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Numerical Ages of Holocene Tributary Debris Fans Inferred from Dissolution Pitting on Carbonate Boulders in the Grand Canyon of Arizona

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Carbonate boulders transported down steep tributary channels by debris flow came to rest on Holocene debris fans beside the Colorado River in Grand Canyon National Park. Weakly acidic rainfall and the metabolic activity of blue-green algae have produced roughly hemispheric dissolution pits as much as 2-cm deep on the initially smooth surfaces of the boulders. The average depth of dissolution pits increases with relative age of fan surfaces. The deepening rate averages 2.4 mm/1000 yr (standard error = 0.2 mm/1000 yr), as calculated from several radiometrically dated surfaces and an archeological structure. This linear rate, which appears constant over at least the past 3000 yr, is consistent with field relations limiting the maximum age of the fans and with the physical chemistry of limestone dissolution. Dissolution-pit measurements (*n* = 6973) were made on 617 boulders on 71 fan surfaces at the 26 largest debris fans in Grand Canyon. Among these fan surfaces, the average pit depth ranges from 1.2 to 17.4 mm, and the resulting pit dissolution ages range from 500 to 7300 cal yr B.P. Most (75%) surfaces are younger than 3000 yr, probably because of removal of older debris fans by the Colorado River. Many of the ages are close to 800, 1600, 2300, 3100, or 4300 cal yr B.P. If not the result of differential preservation of fan surfaces, this clustering implies periods of heightened debris-flow activity and increased precipitation.

Key Words: **Colorado River; debris fan; debris flow; dissolution pitting; Grand Canyon; stratigraphic correlation; weathering rate.**

INTRODUCTION

This paper addresses the ages and stratigraphic correlation of Holocene debris fans along the Colorado River in Grand Canyon (Fig. 1). Debris fans composed of poorly sorted, bouldery sediment with multiple, mostly prehistoric surfaces (Hereford *et al.*, 1996) are ubiquitous in Grand Canyon at the mouths of tributary streams (Hamblin and Rigby, 1968). We estimate their ages and correlate debris-flow deposits using a dating technique based on time-calibrated dissolution of carbonate boulders.

The ages and correlation of prehistoric debris fans have not been studied canyon-wide, although the fans have received much attention as geomorphic elements of the river system (Hamblin and Rigby, 1968; Howard and Dolan, 1981; Webb *et al.*, 1989; Schmidt, 1990; Schmidt and Graf, 1990; Melis and Webb, 1993; Melis *et al.*, 1995; Webb *et al.*, 1996). Most fans are late Holocene as judged by their relation to dated alluvium (Hereford *et al.*, 1996). But the fan surfaces and deposits are difficult to date directly because material suitable for radiocarbon analysis is rare.

In this paper, ages of debris-fan surfaces are estimated from linear relation between surface age and the average depth of dissolution pits on carbonate boulders. Dissolution pits result from a combination of weakly acidic rainfall and the metabolic activity of endolithic cyanobacteria (Danin, 1983; Danin and Garty, 1983). Although the importance of biogenic weathering is uncertain (Cooke *et al.*, 1993, p. 44), one cause of dissolution pits may be the release of excess CO_2 following rainfall-induced photosynthesis. Regardless, atmospheric or metabolic CO_2 combines with water to form carbonic acid (H_2CO_3) that etches the surfaces of carbonate boulders.

Previous Studies of Prehistoric Debris Fans in Grand Canyon

Prehistoric debris fans in Grand Canyon (Fig. 1) were mapped and studied by Hereford (1996), Hereford *et al.* (1996; 1998; in

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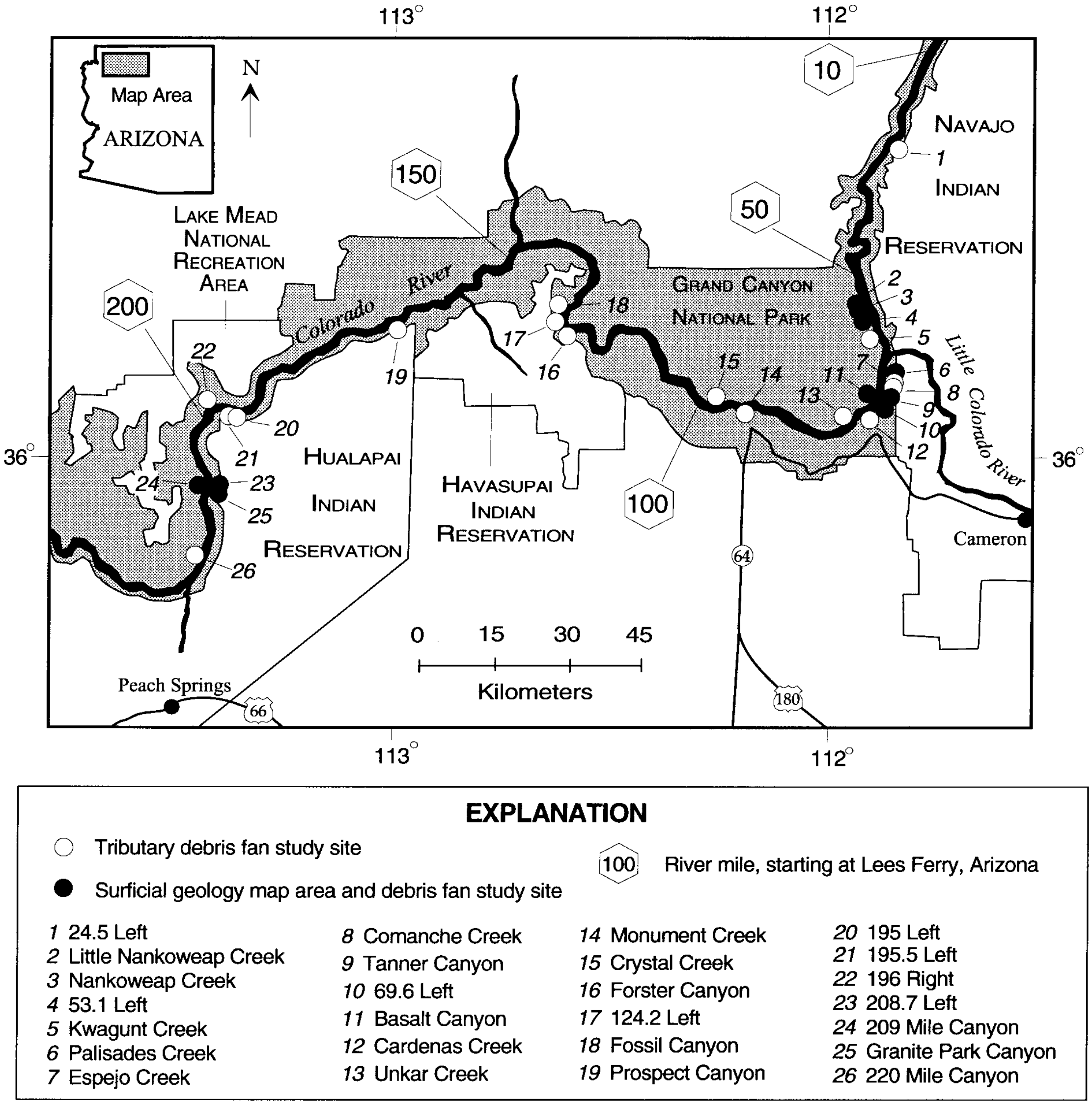

FIG. 1. Study area, Colorado River, Grand Canyon, Arizona.

press), and Webb *et al.* (1996). The typical debris fan has a relatively large inactive fan surface, mostly of prehistoric age, and a historically active (post-A.D. 1890) debris-flow channel that is entrenched into the fan (Fig. 2). The fans have been divided into several surfaces of different ages based on relative topographic position and degree of weathering (see Fig. 3 in Hereford *et al.*, 1996, and Figs. 2–5 in Hereford *et al.*, 1998). The surfaces parallel the underlying deposits and are contemporaneous with deposition. We divide the deposits into three main units that are further subdivided for mapping purposes into 5–6 units; the main units are informally referred to as the older, intermediate, and younger fan-forming surfaces or deposits.

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). Low-altitude color aerial photographs (approximate scale 1:4,800) of the river corridor were used to select debris fans for study. The studied fans, which are among the largest in Grand Canyon, are located where the canyon at river level is wider than average. Each fan typically includes one or more elevated segments having relatively low albedo indicating rock varnish.

Boulders 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 (Huntoon *et al.*, 1986). Most are 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 primarily from the Redwall Limestone (Mississippian).

These carbonate boulders are distinctive and relatively abun-

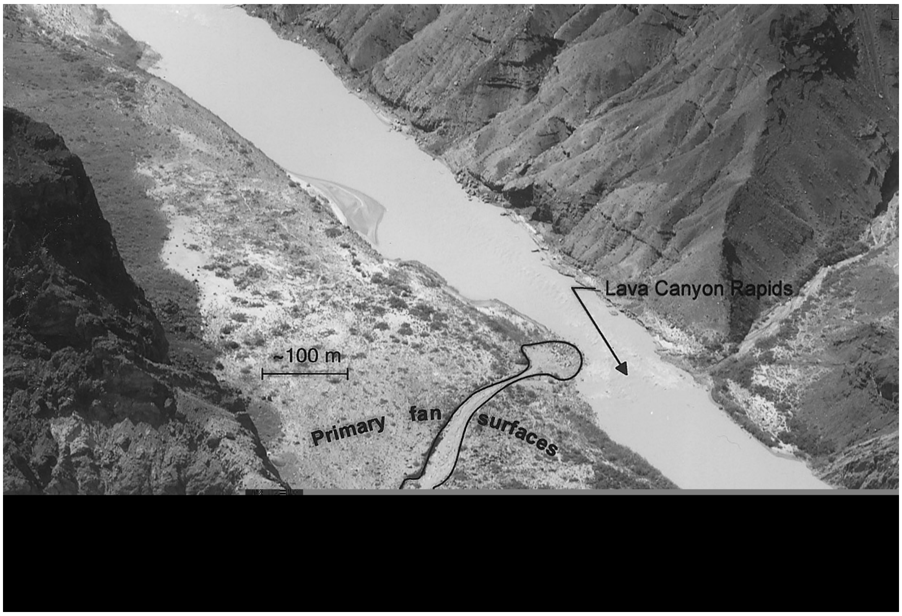

FIG. 2. Palisades Creek debris fan, a typical late Holocene fan in eastern Grand Canyon (Fig. 1, no. 6). The fan is bisected by an entrenched, historically active channel with channelized debris-flow deposits; the relatively dark areas are the inactive primary fan surfaces. The coarse-grained sediment of the debris fan controls the position of the Colorado River against the fan side of the canyon and the location of Lava Canyon Rapids (Stevens, 1990).

dant in the debris-flow deposits. Those with pitted surfaces are very finely to finely crystalline (~4–60 μm) dolomitic limestone derived from the Whitmore Wash, Mooney Falls, and Thunder Springs members of the Redwall Limestone (McKee and Gutschick, 1969 pp. 24–85). Three crystal sizes are typical of the Redwall Limestone boulders, aphanitic, very finely to finely crystalline, and coarsely crystalline. Coarsely crystalline boulders weather mechanically by granular disintegration and aphanitic boulders remain smooth without surface pitting.

At each fan, surfaces were mapped based on the degree of weathering, subsurface soil development, and relative topographic position. This mapping delineated sample areas for pit-depth measurements of carbonate boulders (Fig. 3). The relative age of fan surfaces corresponds to topographic position with the most elevated surface being the oldest. The younger fan-forming surfaces (mostly younger than about 500 cal yr B.P. based on stratigraphic relations with dated alluvium) occupy the lowest position on the fans and are only slightly weathered in most cases. Intermediate-age and older fan-forming surfaces were identified by the presence of Stage-I soil-carbonate morphology (Machette, 1985), which is more fully developed and slightly deeper on the older surfaces (see Fig. 2 in Hereford *et al.,* 1998). In addition, the relative abundance and degree of disintegration of sandstone and siltstone boulders increase 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 *et al.,* 1996).

Sample areas, which are identical to map units on large-scale geologic maps (Hereford, 1996; Hereford *et al.*, 1998; in press), were established from low-altitude aerial photographs, as described previously. The sample areas are too high to have been eroded by prehistoric mainstem floods. We sampled small to medium-size (ca 0.25–1 m) pitted-carbonate boulders (Fig. 3) because they are probably large enough to have been at the surface of the debris flow at the time of deposition. Chemical weathering of the boulders therefore began immediately after deposition rather than during subsequent erosional lowering of the surface.

The number of boulders with surface pitting is not large, ranging from 3 to 15 per sample area. We attempted to obtain depth measurements from each pitted boulder in each sample area. Pit measurements were made across the entire upward-facing, subhorizontal surface of the boulder to obtain an average pit depth.

A depth micrometer with resolution of ± 2.5 μm was used to measure the depth of dissolution pits. For convenience, we treat each pit as a half-sphere with pit depth equivalent to the radius of the sphere, and we assume the rock area between adjoining pits was the initial, unweathered level of the surface of the boulder. The area between dissolution pits, whether peaked or relatively flat, is a stable reference surface because deepening is probably concentrated in the surface depression once dissolution begins.

Analysis of variance (ANOVA) was used to test homogeneity of pit depth among boulders in each sample area. If the analysis showed that boulders of a particular area could be 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. Some sample areas, however, had

FIG. 3. Intermediate-age surface in the Nankoweap Creek area (Fig. 1, no. 3; Hereford *et al.,* 1998). Sandstone boulders are distinctly patinated and spalled; carbonate boulders are well pitted with average pit depth of 4.7 mm. Estimated exposure age is about 2000 cal yr B.P. based on the depth of dissolution pits. Scale, 15 cm long.

one or more boulders with average pit depth much different from most other boulders in the area.

Mixed populations of pit depths on a surface can be expected in certain situations related to the local geomorphic history of the surface. For example, a surface may locally have boulders of two ages where a younger debris flow overtops an older surface adjacent to the debris-flow channel. Large boulders of the older debris flow may remain above the surface of the younger flow. These older boulders would have been exposed longer and have slightly greater average pit depth than the boulders of subsequent flows.

In addition, the lithology of carbonate boulders may influence weathering rate, in which case populations of pit depth would be mixed further. We did not attempt to identify subtle differences in carbonate lithology because, working on pristine land in a National Park, we did not break, overturn, or remove the sampled boulders. Thus, boulders of dolomite and sandy dolomitic limestone were probably sampled inadvertently. These rocks may have slightly different weathering rates than purer carbonate.

If ANOVA revealed mixed populations of measurements within a sample area, for whatever reason, boulders with anomalous measurements were eliminated one at a time by repeated application of multiple-comparison ANOVA (Glantz, 1992, pp. 100–105) until a homogeneous group of boulders with statistically indistinguishable mean and variance was attained. Measurements from the remaining boulders were combined to develop a single sample of the surface. This procedure simplifies further statistical analysis and comparison with other surfaces. In practical application, the procedure has little affect on conclusions regarding age and correlation of debris fans. The effect of dropping anomalous boulders is summarized in Table 1, which shows that the average and standard deviation decrease slightly.

RATE OF PIT DEEPENING

Calibration Points

Three independently dated debris fans and a well-dated archeological feature were used to estimate a constant deepening rate (Fig. 4). The stratigraphic context, location, and statistics of the radiocarbon ages are in Hereford (1996, Table 1, localities 2, 3, and 4) and Hereford *et al.* (1996, Fig. 10, Table 3). The radiocarbon ages were calibrated to calendric years before A.D. 1950 (cal yr B.P.) with the Gronigen Radiocarbon Calibration Program (version of June 1991) using data current through 1989. Depth measurements were made on the dated fan surface as described in the preceding section.

Age-control point 1 is radiocarbon-dated charcoal from a hearth high in a debris-flow deposit at the Palisades Creek debris fan (Fig. 1, no. 6). The age, centered at 840 cal yr B.P. (Fig. 4), is a minimum for the debris-flow deposit. It is consistent with dating at a site where a distal facies of the debris flow is interbedded with alluvium of the Colorado River. The alluvium is older than about 750 cal yr B.P., as judged from archeological remains (Hereford *et al.,* 1996), so the debris-flow deposit is also older than 750 cal yr B.P.

Age-control point 2 is from an archeological structure at the head of Nankoweap Canyon (Fig. 1, no. 3; Hereford *et al.,* 1998). This structure is a small check dam built of boulders of Redwall Limestone by the Kayenta Anasazi. Potsherds show that the structure was built in Pueblo II time between 800–950 cal yr B.P. (the error bar in Fig. 4); construction age is assumed to be 875 cal yr B.P. Because Anasazi collected the boulders used in construction from the bed of a nearby wash, the boulders were not pitted at the time of construction.

Age-control point 3 is the median of two radiocarbon ages on charcoal collected from just below and immediately above the distal facies of a debris-flow deposit interbedded with alluvium of the Colorado River at Palisades Creek (Hereford, 1996, Fig. 2). The median age of 1310 cal yr B.P. is consistent with the age of the underlying surface whose age is between 1250 and 1650 cal yr B.P. (Hereford *et al.*, 1996).

Age-control point 4 is a cosmogenic ^{3}He surface exposure age from basalt boulders (Cerling *et al.*, 1995; Thure E. Cerling, written communication, 1996; Webb *et al.*, 1996) on the topographically highest and oldest surface on the Prospect Canyon debris fan in western Grand Canyon (Fig. 1, no. 19). The age of 2900 cal yr B.P. is presently the oldest radiometrically dated Holocene surface in Grand Canyon. The pitting of limestone boulders on this surface is well developed, although older fan surfaces with greater pit depths are present elsewhere in Grand Canyon.

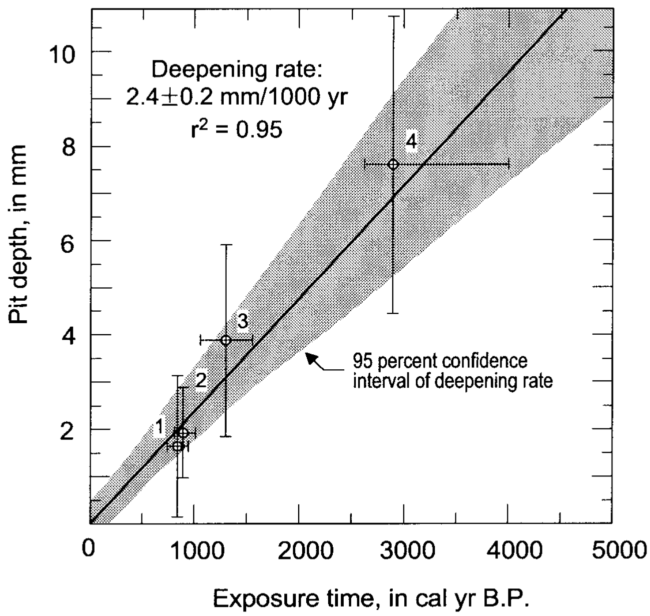

FIG. 4. Surface exposure time related to average pit depth (solid diagonal line). Vertical bars are the ± 2 standard deviation range of all depth measurements on a given surface. Horizontal bars for points 1 and 3 are the range of calibrated ^{14}C ages. The horizontal bar for point 1 is the age range of the archeological structure; the horizontal bar for point 4 is the calculated uncertainty of ^{3}He data reported by Thure E. Cerling (written communication, 1996).

Linearity of Inferred Rate

Weighted least squares was used to fit the age-control data with a straight line passing through the origin. In the computation, weights were assigned to pit depths of the four calibration points. The weights are the inverse of the squared standard deviations of pit depth (Fig. 4; see Taylor, 1997, pp. 198–199, for computational method). This procedure adjusts for the unequal and relatively large variation of pit depth among the four surfaces. The average variation of pit depth is three to four times larger than the average range in age of the surfaces, if expressed as percentages. Thus, the uncertainty in the ages of the surfaces has little influence on the calculated deepening rate (Bevington and Robinson, 1992, p. 100).

The deepening rate is 2.4 mm/1000 yr with standard error of 0.2 mm/1000 yr (Fig. 4). Although some non-linear functions fit the data equally well, a linear relation is consistent with physical processes of limestone dissolution. Whereas the chemical weathering rate of silicate rocks decreases with time, chemical weathering of limestone proceeds at a constant rate that varies only with local climate and solubility of limestone (Colman, 1981; Lipfert, 1989). Weathering of limestone proceeds by congruent dissolution without production of surface residues that eventually slow weathering.

A linear relation is further supported by weathering rates estimated from tombstones and dated archeological structures made of carbonate stone.

Several studies address surface weathering of limestone and marble tombstones (Meierding, 1981; 1993a; 1993b; Klein, 1984; Dragovich, 1986; Neil, 1989; Cooke *et al.*, 1995) and archeological structures as old as 2600 cal yr B.P. (Danin, 1983). Surfaces of carbonate tombstones recede at a constant rate within individual areas, except where influenced by increased atmospheric pollution and the initial polished condition of the surface. Similarly, the depth of dissolution pits is a linear function of time on well-dated limestone walls and monolithic tombs in Jerusalem up to 2600 years old (Danin, 1983), a period comparable to the age of most fan surfaces in Grand Canyon.

Although Danin's (1983) study of archeological sites in Jerusalem most closely resembles our study in terms of method and time scale, its results are not directly comparable with those for Grand Canyon. Danin (1983) measured the maximum depth of dissolution pits on west-facing limestone walls of dated archeological structures. The average pitting rate on these surfaces over 2600 yr is 5 mm/1000 yr, which is more than twice the rate of 2.4 mm/1000 yr estimated for carbonate boulders in Grand Canyon. Comparison of pitting rates is difficult because west-facing vertical surfaces rather than mostly sub-horizontal boulder surfaces were sampled, and

TABLE 1
Statistics of Pit-Depth Data before and after Multiple-Comparison Analysis of Variance (ANOVA)

	Before ANOVA	After ANOVA
Sample areas (n)	114	114
Boulders (n)	617	506
Depth measurements (n)	6,973	5,401
Range (mm)	0.25–24.46	0.36–24.13
Average depth (mm)	4.90	4.61
Standard deviation (mm)	2.77	2.51

maximum pit depth rather than average depth was used to calculate the deepening rate.

Our data indicate that the average depth of dissolution pits on carbonate boulders increases on average by 2.4 mm/1000 yr (standard error, 0.2 mm/1000 yr). This rate is probably a linear function of time over the past 3000 yr. If the deepening rate greatly decreased with age, many of the ages estimated from it would be older than late Holocene. However, the oldest debris fans are stratigraphically equivalent to dated alluvium that is no older than late Holocene (Hereford *et al.*, 1996). Conversely, if the rate increased with age, then pit depth would not increase in proportion to the degree of surface weathering expressed independently by varnish darkness and degree of soil development. The increase of varnish darkness and soil development with age are well-supported by field observations (Hereford *et al.*, 1996).

The pit-deepening process may continue for tens of thousands of years. Dissolution pits on carbonate boulders of late Pleistocene surfaces in Grand Canyon, although we have not measured systematically, are much larger and deeper than those reported here.

For the dating of surfaces in Grand Canyon, we assume the deepening rate is constant through the past 7500 years. We further assume that the 2.4 mm/1000 yr rate applies throughout Grand Canyon along the Colorado River, a region of broadly similar elevation and precipitation. Finally, although dissolution of carbonate stone is closely linked to annual precipitation (Reddy, 1989), the dissolution process is cumulative (Lipfert, 1989). Thus, the influence of precipitation change on dissolution rate averages out over time, maintaining an essentially constant long-term average rate.

AGES AND CORRELATION OF PREHISTORIC FAN SURFACES

The ages of the fan surfaces were estimated from the 2.4 mm/1000 yr average deepening rate. The uncertainty or range of the ages is given by the standard error of 0.2 mm/1000 yr and is shown in Figure 5. The estimated ages range from about 500 to 7300 cal yr B.P. (Fig. 5). The oldest surface preserved on a fan is at river mile 124.2 (Fig. 1, no. 17) with dissolution pits averaging 12.22 mm deep. This average depth corresponds to 5100 cal yr B.P. Even older surfaces are at Forster and Fossil Canyons and in the tributary canyon at river mile 220 (Fig. 1, nos. 16, 18, and 26). The three surfaces have dissolution pits averaging 17.29, 17.41, and 17.42 mm, respectively; this is about 7200 cal yr B.P. as calculated from the mean of the three depths. These surfaces are debris-flow levees preserved in the mouths of the tributary canyons. This location protected them from the erosional effects of the Colorado River.

The youngest surfaces dateable by this method are at Nankoweap Creek, Palisades Creek, 209 Mile Canyon, and Granite Park Wash, (Fig. 1, nos. 3, 6, 24, and 25). Dissolution pits on the four surfaces average 1.2 to 1.47 mm deep, which is about 500–600 cal yr B.P. An average depth of around 1.2 mm is probably the minimum surface pitting detectable by this method; carbonate boulders on surfaces younger than this do not have measurable dissolution pits.

The typical time between the 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 the average depth of the 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 differ in age by about 900 yr within a range of 500 to 1300 yr.

This 900-yr interval is much longer than the 1-to-100 yr average recurrence interval (Melis *et al.*, 1995) of channelized debris flows during historic time. Deposition on the primary fan surfaces evidently occurs infrequently compared with deposition in the entrenched channels (Fig. 2). We infer that deposition on a primary fan surface may require either a single high-volume debris flow or a large number of small debris flows. Frequent, relatively low-volume debris flows, comparable in volume to historic-age flows, could eventually overtop the entrenched channel and spread sediment across the primary fan surface.

Several widely spaced tributaries have debris-fan surfaces with exposure times that cannot be shown to be different based on average pit depth (Fig. 5, horizontal lines). The surfaces evidently correlate within the limitations of the dating. Such correlation implies that conditions leading to formation of fan surfaces influence the entire Grand Canyon region, although these conditions do not necessarily affect every tributary.

A smoothed histogram or density trace of average pit depth (Fig. 6; Chambers *et al.*, 1983, pp. 24–41) of the 71 studied surfaces indicates they are mainly late Holocene. This is illustrated by the progressive increase in the number of surfaces beginning about 5000 cal yr B.P. Overall, 75% of the surfaces are younger than 3000 yr. The concentration of fan surfaces in the late Holocene contrasts with the lack of early and middle Holocene surfaces, but the overall concentration probably did not result entirely from increased debris-flow activity during the late Holocene. Older fan surfaces are under-represented because of progressive erosion and removal by the Colorado River. The abundance of relatively young fan surfaces, therefore, indicates a lack of long-term preservation. Early and middle Holocene fan surfaces are not preserved at the river due to vigorous erosion in the narrow river corridor.

The density trace (Fig. 6), which is not heavily smoothed in order to reveal detail in the distribution of data, has five peaks between about 1 and 10 mm average pit depth. These peaks may correspond with a relatively high number of broadly correlative surfaces at five times in the late Holocene (Fig. 5). We used k-means cluster analysis (Davis, 1986, pp. 513–514) with the number of clusters set at five, as suggested by the density trace and field studies, to identify natural clusters in the age data. This procedure minimizes the variability within clusters and maximizes the variability between clusters. Determining the appropriate number of clusters is subjective. Formal

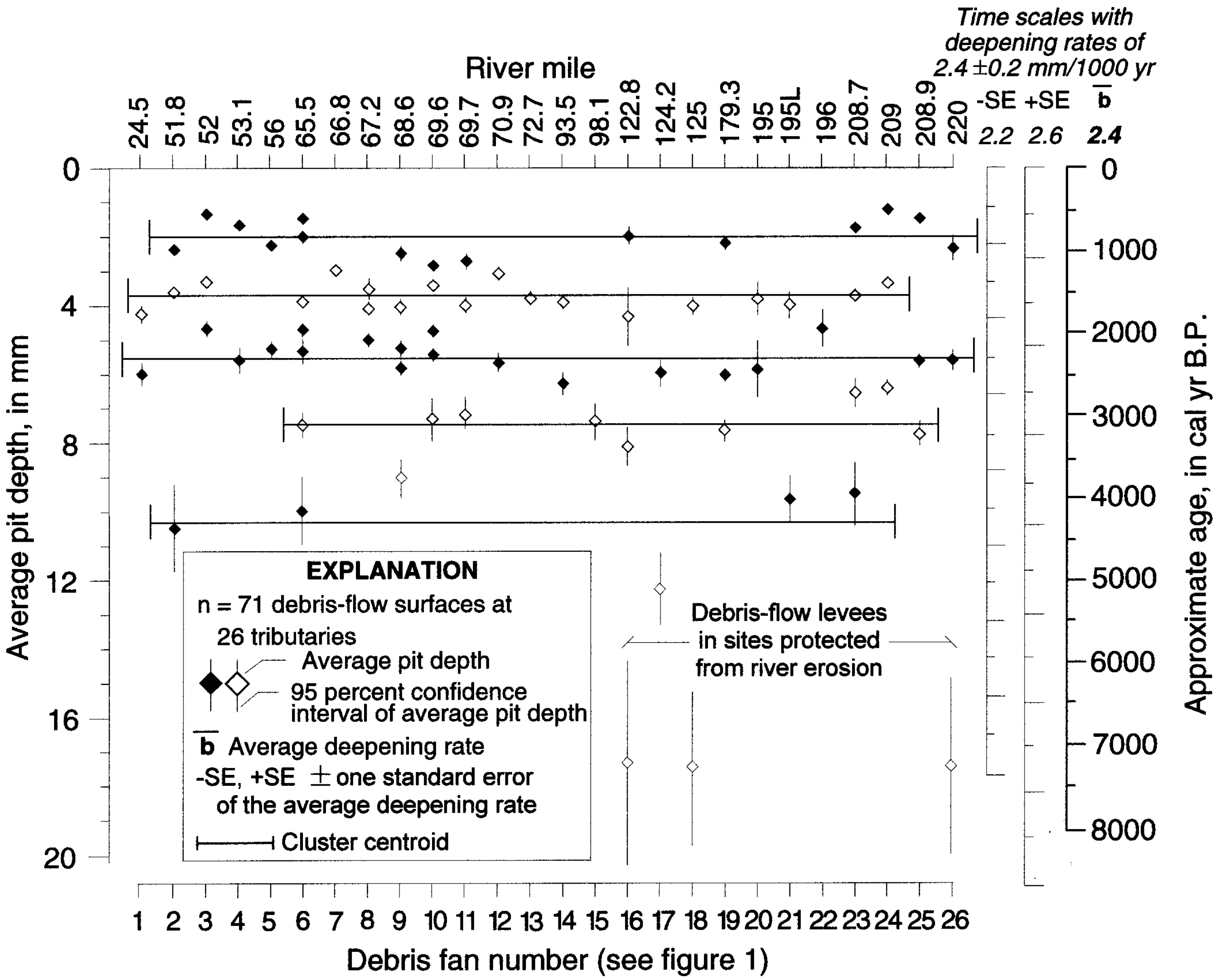

FIG. 5. Age and correlation chart of debris-fan surfaces inferred from the average depth of dissolution pits. The approximate age calculated from the 2.4 mm/1000 yr deepening rate is shown with a labeled time scale. The error of estimated ages is shown by two unlabeled time scales. From top to bottom, the alternating solid and open symbols with heavy lines are surfaces clustered about the five horizontal lines, respectively; open symbols with thin lines are not clustered.

statistical tests offer no guidance for evaluating whether the number of clusters is statistically significant (Everitt, 1980, pp. 64–67). We do not claim statistical significance for either the number or the age of the clusters. However, five clusters are reasonable based on our detailed mapping, which delineates five to six surfaces of different ages canyon-wide (Hereford *et al.*, 1998; in press).

The surfaces in each cluster are shown by the pattern of alternating solid and open symbols with heavy lines in Figure 5. Surfaces at the younger and older limits of a cluster are not clearly separated from adjoining clusters. However, in most cases, surfaces within about ±0.5 mm of the cluster centroid (vertical bars on horizontal lines in Fig. 5) are clearly separated from those in nearby clusters, based on non-overlapping confidence intervals. The five clusters are around 2, 3.9, 5.5, 7.5, and 10.4 mm average pit depth, which corresponds to about 800, 1600, 2300, 3100, and 4300 cal yr B.P., respectively.

Thus, five broadly defined episodes of heightened debris-flow activity are discernable, although the occurrence of fan-forming debris flows was highly variable during the late Holocene. These episodes in turn may correspond to times of increased precipitation each lasting perhaps several centuries.

Debris flows require intense precipitation, which in Grand Canyon results from winter frontal-type storms, dissipating tropical cyclones, and monsoonal convective storms during summer (Melis *et al.*, 1995). Winter precipitation of regional extent can trigger debris flows in Grand Canyon. The climate conditions associated with episodes of heightened prehistoric debris-flow activity are not clear, but a sustained increase of winter precipitation could produce a high number of large, temporally correlative debris flows across the region.

CONCLUSIONS

On middle to late Holocene debris fans and levees along the Colorado River in Grand Canyon, the exposed surfaces of limestone boulders progressively roughen by development of small, roughly hemispheric dissolution pits. The depth of dis-

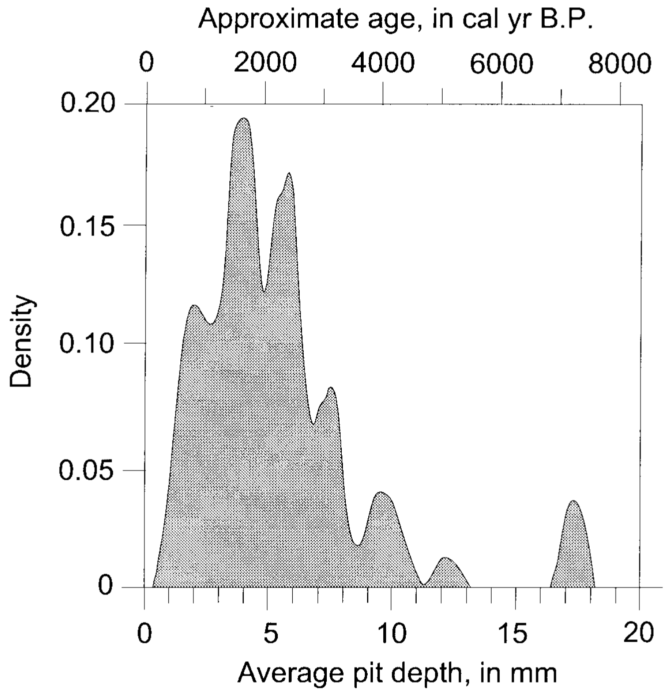

FIG. 6. Smoothed histogram or density trace of average pit depth with the number of intervals at 7 and tension or degree of smoothing set at 0.15. The time scale is based on a 2.4 mm/1000 yr deepening rate.

solution pits increases on surfaces known to be increasingly older from independent evidence. Pit depths increase in proportion to the degree of surface weathering expressed by soil development, disintegration of sandstone and siltstone boulders, and darkness of rock varnish.

The rate of pit deepening was calculated from average pit depths on three radiometrically dated debris-flow related deposits and an archeological structure of known age. These data suggest that the deepening rate is a linear function of time over at least the past 3000 yr and that pit depth increases on average by 2.4 $\pm$ 0.2 mm/1000 yr. A constant rate is supported by the physical chemistry of limestone dissolution, by empirical studies of carbonate dissolution on tombstones and other dated archeological structures, and by field relations that limit the maximum age of studied fan surfaces. In addition, carbonate boulders on late Pleistocene fan surfaces have dissolution pits that are substantially larger and deeper than those on Holocene surfaces. The dissolution process, therefore, may continue for several tens of thousands of years.

The technique developed here can be used to estimate the age of any Holocene weathered fan surface in Grand Canyon having carbonate boulders. In addition, the age of walls and other structures built of carbonate stone by prehistoric people can be determined in the absence of temporally diagnostic potsherds or other dated material. Generally, the surface exposure age of middle to late Holocene deposits in an arid to semiarid climate having unmetamorphosed carbonate boulders can be estimated by this method. The method depends on geologic dating to establish the local pit-deepening rate and an understanding of the relative ages of surfaces based on weathering criteria and topographic relations.

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