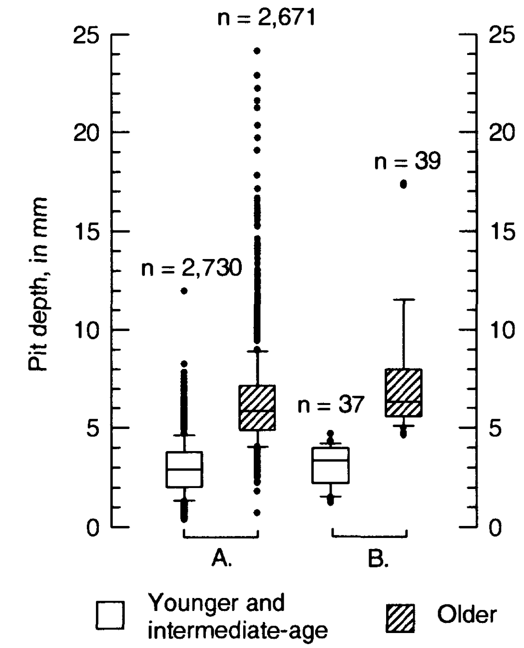


Figure 3. Box-plot statistical summary of pit-depth measurements by age category. A) Full range of all individual measurements grouped by surface age, and B) Average pit depth of mapped surfaces. Box is interquartile range, horizontal line is median depth, capped vertical line is range of 5 to 95 percentiles, and solid circles are measurements and averages below and above the 5 and 95 percentiles, respectively.

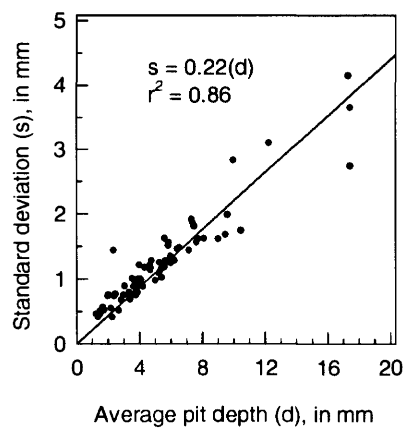


Figure 4. Standard deviation of depth measurements as a function of average depth.

ual measurements overlap widely on surfaces known to be of different age based on degree of weathering of sandstone boulders, darkness of rock varnish, soil-carbonate morphology, and relative elevation.

Figure 3b shows the distribution of average depths of all sampled intermediate-age and older surfaces. Average pit depth of intermediate-age surfaces, which includes the oldest of the younger age category, ranges from 1.2 to 4.67 mm; average pit depth of older surfaces ranges from 4.62 to 17.42 mm. This plot (fig. 3b) shows that intermediate-age and older surfaces are clearly differentiated on the basis of average pit depth. Variability of pit depth increases with age of the surface as shown in figure 4, which shows standard deviation of pit depth as a function of average depth without classification into intermediate-age and older categories. On average, the variability of depth increases by about 0.2 times the average depth.

Rate of Pit Deepening

This section of the report derives the pit-deepening rate of carbonate boulders on debris fans in Grand Canyon from the depth of dissolution pits on independently dated surfaces. Three dated debris fans and a closely dated archeologic feature were used to estimate deepening rate. Figure 5 shows the mean value of the ages and pit depths, the variability of this data, and the estimated deepening rate, which is a linear function of time as discussed in a following section of the report.

Samples one and three are radiocarbon ages of debris-flow deposits. The location and stratigraphic context of these deposits and surfaces are described in Hereford (1996, table 1, localities 2, 3 and 4) and Hereford and others (1996a, fig. 10, table 3). The radiocarbon ages were calibrated to calendar years and plotted as calibrated years B.P. (cal yr B.P.). Measurements were made on the fan surface of the same deposits near the medial portion of the debris fan. Sample one is a radiocarbon-dated hearth penetrating the

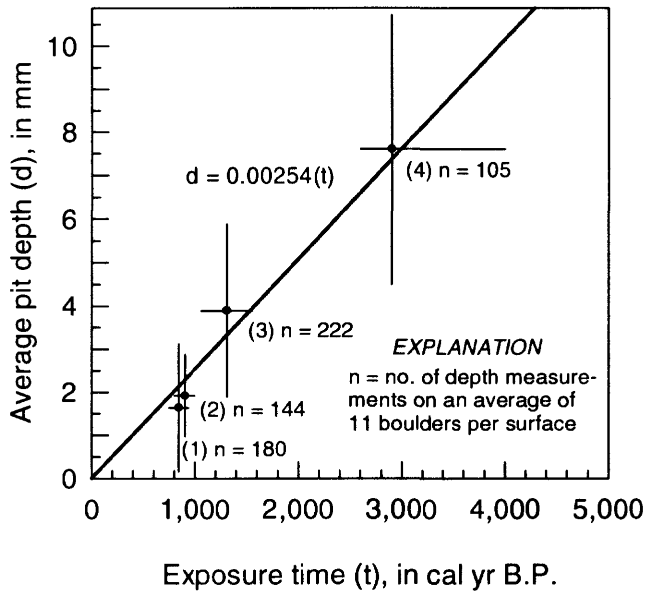


Figure 5 (opposite). Age of fan surfaces (nos. 1, 3, and 4) and an archeologic structure (no. 2) with corresponding average depth of dissolution pits (solid circles). Vertical bars are the ±2 standard deviation range of pit depth. Horizontal bars of numbers 1 and 3 are the ±2 standard deviation range of calibrated radiometric dates. Number 2 horizontal bar is age range of archeologic structure made of carbonate boulders; number 4 horizontal bar is calculated uncertainty of ^{3}He data (Thure E. Cerling, written commun., 1996).

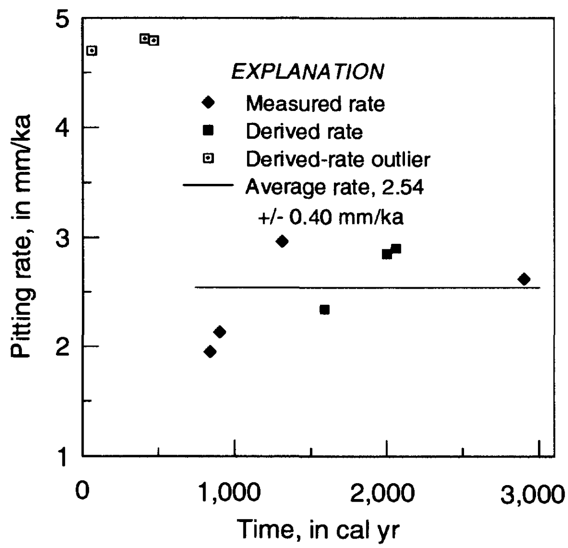


Figure 6 (opposite). Calculated pitting rates. Derived rates (solid squares) are the absolute differences of all paired combinations of ages and average pit depths.

surface of a younger intermediate-age deposit at the Palisades Creek debris fan. The age (840 cal yr B.P., fig. 5) provides a minimum age of the debris-flow deposit. This age, however, is almost identical to another from just below the base of the deposit where the distal, fine grained facies of the debris flow is interbedded with alluvium of the Colorado River. This alluvium is older than about 750 cal yr B.P. based on archeologic remains (Hereford and others, 1996a). The debris-flow deposit is near the top of the alluvium. The deposit, therefore, is somewhat older than 750 cal yr B.P., which is consistent with the radiocarbon ages.

Sample three is the median of two radiocarbon ages collected from just below and immediately above the distal facies of an older intermediate-age debris flow interbedded with alluvium of the Colorado River. The charcoal samples were collected in the subsurface where the debris-flow deposits are interbedded with alluvium. The age of 1310 cal yr B.P. is consistent with the age of the underlying surface whose age is between 1250-1650 cal yr B.P. (Hereford and others, 1996a).

Sample two is from an archeologic feature near the head of Nankoweap Canyon (Hereford and others, 1996a). This archeologic structure is a small check dam built of Redwall Limestone boulders by the Kayenta Anasazi. Potsherds indicate clearly that the structure was built in Pueblo II time between 800-950 cal yr B.P. (the error bar in fig. 5); construction age is assumed to be 875 cal yr B.P. The Anasazi collected the limestone boulders used in construction from the bed of a nearby wash, therefore, the boulders were not pitted at the time of construction.

Sample four is a cosmogenic ^{3}He surface exposure age from basalt boulders (Robert H. Webb, 1995, oral commun.; Cerling and others, 1995) on the topographically highest and oldest surface on the Prospect Canyon debris fan in western Grand Canyon (fig. 1). The age of 2,900 cal yr B.P. is the oldest Holocene surface yet dated in Grand Canyon. Pitting of limestone boulders on this surface is well developed, although older fan surfaces with greater pit depths are not unusual elsewhere in Grand Canyon.

Calculation of pit deepening rate

Measured deepening rates and rates derived from the absolute differences among the measured data (fig. 5) are shown in figure 6. The average deepening rate was calculated from the four measured and three derived rates, excluding the three derived-rate outliers. These rates are normally distributed with average of 2.54 ± 0.40 mm/ka ($n = 7$); the probability that the rates are not normally distributed is 0.42. Rate of pit deepening is independent of time as indicated by linear regression and the lack of correlation between time and average depth. Slope of the regression line is 0; probability that slope is not 0 is only 0.18. Time and pit deepening rate are unrelated, as the correlation coefficient is not significantly different from 0 with probability > 0.05. These results suggest that pit deepening rate of the carbonate rocks is constant and has not changed during the late Holocene or at least the last 3 ka.

Three of the derived rates are outliers (fig. 6). The anomalous rates are 4.81, 4.79, and 4.7 mm/ka. These rates are too large for the known age of intermediate-age fan surfaces (750-1,290 cal yr B.P., Hereford and others, 1996a) in eastern Grand Canyon. For example, if the rate was actually 5 mm/ka, these dated intermediate-age surfaces should have average depths ranging from 3.75 to 6.45 mm. About 75 percent of intermediate-age surfaces, however, have average pit depth < 4 mm, and even the oldest intermediate-age surfaces have depths < 6.45 mm (fig. 3).

A variety of mathematical functions fit the data shown in figure 6, however, a linear function is conservative and is expected from physical processes of limestone weathering. A linear relation is also supported by weathering rates estimated from dated tombstones and archeologic structures made of carbonate stone. Weathering of limestone proceeds at a constant rate that varies only with climate and solubility of limestone (Colman, 1981), whereas weathering of silicate rocks decreases with time. Weathering of limestone is a congruent dissolution process which does not produce surface residues that eventually slow weathering. The carbonate rocks in debris fans of Grand Canyon are not pure limestone. Nevertheless, weathering of these rocks as measured by surface roughness and pitting appears to approximate a constant rate during at least the late Holocene (fig. 6).

Numerous studies address surface weathering and pitting of limestone and marble tombstones and archeologic structures as old as 2,600 cal yr B.P. (Danin, 1983; Meierding, 1981; 1993; Klein, 1984; Dragovich, 1986; Neil, 1989; Cooke and others, 1995). The depth of dissolution pits is a linear function of time on well-dated limestone walls and monolithic tombs in Jerusalem up to 2,600 years old (Danin, 1983), a period comparable to the age of debris-fan surfaces in Grand Canyon. On a shorter time-scale, pitting of carbonate tombstones reveals a constant pitting rate, although rates vary widely within an area and from region-to-region. These studies, described below, report constant pitting rates, with the exception of Klein (1984) and Cooke and others (1995).

Klein (1984) questioned the application of linear regression for estimation of pitting rate and suggested an exponential function was more appropriate. Klein (1984) also suggested that changing weathering rates are related to the additional time needed to attack the polished surface of the tombstone. Cooke and others (1995) inferred that short-term pitting rates could increase with time, remain constant, decrease with time, or follow some combination of the three. In urban areas, for example, gradually increasing atmospheric pollution would increase weathering. Constant rate implies that the stone is in equilibrium with the environment. Decreasing rate suggests that the weathering process is self limiting, as shown by Colman (1981) for silicate rocks. It seems unlikely, however, that atmospheric pollution has affected pitting of limestone boulders in Grand Canyon and we see no evidence that carbonate weathering is self limiting on a time scale of several thousand years.

The main non-anthropogenic factor controlling weathering rate of carbonate tombstones and presumably naturally occurring carbonate stone is average annual rainfall (Meierding, 1981; 1993; Neil, 1989; Reddy, 1989). In a study of aqueous geochemistry of rainfall runoff from carbonate stone, Reddy (1989) found that surface recession was directly proportional to the rainfall amount and that the rate of recession is the same for limestone and marble. Likewise, in a study of marble tombstones in areas of widely different climate, Meierding (1981) found that pitting rate is directly proportional to the amount of rainfall; pitting rates range from of 1.7 to 15 mm/ka with mean annual rainfall of 200 to 1,000 mm/yr, respectively. The influence of mean annual temperature on pitting rate is ambiguous and studies have not specifically analyzed this factor (Neil, 1989), although one could argue that temperature is equally as important as precipitation.

Reported rates of limestone weathering (Cooke and others, 1995, table 1, summarize recent studies) are difficult if not impossible to compare with pitting of carbonate boulders in Grand Canyon because of different methods used to estimate weathering, aspect of the stone, and climate. The various methods used to measure surface recession of tombstones differ considerably from measurement of pit depth used in this study. Typically, legibility of the tombstone inscription, relief of lead lettering, or relief of siliceous veins (which are relatively unaltered by weathering) are used to measure surface recession due to weathering. We cannot compare measured surface recession from these earlier studies with the depth of dissolution pits on carbonate boulders in Grand Canyon. Studies of tombstones control for aspect of the stone, but aspect is nearly impossible to control with irregularly shaped and randomly oriented boulders on debris-fan surfaces. Finally, climate of Grand Canyon is substantially drier than temperate regions where most carbonate weathering rates have been determined.

Of the several investigations cited above, Danin's (1983) study of archeologic sites in Jerusalem most closely resembles the present study in terms of method and time scale; nevertheless results are not directly comparable with Grand Canyon. Danin (1983) measured the maximum depth of dissolution pits on west-facing limestone walls of dated archeologic structures. The average pitting rate on these surfaces over 2,600 years is 5 mm/ka, which is nearly twice the rate of 2.54 mm/ka estimated for carbonate boulders in Grand

Canyon. Comparison of pitting rates is difficult because maximum pit depth rather than average depth was used, west-facing vertical surfaces rather than mostly sub-horizontal boulder surfaces were sampled, and the climate of Jerusalem is substantially wetter and cooler than the Grand Canyon (Hereford and others, 1996a).

In summary, average pit depths of carbonate boulders on four dated surfaces in Grand Canyon show that pit depth increases on average by 2.54 mm/ka. This rate is a linear function of time over the past 3 ka, which is consistent with physical process of limestone weathering. For purposes of dating surfaces in Grand Canyon, we assume that the rate is essentially constant over at least the mid- to late Holocene and that the 2.54 mm/ka rate applies throughout Grand Canyon along the Colorado River, a region that is broadly similar in terms of elevation and precipitation. Finally, dissolution of carbonate stone is closely linked to annual precipitation. Because the process is cumulative, increases and decreases of precipitation tend to average out, resulting in an essentially constant long-term average pitting rate.

Age and Correlation of Prehistoric Fan Surfaces

This section of the report deals with the ages and spatial and temporal correlation of debris-fan surfaces. Ages were estimated from the 2.54 mm/ka average deepening rate; estimated ages range from 500 to 7,000 cal yr B.P. The dates reported here are subject to revision because additional radiometric dating may further refine the pitting rate.

Average depth of dissolution pits and estimated ages of 71 fan surfaces at the 26 tributary fans are shown in figure 7. The five shaded areas (fig. 7) are clusters with relatively high number of correlative surfaces that include 66 percent of the surfaces. The mid-point of the clusters (horizontal lines) correspond with the peaks in figure 8. Overall, 75 percent of the surfaces are younger than 2.8 ka. The oldest surface preserved on a fan is at River mile 124.2L (fig. 1) with dissolution pits averaging 12.22 mm deep. This corresponds to about 4,800 cal yr B.P. Even older surfaces are located at the mouths of Forster and Fossil Canyons and in the tributary canyons at River mile 220R. The three surfaces have dissolution pits averaging 17.29, 17.41, and 17.42 mm, respectively; this is about 6,850 cal yr B.P. These debris-flow levees are preserved in the mouths of the canyon away from the erosional effects of the Colorado River.

The youngest surfaces dateable by this method are at 209 Mile Canyon, Granite Park Wash, Palisades Creek, and Nankoweap Canyon (figs. 1 and 7). Dissolution pits on the four surfaces average 1.2 to 1.47 mm deep, which is probably between 500 to 600 cal yr B.P. An average depth of around 1.2 mm is probably the minimum amount of surface pitting detectable by this method; carbonate boulders on fan-forming surfaces younger than this do not have measurable dissolution pits.

Many widely spaced tributaries have debris-fan surfaces with essentially identical exposure times, as shown by average depth of dissolution pits on carbonate boulders (figs. 1, 7). The degree of time-stratigraphic correlation of fan surfaces (or the between fan surface-age variation) among the 26 debris fans is quantified by considering the nonparametric statistics of the differences (n = 70) of the sorted list of average depths. The median difference in pit depth among the surfaces is only 0.1 mm, and the interquartile range is 0.05 to 0.16 mm. In many cases, this median difference and range are smaller than the measurement errors. Nevertheless, fan surfaces with carbonate boulders having nearly identical average pit depth are typical of widely spaced tributaries, which suggests the surfaces are time correlative within the limits of this method. This result suggests that the conditions leading to formation of debris-fan surfaces influence the entire

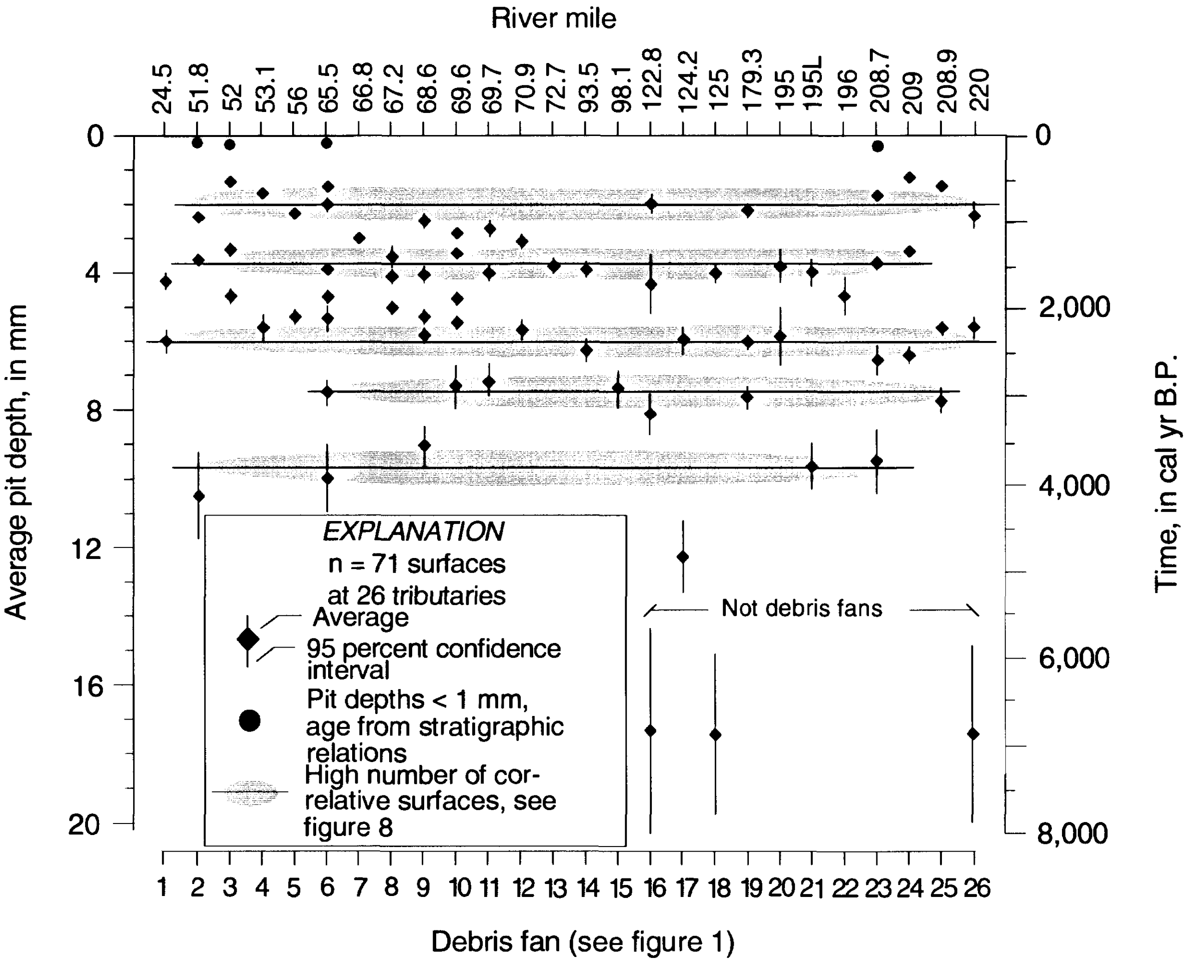


Figure 7. Age and correlation chart of debris-fan surfaces inferred from average depth of dissolution pits.

Grand Canyon, although these conditions do not affect every tributary.

The typical time between formation of fan surfaces (or the within fan variation of surface ages) is estimated from the differences in pit depth calculated for each tributary fan with more than one surface (23 of the studied fans). The median difference (n = 45) in average depth of dissolution pits on the 23 fans is 2.13 mm and the interquartile range is 1.32 to 3.22 mm. This suggests that surfaces of the typical fan in the period 500 to 7,000 cal yr B.P. (fig. 7) differ in age by about 850 years within a range of 500 to 1,250 years. This 850 year recurrence interval is much longer than the 1-to-100 year average recurrence interval (Melis and others, 1993) of channelized debris flows during historic time.

A smoothed density trace of average pit depth (fig. 8; Chambers and others, 1983, p. 32-41) of the 71 studied surfaces suggests that ages of the surfaces cluster in time. A striking feature of the density trace is the progressive increase in the number of older surfaces beginning about 4,700 cal yr B.P. The clustering of fan surfaces in the late Holocene contrasts with the lack of early and middle Holocene surfaces, but the clustering probably did not result entirely from increased debris-flow activity. Older fan surfaces are under-represented because of progressive erosion and removal by the Colorado River. The dominance of relatively young fan surfaces, therefore, is largely a function of preservation.

The density trace has five peaks or clusters (fig. 8). The youngest and least prominent is

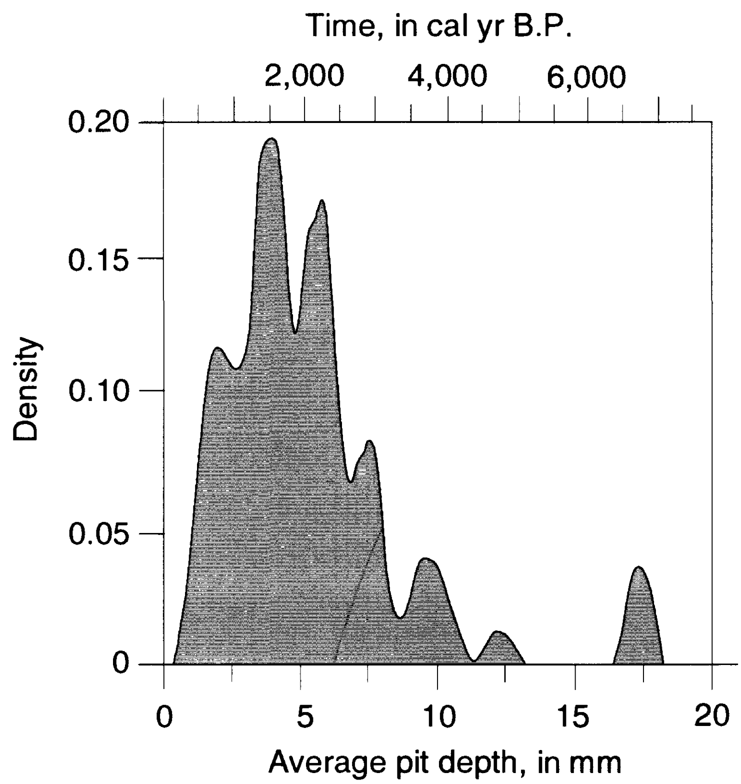


Figure 8. Density trace of average pit depth.

around 2.0 mm average depth, corresponding to an age of 790 cal years B.P. Two prominent peaks around 3.7 and 6.0 mm average depth account for 41 percent of the surfaces. These two periods, around 1,460 and 2,360 cal yr B.P., have a large number of preserved fan surfaces, suggesting that debris-flow frequency was relatively high at these times. Two other peaks at 7.5 and 9.7 mm average depth include about 13 percent of the studied surfaces. These are also episodes of increased fan preservation around 2,950 and 3,820 cal yr B.P.

Briefly, fan surfaces at widely separated tributaries are correlative as they have similar exposure times. Increased debris-flow activity is clustered into at least two and possibly five distinct episodes in the late Holocene. In most cases, the surfaces of any particular fan differ in age by about 850 years, which is probably the recurrence interval of fan-forming debris flows in the Grand Canyon. Early and mid-Holocene fan surfaces are not preserved at the river.

Discussion and Conclusions

Preservation of prehistoric debris fans is linked to interaction between the frequency of fan-forming debris flows and removal of the deposits by the Colorado River. This interaction has probably been controlled by climate of the Grand Canyon region through its affect on local runoff and by the climate of the Colorado River drainage basin which controlled the size of mainstem floods. Only fans deposited in the last 3 to 4 ka have been preserved (fig. 7), suggesting that gradual, flood-related shifting of the main channel eventually removed the earlier deposits.

Erosional modification of debris fans in the past several thousand years by relatively large floods was suggested by Kieffer (1985; 1990). Large-scale topographic maps show that debris fans are extensively modified. For example, the distal margins of debris fans in eastern Grand Canyon, Nankoweap rapids area, Prospect Canyon at Lava Falls Rapid, and

Granite Park (fig. 1) are truncated along the river (Hereford and Thompson, 1994a, b; Hereford and others, 1996a, b; Webb and others, 1996). Truncated debris fans were eroded by the river in the past 1-3 ka, most likely by relatively rare and large floods such as those documented by O'Connor and others (1994). In the future and without the reduction of floods caused by Glen Canyon Dam, existing debris fans would probably be removed entirely or reduced to high-level remnants near the margins of the channel. This gradual removal of the fans is presently interrupted or greatly curtailed by regulated streamflow, but the possibility of a fan-forming debris flow at any of the large fans studied in this report is unchanged.

Mainstem floods are clearly implicated in erosion of debris fans. The frequency of large floods of the Colorado River in Marble Canyon (O'Connor and others, 1994) and in nearby tributaries outside of Grand Canyon (Ely and others, 1993) is broadly correlated with the number of preserved debris fans. Large floods, both studies agree, were relatively frequent from 4,800 to 3,100 cal yr B.P. and from 1,300 cal yr B.P. up to the present. In Marble Canyon, these floods were estimated to be larger than 5,700 m^3/s; floods of this size have annual exceedence probability of 1 percent or less (O'Connor and others, 1994). In addition, slackwater flood deposits at the mouth of Lava Creek in eastern Grand Canyon have nine beds deposited by the Colorado River from 550 to 110 cal yr B.P. (Hereford, 1996). Although the maximum size of the floods is not determined, the deposits are above the historic flood level of 8,500 m^3/s. Large floods, therefore, were relatively numerous during 550 to 110 cal yr B.P.; these floods probably reworked the toes of the debris fans forming the present configuration of the channel. Likewise, the early period (4,800 to 3,100 cal yr B.P.) of frequent floods probably removed older debris fans or continued an erosional episode that began earlier in the Holocene.

An alternative explanation for the lack of old debris fans is that early and mid-Holocene deposits are present and buried by net aggradation of the fans, but this seems unlikely given that older surfaces have the highest elevation relative to younger surfaces on any particular fan. Early Holocene debris-flow deposits are present (fig. 7) in protected sites in the mouths of tributary canyons. However, the surfaces of the early Holocene deposits project downstream to the debris fan where they are topographically above younger surfaces.

Temporal clusters in the ages of fan surfaces (figs. 7, 8) probably result from increased debris-flow activity. The late Holocene climate of the Grand Canyon region is not well understood, so it is not possible to compare increased debris-flow activity with episodes of increased precipitation. Increased debris-flow activity around 3,820 and 1,460 cal yr B.P., however, is roughly contemporaneous with high stands of Mono Lake in eastern California (Stine, 1990). The level of Mono Lake fluctuates directly with the amount of snowmelt runoff from the Sierra Nevada. In addition, the period 3,000 to 4,000 cal yr B.P., known as the early Neoglacial climate episode, was probably cooler and wetter than at present throughout the Southwest (Enzel and others, 1992). These fluctuations and the Neoglacial episode suggest that winter precipitation in the Grand Canyon region may also have been high, leading to a relatively large number of debris flows around 3,000 to 4,000 cal yr B.P. and 1,460 cal yr B.P.

Implications for channel evolution and river navigability

With Glen Canyon Dam in place, future development of the river channel and navigability of the river are controlled by tributary debris flows rather than the large mainstem floods of the pre-dam era. Constriction of the channel by deposition of debris-flow sediment and subsequent reworking by floods are well understood for channelized debris flows of the past hundred years (Kieffer, 1985; Webb and others, 1989; 1996). However, these recent debris flows are small relative to the prehistoric, fan-forming debris flows discussed in this report. In addition, the prehistoric floods that reworked the deposits were probably larger than any historic-age flood, controlled or otherwise. Sediment from fan-forming debris flows probably extended across the channel to a depth of several meters (Hereford and others, 1996a), unlike recent deposits that typically did not cross the channel (Webb and others, 1996). The large volume of sediment deposited in the channel by prehistoric debris flows quite likely increased the severity of any particular rapid, possibly forming a waterfall (Kieffer, 1985). A striking example of an ancient waterfall is the Prospect Canyon debris fan in western Grand Canyon (fig. 1). Reconstruction of the 2,900 cal yr B.P. deposits shows they must have extended across the channel to a depth of 5-10 m (Webb and others, 1996, fig. 35). Although not as dramatic, debris-flow deposits extended across the channel several times in the past 1-3 ka at most tributary fans in eastern Grand Canyon and Marble Canyon (Hereford and others, 1996a, b; Hereford, 1996).

Any attempt to predict the occurrence of debris flows in Grand Canyon is difficult at best and impossible at worst. Nevertheless, fan-forming debris flows will occur during the projected life span of Glen Canyon Dam. Moreover, if the prehistoric patterns of debris-flow activity (figs. 7, 8) are repeated in the future, the channel will likely become severely constricted at many of the major tributaries (fig. 1). The cluster of prehistoric debris-flow activity about 790 cal yr B.P. (fig. 7) suggests that another episode might begin in only 60 years, assuming the average time between events canyon-wide is 850 yrs. The youngest fan-forming deposits known to us are in Marble Canyon and eastern and western Grand Canyon; these deposits might be the precursors of fan forming debris-flow activity.

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References

Cerling, T.E., Rigby, A., Webb, R.H., and Poreda, R.J., 1995, Cosmogenic ^{3}He exposure ages of debris flows and lava outburst dams in the Grand Canyon, USA (abs.): Eos, Transactions, American Geophysical Union, v. 76, no. 46, Suppl., p. 684.

Chambers, J.M., Cleveland, W.S., Kleiner, Beat, and Tukey, P.A., 1983, Graphical methods for data analysis: Belmont, California, Wadsworth International, 395 p.

Colman, S.M., 1981, Rock-weathering rates as functions of time: Quaternary Research, v. 15, p. 250-264.

Cooke, R.U., Warren, Andrew, and Goudie, A.S., 1993, Desert geomorphology: London, University College of London Press, 526 p.

Cooke, R.U., Inkpen, R.J., and Wiggs, G.F.S., 1995, Using gravestones to assess changing rates of weathering in the United Kingdom: Earth Surfaces Processes and Landforms, v. 20, p. 531-546.

Danin, Avinoam, 1983, Weathering of limestone in Jerusalem by cyanobacteria: Zeitschrift für Geomorphologie, v. 27, p. 413-421.

Danin, Avinoam, and Garty, Jacob, 1983, Distribution of cyanobacteria and lichens on hillsides of the Negrev Highlands and their impact on biogenic weathering: Zeitschrift für Geomorphologie, v.27, p. 423-444.

Dragovich, D., 1986, Weathering rates of marble in urban environments, eastern Australia: Zeitschrift für Geomorphologie, v. 30, p. 203-

214.

Ely, L.L., Enzel, Yehouda, Baker, V.R., and Cayan, D.R., 1993, A 5000-year record of extreme floods and climate change in the southwestern United States: Science, v. 262, p. 410-412.

Enzel, Yehouda, Brown, W.J., Anderson, R.Y., McFadden, L.D., and Wells, S.G., 1992, Short-duration Holocene Lakes in the Mojave River drainage basin, southern California: Quaternary Research, v. 38, p. 60-73.

Fairley, H.C., Bungart, P.W., Coder, C.M., Huffman, Jim, Samples, T.L., and Balsom, J.R., 1994, The Grand Canyon river corridor survey project: archaeological survey along the Colorado River between Glen Canyon Dam and Separation Canyon: Report prepared for Grand Canyon National Park Service, Cooperative Agreement No. 9AA-40-07920, 276 p.

Hamblin, W.K., and Rigby, J.K., 1968, Guidebook to the Colorado River Part 1: Lee's Ferry to Phantom Ranch in Grand Canyon National Park: Provo, Utah, Brigham Young University Geology Studies, v. 15, part 5, 125 p.

Hereford, Richard, 1996, Map showing surficial geology and geomorphology of the Palisades Creek area, Grand Canyon National Park, Arizona: U.S. Geological Survey Miscellaneous Investigation Series Map I-2449, scale 1:2,000 (with discussion).

Hereford, Richard, and Thompson, K.S., 1994a, Topographic map of the Nankoweap Rapids area, Marble Canyon, Arizona: U.S. Geological Survey Open-File Report 94-564, scale 1:2,000.

_____, 1994b, Topographic map of the Granite Park area, Grand Canyon, Arizona: U.S. Geological Survey Open-File Report 94-563, scale 1:2,000.

Hereford, Richard, Thompson, K.S., Burke, K.J., and Fairley, H.C., 1996a, Tributary debris fans and the late Holocene alluvial chronology of the Colorado River, eastern Grand Canyon, Arizona: Geological Society of America Bulletin v. 108, p. 3-19.

Hereford, Richard, Burke, K. J., and Thompson, K. S., 1996b, Map showing Quaternary geology and geomorphology of the Nankoweap Rapids area, Marble Canyon, Arizona: U.S. Geological Survey Open-File Report 96-502, scale 1:2,000 (with discussion).

Howard, Alan, and Dolan, Robert, 1981, Geomorphology of the Colorado River in the Grand Canyon: Journal of Geology, v. 89, p. 259-298.

Huntoon, P.W., Billingsley, G.H., Breed, W.J., Sears, J.W., Ford, T.D., Clark, M.D., Babcock, R.S., and Brown, E.H., 1986, Geological map of the eastern part of Grand Canyon National Park, Arizona: Grand Canyon, Arizona, Grand Canyon Natural History Association, scale 1:62,500.

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. 385-405.

_____, 1990, Hydraulics and geomorphology of the Colorado River in the Grand Canyon, *in*, Beus, S.S., and Morales, Michael, *eds*., Grand Canyon Geology: New York, Oxford University Press, p. 333-383.

Klein, Micha, 1984, Weathering rates of tombstones measured in Haifa, Israel: Zeitschrift für Geomorphologie, v. 28, p. 105-111.

Machette, M.N., 1985, Calcic soils of the southwestern United States: Geological Society of America Special Paper 203, p. 1-21.

Meierding, T.C., 1981, Marble tombstone weathering rates: A transect of the United States: Physical Geography, v. 2, p. 1-18.

_____, 1993, Inscription legibility method for estimating rock weathering rates: Geomorphology, v. 6, p. 273-286.

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, H.W., Su, S.T., and Wen, Feng, *eds*., Hydraulic engineering '93, Proceedings of the 1993 conference: Hydraulics Division, American Society of Civil Engineers, v. 2, p. 1290-1295.

Melis, T.S., Webb, R.H., and Wise, T.W., 1993, Effect of historic debris flows on the Colorado River in Grand Canyon (abs.): Geological Society of America Abstracts with Programs, v. 25, p. A-142.

Melis, T.S., Webb, R.H., Griffiths, P.G., and Wise, T.W., 1995, Magnitude and frequency data for historic debris flows in Grand Canyon National Park and vicinity, Arizona: U.S. Geological Survey Water-Resources Investigations Report 94-4214, 285 p.

Neil, David, 1989, Weathering rates of subaerially exposed marble in eastern Australia:

Zeitschrift für Geomorphologie, v. 33, p. 463-473.

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 4500-year record of large floods on the Colorado River in the Grand Canyon, Arizona: Journal of Geology, v. 102, p. 1-9.

Reddy, M.M., 1989, Acid rain damage to carbonate stone: A quantitative assessment based on the aqueous geochemistry of rainfall runoff from stone: Earth Surface Processes, v. 13, p. 335-354.

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 1985, Colorado River, Grand Canyon National Park, Arizona: U.S. Geological Survey Professional Paper 1493, 74 p.

Schwartz D.W., Chapman, R.C., and Kepp, Jane, 1980, Unkar delta: School of American Research Press, Grand Canyon Archaeology Series, v. 2, 405 p.

Stevens, Larry, 1990, The Colorado River in Grand Canyon, a guide: Flagstaff, Arizona, Red Lake Books, 110 p.

Stine, Scott, 1990, Late Holocene fluctuations of Mono Lake, eastern California: Palaeogeography, Palaeoclimatology, Palaeoecology: v. 78, p. 333-381.

Webb, R.H., Pringle, P.T., and Rink, G.R., 1989, Debris flows from tributaries of the Colorado River, Grand Canyon National Park, Arizona: U.S. Geological Survey Professional Paper 1492, 39 p.

Webb, R.H., Melis, T.S., Wise, T.W., and Elliot, J.G., 1996, The great cataract: Effects of late Holocene debris flows on Lava Falls Rapid, Grand Canyon National Park and Hualapai Indian Reservation, Arizona: U.S. Geological Survey Open-File Report 96-460, 96 p., 1 plt.