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TO ACCOMPANY MAP I–2449



# Surficial Geology and Geomorphology of the Palisades Creek Area, Grand Canyon National Park, Arizona

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## INTRODUCTION

The mapped area lies mostly downstream of River Mile 65.5 along the Colorado River in the eastern Grand Canyon, which is 65.5 miles downstream of Lees Ferry, Ariz. The geologic mapping and related investigations were undertaken to determine the late Holocene history of erosion and deposition along the Colorado River and to determine how this erosion damages archeologic sites. Archeologic sites are abundant along the Colorado River between River Miles 65–72, averaging more than 5 sites/km, which is the largest concentration of sites in Grand Canyon. The sites are mostly of Anasazi affiliation, dating from the Pueblo I and II periods (A.D. 800–1200), although younger sites of Native American and Anglo affiliation are also present (Hereford and others, 1993).

The geologic mapping was directed at determining how the ongoing erosion of terraces and archeologic remains is affected by regulated streamflow, which began in 1963 with the closure of Glen Canyon Dam, 131 km upstream of the mapped area. In addition, the map was made to provide baseline topographic and geologic information against which future changes resulting from regulated streamflow or natural conditions can be judged. The work was part of the Glen Canyon Environmental Studies in cooperation with the U.S. Bureau of Reclamation.

Regulated streamflow, defined here as the water and sediment discharge regimen of the Colorado River since 1963, is substantially reduced in sediment load, sediment concentration, duration of high flows, and peak-flow rates compared with the unregulated streamflow of the pre-dam era. In the present discharge regimen, sediment load has been reduced by a factor of six and the annual flood, which was the principal agent of geologic change, has been eliminated. It is almost certain that changes of this magnitude are not possible under natural conditions (Hereford and others, 1993). Surficial geologic processes along the river are dominated by the interaction between the Colorado River and tributary streams. This interaction has been changed by the long-term sediment depletion and elimination of the annual flood. The capacity of the river to remove boulder-size sediment carried to the main channel by Palisades Creek is greatly reduced, and the amount and areal extent of sand deposition by the river is also substantially reduced. Reduced transport capacity of the river will lead to constriction of the main channel by tributary-stream sediment transported mainly by debris flows originating in the Palisades Creek drainage basin. The reduced concentration of sand-sized sediment in the river has probably altered the erosional balance of the river corridor; this change increases erosion by the small, ephemeral streams that drain the corridor.

The large-scale topographic base map was made to show the geologic and geomorphic elements of the river corridor, which are too small to show on standard U.S. Geological Survey 1:24,000-scale topographic maps. The 1:2,000-scale base map was produced photogrammetrically using low-altitude aerial photographs mounted in a stereo analytical plotter. A ground survey was done in 1990 to rectify the aerial photographs; vertical control and latitude and longitude were obtained from maps and field measurements made by Lucchitta (1991). The coordinates of the base map differ slightly from the map of Lucchitta (1991), which should be used for critical measurements of latitude and longitude.

## GEOLOGIC SETTING

[See map sheet for Description of Map Units]

The Palisades Creek area is in eastern Grand Canyon near the mouths of Palisades Creek and Lava Canyon; a variety of surficial deposits and related geomorphic surfaces are present in this area. The mapped deposits, except the older gravel deposits (gvo, gvy), lie in the river corridor, which is defined as the area between the lowest exposures of bedrock on the east and west sides of the river. The width of the river corridor ranges from 200 m upstream of Lava Canyon Rapids to 400 m downstream of the rapids. Radiometric dating (table 1), correlation with dated surficial deposits elsewhere in Grand Canyon, and archeologic remains indicate that the age of the deposits in the study area is late Holocene, that is from 2,000 years ago to the present (1992).

Bedrock (Ybr) in the area is the Dox Formation and Cardenas Lavas (Huntoon and others, 1986), two of the thickest formations of the Middle Proterozoic Unkar Group, according to Hendricks and Stevenson (1990). The Dox Formation is fine-grained sandstone with interbedded shale and siltstone, all of distinctive reddish color. Reworked clasts of the Dox Formation occur in the surficial deposits of talus that form beneath steep slopes. The Cardenas Lavas, a series of dark-colored basalt and basaltic andesite flows, are not present in the river corridor, although reworked clasts of the Cardenas occur in the alluvial and colluvial surficial deposits.

A major geologic structure, the northwest-trending Palisades segment of the east Kaibab monocline, passes through the area upstream of Lava Canyon Rapids. Copper mineralization along this structure attracted prospectors to the area around the turn of the nineteenth century. Remains of this mining activity occur south of Palisades Creek and north of the mouth of Lava Canyon.

Deposits of mostly consolidated gravels (**gvy**, **gvo**) occur just outside of the river corridor from near river level on the west side of the corridor to more than 60 m above river level on the east side of the corridor. The gravels consist of moderately well rounded, boulder-size clasts of Paleozoic limestone and sandstone. Distinctive well-rounded pebble-size clasts of porphyritic rock carried by the river from distant sources in the laccolithic mountains of the Colorado Plateau occur sparingly in these gravels.

The gravels are ancient, high elevation channel-fill deposits of the Colorado River dating from the Pleistocene. North of Palisades Creek, the base of the older gravel (**gvo**) is about 30 m above the level of the Colorado River. During the early part of the late Pleistocene, the river flowed in a channel, now only partially preserved, whose base was on bedrock 30 m above the present river level. This channel gradually filled with more than 25 m of sedimentary materials. Following this aggradational episode, the river downcut through the older gravel (**gvo**) and through at least 30 m of bedrock.

By the late Pleistocene, the river had downcut to near its present elevation, where deposition of the younger gravel (**gvy**) began in the new, lower elevation channel. Gravel accumulated in this channel to a thickness greater than 20 m. This aggradation was followed by an episode of downcutting through the gravel and bedrock, resulting in an eastward shift of the channel and removal of most of the younger gravel. A remnant of this channel is preserved on the west side of the river downstream of Lava Canyon Rapids. The width and depth to bedrock of the present river corridor were probably attained during this erosion, which began during the late Pleistocene and may have continued into the late Holocene. This erosion and deposition probably resulted from the climate fluctuations of the Pleistocene. These fluctuations effected the water and sediment discharge of the Colorado River as well as the sediment supply of tributary streams such as Palisades Creek.

The Pleistocene age of the gravels is inferred from the topographic position above known Holocene deposits and by correlation with dated late Pleistocene deposits elsewhere in eastern Grand Canyon (Machette and Rosholt, 1991). The younger gravel (**gvy**) probably correlates with river levels one to three, and the older gravel (**gvo**) probably correlates with river levels four and five of Machette and Rosholt (1991). River levels one to three range in age from 5 ± 5 to 40 ± 24 ka; river levels four and five range from 75 ± 15 to 150 ± 30 ka. I infer that the younger gravel is probably older than about 10 ka and younger than 40 ka, and the older gravel is older than 75 ka and younger than 150 ka. The younger gravel is considered to be late Pleistocene in age, rather than late Pleistocene and Holocene, based on its coarser grain size (gravel compared with sand), greater thickness (tens of meters compared with several meters), and evidence of extensive bedrock erosion and channel realignment that widened and deepened the canyon after deposition of the gravel.

## GEOMORPHOLOGY OF THE RIVER CORRIDOR

The principal geomorphic elements of the mapped area consist of (1) debris fans, (2) terraces formed by alluvial deposits of the Colorado River associated with the fans and alluvium deposited in a slackwater area at the mouth of Lava Creek, (3) arroyos of tributary streams, and (4) sand dunes. The fans form prominent topographic features at the mouth of Palisades Creek and the mouth of the relatively small, unnamed wash upstream of Palisades Creek. Alluvium of the Colorado River is present as terraces and channel-side bars that form relatively flat strips of sand parallel to the river; they occupy progressively lower elevations such that the youngest terrace or bar has the least elevation and is closest to the river. At the mouth of Lava Canyon, paleoflood deposits of the upper mesquite terrace (**umt**) occur upstream of a bedrock abutment in a slackwater area that formed during large floods of the Colorado River. The area of slackwater deposition is only a small part of the mapped area, yet it contains a rich paleoflood record.

Most of the archeologic remains are associated with the prehistoric terraces, although archeologic remains also occur with the pre-dam terraces and terrace-like features. The terraces are crossed by entrenched channels of small tributary streams referred to as arroyos or gullies. The arroyos are erosional features that dissect terraces as they extend headward. The process of arroyo development destroys or damages surface and subsurface archeologic sites. Sand dunes (**ecs**) form an extensive sand field south of Palisades Creek that overlies and was derived from reworking of the older alluvial deposits.

## DEBRIS FANS AND ALLUVIAL DEPOSITS OF THE COLORADO RIVER

Debris fans (Hamblin and Rigby, 1968) result from debris flows that originate outside of the river corridor in the basin of Palisades Creek and the smaller unnamed wash to the north, although streamflow deposits are present locally. Debris flows, a slurry of sediment and water having less than 40 percent water by volume, are ubiquitous in Grand Canyon and result from slope failure initiated by intense rainfall (Webb and others, 1989) outside of the river corridor. The age and distribution of the older debris-flow deposits (dfo) indicates that the fans are relatively persistent features of the river corridor, having been in their present configuration since at least the late Holocene.

The surface of each fan exposes the deposits of at least three fan-forming debris flows (dfo, dfi, dfy). Channelized debris-flow deposits (dco, dcy) occur in the channels of Palisades Creek and the unnamed wash; these deposits are localized, being confined to the entrenched channels of the fans, and they are younger than the fan-forming debris-flow deposits. In contrast, the deposits of the fan-forming debris flows (dfo, dfi, dfy) are aerially extensive and make up most of the fan surface.

These deposits form large-scale geomorphic surfaces, and the deposits result from rare, infrequent events. These areally and volumetrically larger flow deposits are differentiated from each other by the degree of weathering and relative topographic position. The younger debris flow deposit (dfy) has little or no weathering and the surface appears fresh. The deposits of this debris flow surround elevated, erosional remnants deposited by the older flows. The two older debris-flow deposits (dfo, dfi) have clasts darkened with rock varnish; limestone clasts have pitted surfaces with average pit depth ranging from 1.5 to 3.9 mm for the intermediate debris-flow deposit and from 3.9 to 9.2 mm for the older deposits. Sandstone clasts in the older debris-flow deposits (dfo) have tafone weathering with honeycomb or cavernous structure.

Clasts in the debris-flow deposits are largest at the apex of the fans near the mouths of Palisades Creek and the unnamed wash. On the Palisades Creek fan, the closed contours between 825 and 845 m are individual clasts or alignments of two or more clasts which form debris-flow levees. At the margin of the fans, grain size decreases and individual debris-flow deposits become thinner. At the south margin of the Palisades Creek fan near locality 2, the younger and intermediate debris-flow deposits are only about 20 cm thick and grain size of the larger clasts is only granule to small pebble. At localities 2 and 3, the distal, fine-grained facies of the intermediate debris-flow deposit underlies alluvial deposits of the alluvium of Pueblo-II age (ap). The younger debris-flow deposit (dfy) at locality 2 overlies alluvium of the upper mesquite terrace (umt), although the alluvium cannot be shown at map scale.

To a large extent, the presence of the debris fans controls where alluvium of the Colorado River is deposited, the course of the river in the corridor, and the presence of Lava Canyon Rapids. This geomorphic control on the river corridor is typical of the Grand Canyon wherever debris fans are present (Howard and Dolan, 1981). Even before Glen Canyon Dam brought about elimination of floods, the fans were relatively immobile because the river was unable to remove the abundant, large clasts carried to the river corridor by debris flows. This coarse material forms Lava Canyon Rapids at the foot of the Palisades Creek fan and causes the river to flow against bedrock (Ybr) on the west side of the river corridor. Thus, Lava Canyon Rapids is a relict geomorphic feature that has probably been present in some form since emplacement of the Palisades Creek fan in the late Holocene. Graf (1979) suggested that most rapids in canyon rivers are relict features resulting from emplacement of coarse debris that the river is unable to remove in the present hydrologic regimen.

Little sediment accumulates on the west side of the river, except in the slackwater area at the mouth of Lava Canyon and the narrow strip of discontinuous post-dam channel-side bar deposits downstream of Lava Canyon. Alluvial deposits are areally extensive, however, on the east side of the river corridor downstream of the fans. Sediment has accumulated at progressively lower topographic levels in these areas for at least the past 1,000 years, although the deposits are extensively reworked by eolian activity. Water velocity in these areas is evidently low through a wide range of discharges, which enhances deposition of sand- to silt-size sediment.

Deposition downstream from the Palisades Creek and unnamed fans probably results from recirculating flow and flow in overbank channels. A recirculating flow pattern typically occurs downstream of a channel constriction, usually the result of a debris fan, where the flow separates from the main current and moves upstream, rejoining the main current at the head of the recirculation zone (Schmidt, 1990). The channel expansion downstream of the unnamed fan is well defined by the arcuate pattern of the 819–826 m contours. Downstream of the Palisades Creek fan, the channel expansion is defined roughly by the 816–819 m contours. The post-dam channel-side bar deposits (ff, hf, fs) were formed by the recirculating flow that develops in these areas in the present discharge regimen.

The deposits of the unnamed fan have constricted the channel for at least 2,000 years, based on the age of the oldest debris-flow deposit present on the fan (dfo), and the pre-dam and prehistoric alluvial deposits in this area were probably formed by recirculating flow. Pre-dam discharge levels in the recirculating zone were substantially larger than 2,700 $m^3/s$ (96,000 $ft^3/s$). The width of the channel measured at the level of the 1983 flood sand (fs) to the east edge of the alluvium of Pueblo-II age (ap) is 50 m larger and stage is 7 m higher, an increase in width from 170 to 220 m and in stage elevation from about 820 to 827 m. This zone of recirculating flow is present through a wide range of discharges.

The alluvial depositional site downstream of the Palisades Creek debris fan lacks the distinctive, arcuate expansion of channel width. This suggests that recirculating flow did not develop in this area during large pre-dam discharges. Recirculating flow probably did not develop in this area because return flow to the main channel was blocked by the topographic barrier formed by the coppice dune field (**ecs**), which has been present since at least 1890. Thus, the area between the 820 to 823 m elevation was probably dominated by non-recirculating flow at discharge levels that were well in excess of 2,700 $m^3/s$ (96,000 $ft^3/s$).

Although partly covered by the coppice dune field (**ecs**), the outcrop pattern of the lower mesquite terrace (**lmt**) at the south end of the area between about 820 to 821 m elevation suggests that it was deposited in an overbank channel that formed when the current split around the elevated gravel surface shown by the closed 821 m contour. This area was photographed by Robert B. Stanton in January 1890 in conjunction with a railway that Stanton was planning to construct along the Colorado River through Grand Canyon (Smith and Crampton, 1987). These photographs (Stanton numbers 382 and 385) show lightly vegetated, high-albedo deposits of sand with dark, elongated objects interpreted as widely scattered pieces of driftwood. The fresh-appearing sand and driftwood in the photograph implies that a large flood had recently overtopped the gravel bar. The flood could have been the flood of July 1884 with estimated peak discharge of 8,500 $m^3/s$ (300,000 $ft^3/s$).

Driftwood present now in this area is weathered and contains less than 1–5 percent cut wood. The paucity of cut wood suggests that the driftwood is relatively old compared with younger driftwood associated with the pre-dam alluvium, which contains abundant cut wood. The driftwood could have been deposited by one or more floods in the early 1900s. The largest flood of this period occurred in 1921 with discharge estimated at 6,200 $m^3/s$ (220,000 $ft^3/s$). In short, the deposits of the lower mesquite terrace were probably deposited by the largest floods of late 1800s and early 1900s, which ranged from less than 6,200 to 8,500 $m^3/s$ (220,000 to 300,000 $ft^3/s$).

The upper mesquite terrace (**umt**) occupies a channel-like feature that roughly parallels the 823 m contour. Exposures are poor, but deposits of the upper mesquite terrace are traceable between the 822–823 m contours, although they are too small to show at map scale. The alluvium was probably deposited in an overbank channel on the eroded surface of the alluvium of Pueblo-II (**ap**) age. The channel trends east-southeast roughly along the present course of the arroyo deposits (**ad**) to the base of the talus slope where it turned south to re-enter the main current near the present southern outcrops of the upper mesquite terrace. When the river flowed in the overbank channel, discharge in the main channel was probably greater than 8,500 $m^3/s$ (300,000 $ft^3/s$).

At locality 2, a radiocarbon date from the outermost rings of fresh appearing pine driftwood near the top of the alluvium of the upper mesquite terrace yielded a minimum date of A.D. 1840–1880 (table 1, sample 2-1). This driftwood and sand could have been deposited in 1862 by the largest historic flood of the Colorado River. Minimum discharge estimates of this flood vary from 11,300 to 14,100 $m^3/s$ (400,000 to 500,000 $ft^3/s$). The U.S. Bureau of Reclamation (1990, p. 8) estimates the discharge of this flood to have been at least 14,100 $m^3/s$ in the Grand Canyon. Near Topock, Ariz., below the mouth of Grand Canyon, floodmarks indicate that discharge of this flood was greater than 11,300 $m^3/s$ (Gatewood, 1950, p. 574). The upper mesquite terrace probably resulted from floods with discharges greater than 8,500 $m^3/s$ (300,000 $ft^3/s$) up to the historic maximum of 11,300 to 14,100 $m^3/s$.

## POST-DAM CHANNEL-SIDEBAR DEPOSITS

The post-dam channel-side bar deposits (**fs**, **hf**, **ff**), referred to as beaches by river runners, form three distinct topographic levels adjacent to the river. For the most part, the deposits record the depositional activity of the Colorado River since 1983. Deposits dating from A.D. 1963–1983 are not present, except for the flood-plain-like deposits (**sd**) at the mouth of Lava Canyon. This lack of post-dam deposits before 1983 suggests that either very little deposition occurred during 1963–83 or that the deposits were eroded during the flood of 1983.

Generally, the declining pattern of seasonal maximum water releases from Glen Canyon Dam since 1983 (Hyatt, 1990) resulted in formation of the channel-side bar deposits at three topographic levels. The largest flows of the post-dam era were in June-August of 1983, when peak discharge was 2,700 $m^3/s$ (96,000 $ft^3/s$) and sustained flows were above 1,400 $m^3/s$ (50,000 $ft^3/s$). During May–June of 1984–86, sustained daily releases were the second highest of the post-dam era ranging from about 900 to 1,400 $m^3/s$ (32,000–50,000 $ft^3/s$). After 1986 through October 1989, seasonal variation was largely eliminated and flows fluctuated up to a daily maximum of about 900 $m^3/s$ (32,000 $ft^3/s$).

The channel-side bar deposits were formed by the largest flows of the post-1983 era. Declining seasonal flow rates resulted first in partial erosion of the earlier formed side bar followed by deposition of sand at the level of the prevailing flow regimen. This broad pattern of erosion followed by deposition at progressively lower levels was repeated three times beginning in 1983, resulting in the three topographic levels of channel-side bars.

## ARROYOS OF TRIBUTARY STREAMS

Small tributary streams that occupy entrenched channels, termed arroyos or gullies, drain the terraces and debris fans of the river corridor. Geomorphic studies here and elsewhere in eastern Grand Canyon show that the streams typically have catchment area of less than 20,000 to 30,000 $m^2$ and channel length of less than 300–400 m (Hereford and others, 1993). These streams are ephemeral and flow in direct response to

**Table 1.** *Radiocarbon ages and sample localities in the Palisades Creek area, Grand Canyon National Park, Ariz.*

| Map Locality No. and Sample No.* | Lab. No.[1] Field No. | Material | Stratigraphy[2] (see map sheet for Description of Map Units) | Age, in years before 1950 (B.P.) | Date, in calendar years A.D. calibrated[3] |
|---|---|---|---|---|---|
| 1–1 | W-6308<br>LCRC1 | Charcoal | Hearth in map unit ap | 900 ± 80 | 1000–1270 |
| 1–2 | W-6309<br>LCRC2 | Charcoal | Hearth in map unit ap | 950 ± 80 | 900–910<br>950–1260 |
| 1–3 | W-6310<br>LCRC3 | Charcoal | Hearth in map unit umt | 560 ± 80 | 1270–1460 |
| 1–4 | W-6317<br>LCRC4 | Charcoal | Map unit umt | <200 | Modern |
| 1–5 | AA-9525<br>LCRC5 | Charcoal | Map unit umt | 1390 ± 90 | [4] |
| 1–6 | W-6404<br>LCRC7 | Charcoal | Map unit umt | 840 ± 70 | 1040–1270 |
| 1–7 | W-6371<br>LCRC9 | Charcoal | Map unit umt | 635 ± 120 | 1050–1090<br>1120–1140<br>1150–1490[5] |
| 1–8 | AA-9525<br>LCRC10 | Charcoal | Map unit umt | 240 ± 90 | 1470–1890 |
| 1–9 | W-6372<br>LCRC11 | Mesquite pith | Map unit umt | 550 ± 80 | 1280-1470 |
| 2–1 | W-6288<br>PCRC4 | Driftwood, outer rings | Map unit umt | 190 ± 40 | 1640–1700<br>1720–1830<br>1840–1880[6] |
| 2–2 | W-6289<br>PCRC5 | Charcoal | Base of map unit dfi | 1170 ± 60 | 690–700<br>710–750<br>760–980 |
| 2–3 | β-51470<br>PCRC11 | Charcoal | Penetrates map unit dfi | 1410 ± 120 | 390–890 |
| 2–4 | β-51471<br>PCRC12 | Charcoal | Map unit ap | 1380 ± 140 | 390–960 |
| 2–5 | W-6373<br>PCRC14 | Driftwood, outer rings | Map unit ap | 885 ± 60 | 1030–1250 |
| 3 | W-6398<br>PCRC7 | Charcoal | Hearth in map unit ap | 890 ± 50 | 1030–1240 |
| 4 | W-6401<br>PCRC8 | Charcoal | Hearth on surface of map unit dfi | 940 ± 50 | 1010–1210 |
| 5 | W-6402<br>PCRC9 | Charcoal | Hearth on surface of map unit dfi | 340 ± 50 | 1450–1640 |
| 6 | W-6291<br>PCRC6 | Charcoal | Map unit ap overlain by alluvial fan | 1140 ± 60 | 720–730<br>770–10 |
| 7 | β-51473<br>C:13:272b | Charcoal | Hearth or roaster in map unit umt | 330 ± 50 | 1460–1650 |
| 8 | W-6403<br>PCRC10 | Inner rings of bush mesquite | Plant rooted on map unit ap? | 550 ± 50 | 1290–1370<br>1370–1440 |
| 9 | W-6349<br>PCRC-16 | Inner rings of dead mesquite bush | Plant rooted on terrace rise between map units umt and ap | 840 ± 60 | 1040–1100<br>1110–1270[5] |

* Where more than one sample per site

(1) W- and AA- dated by U.S. Geological Survey Radiocarbon Laboratory, Reston, Virginia; β—dated by Beta Analytical Radiocarbon Laboratory

(2) Stratigraphic context of sample based on mapped geologic and geomorphic relations

(3) Radiocarbon date (B.P.) calibrated to calendar years (A.D.) using relations developed though measurement of 14C activity of dendrochronologically dated wood (Klein and others, 1982). Range is the 95 percent confidence interval, multiple dates are possible because of 14C fluctuations (Stuiver, 1982). Radiocarbon date automatically transformed to calendar years by Groningen calibration program (version June 1991) using calibration data current through 1989

(4) Radiocarbon date is too old; date is not possible stratigraphically

(5) This age range is the most likely, since it post-dates the alluvium of Pueblo-II age

(6) This age range is the most likely of the three, as sample is from uppermost part of deposit

intense rainfall. The arroyos are important erosional geomorphic elements of the river corridor, because as they develop, older deposits containing archeologic remains are eroded and dissected. Although the arroyos are small features relative to those discussed above, the drainage basin of an arroyo typically occupies a large portion of the pre-dam and prehistoric surfaces. The arroyos are formed by runoff and erosion that results from intense rainfall in the river corridor, unlike the Colorado River alluvial deposits and the debris-flow deposits which result from events that occur outside of the river corridor.

The arroyos are best developed on the east side of the river where they cross the prehistoric and historic terraces. Base level of the streams is either the Colorado River or a higher terrace or channel-side bar. Two of the largest arroyos occur near locality 2. These arroyos are flat-floored and partly filled with sedimentary materials (**ad**). In the vicinity of localities 3 and 6, ten arroyos are present (not counting the arroyo at locality 6); they dissect the alluvium of Pueblo-II age (**ap**) and the lower and upper mesquite terraces (units **lmt**, **umt**, respectively). Deposits in these arroyos are too small to show at map scale, and the channels are narrow and V-shaped.

The arroyos are recent developments (apparently after 1890) in the late Holocene evolution of the river corridor. Near locality 2, a trash midden of rusted-iron artifacts from around 1900 rests on a poorly defined, gently sloping surface that might have been the north side of a shallow arroyo. This was probably the incipient form of the present arroyo. In addition, a photograph taken in 1890 of the area around locality 3 (Stanton number 384) does not show the present arroyos. Most of the arroyos, therefore, were probably not present in 1890, or if present they were poorly developed and mostly unentrenched.

Comparison of low-altitude aerial photographs taken in 1965, 1973, and 1984 document entrenchment of the arroyos; detailed photographic information between 1890–1965 is unavailable. Aerial photographs taken in May 1965 (approximate scale 1:6,000) show several of the present arroyos, including the two arroyos near locality 2, and 3 and possibly four of the 10 arroyos near localities 3 and 6. In 1965 and 1973, the arroyos appear subdued and relatively shallow compared with the same arroyo in aerial photographs taken in October 1984 (approximate scale 1:3,200). The sides of the arroyos in 1965 and 1973 were dark, suggesting that the arroyos were stable; in 1984, however, the sides were steep and have high albedo, indicating recent erosion. In 1965 and 1973, the two large arroyos near locality 2 were present, but they ended at the terrace of the pre-dam alluvium near the 821 m contour. By 1984, the streams drained to the Colorado River through downstream erosional extension of the channels. The southernmost arroyo extended its channel 100 m and the arroyo to the north extended 80 m. The resulting arroyos are up to 4 m wide and 1-2 m deep. In addition, the arroyo upstream of the channel extension is deeper, wider, and longer.

This evidence suggests that arroyo cutting and related erosion of the pre-dam and prehistoric terraces increased between 1965 and 1984, with much of the erosion resulting from the unusual rainfall that occurred between 1978 and 1984 (Hereford and others, 1993). The erosion resulted in rejuvenation and extension of existing arroyos, incision of new arroyos, and destruction of archeologic sites. Rainfall and the resulting runoff were the immediate causes of erosion. However, the base level of these streams, as controlled by formation of the channel-side bar deposits (**ff**, **hf**, **fs**), is lower than it was in the pre-dam era; this lowered base level probably exacerbated arroyo cutting. Base level of two and possibly all of the arroyos was at or above the level of the pre-dam alluvium before closure of the dam. The pre-dam alluvium is 1–2 m above the flood sand of summer 1983 (**fs**) and 3–4 m above the fluctuating-flow sand (**ff**). Thus, the level of alluvial deposition by the Colorado River and base level of small tributary streams was reduced by 3–4 m in the post-dam era. The instability of the arroyos since 1965–73 probably resulted from this reduced depositional level and lowered base level.

In most cases, entrenchment occurred when the streams reached and flowed over the edge of the pre-dam terrace, which probably occurred infrequently before regulated flows began in 1963. The pre-dam terrace forms a wide, nearly horizontal bench at the mouth of many arroyos that is about 15 to 40 m wide, which is a sizeable portion of channel length. Runoff debouching from the mouth of an arroyo loses velocity rapidly as it spreads unconfined over the porous, permeable sand of the essentially horizontal terrace. This reduced velocity causes deposition of small alluvial fans (which do not show at map scale) on the terrace at the mouths of the arroyos and prevents arroyo cutting upstream. Eventually, deposition and build-up of the alluvial fan increases the channel gradient across the surface, and the stream will flow across the edge of the terrace. When this happens, a channel is established across the terrace, initiating a wave of arroyo cutting and erosion as the system adjusts to the new, lower base level. In the pre-dam era, this process was probably interrupted every year or so when the river overtopped the terrace of the pre-dam alluvium during the May to early July snowmelt runoff. The annual flood removed any previously formed alluvial fans and filled incipient channels through deposition and partial erosion of the terrace.

## SAND DUNES

An extensive and active coppice-dune field (**ecs**) is present downstream of the Palisades Creek debris fan. The term "coppice dune" is applied to sand hummocks or mounds that develop around plants, which partially anchor the wind-blown sand (McKee, 1982, p.48–49). The eolian sand is moderately well sorted and fine grained with an average silt and clay content less than 6 percent; this contrasts with alluvium which typically has silt and clay content of 10–20 percent.

In the river corridor, mesquite trees and shrubs are typically associated with the coppice dunes. The mounds and hummocks of the dune field are shown by the closed 821 and 822 m contours. The sand deposits downstream of the Palisades Creek fan and elsewhere are reworked by eolian erosion of the underlying alluvial deposits. Thus, the dune field post-dates the pre-dam Colorado River alluvial deposits, and most of the dune field is probably younger than the upper mesquite terrace (umt).

## STRATIGRAPHY

### FAN-FORMING DEBRIS-FLOW DEPOSITS

The fan-forming debris-flow deposits are exposed on the south side of Palisades Creek at stream bed elevation of 834–836 m; this is the only complete stratigraphic section of the fan-forming deposits in the map area. Figure 1 illustrates the stratigraphy of the debris-flow deposits. The section consists of four gravelly debris-flow deposits interbedded with fluvial gravel derived from Palisades Creek. The debris-flow deposits are moderate reddish orange (10R 6/6), which is the color of the matrix. Texture is clast supported and the clasts are angular to subangular and range in size from pebbles to boulders; numerous boulders are larger than 2 m on an edge. The matrix, which makes up less than 10 percent of an individual flow, consists of clayey coarse silt to very fine sand. Individual flows are massive and lack both stratification and imbrication.

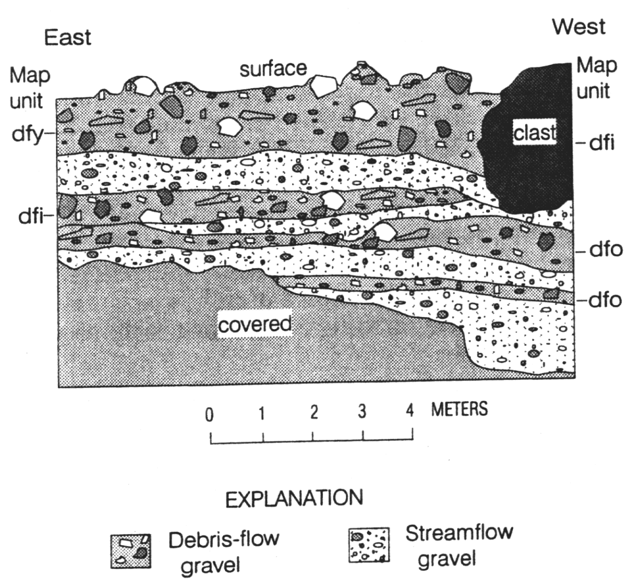


**Figure 1**. Stratigraphic cross section on south side of Palisades Creek at streambed elevation of 834–836 m, showing interbedded streamflow and debris-flow gravels. See Description of Map Units for explanation of map-unit symbols.

The fluvial gravels have clast-supported texture, and the clasts, which range in size from granule to small boulder, are subangular to subrounded. The fluvial matrix is yellowish-gray (5Y 7/2), fine to very coarse sand or granule gravel and makes up about 10–25 percent of each bed. Weakly developed parallel laminations are present in the matrix, and clasts are weakly imbricated. The contact between streamflow gravel and the underlying debris-flow deposits occurs over 1–5 cm and is generally sharp and scoured. Evidence of weathering and extended subaerial exposure is lacking, except for the large clast on the west side of the exposure which has rock varnish and a thin coating of $CaCO_3$.

Organic material is lacking at this outcrop, and the stratigraphic section is undated. However, surface relations suggest that the lower two flow deposits correspond with the older debris-flow deposits (**dfo**); the overlying flow deposit and associated large clast (fig. 1) correspond to the intermediate debris-flow deposit (**dfi**); and the flow deposit at the surface is the younger debris-flow deposit (**dfo**). The absolute age of the flow deposits, which is discussed in a following section, was determined by dating the distal facies of the flows at the margins of the fan.

### ALLUVIUM OF PUEBLO-II AGE AND UPPER MESQUITE TERRACE

A stratigraphic section of alluvial deposits of the Colorado River interbedded with the distal facies of three debris-flow deposits (**dfy**, **dfi**, **dfo**) is exposed in the arroyo at locality 2. This section illustrates the stratigraphy at the margin of a debris fan (fig. 2) where alluvial and debris-flow processes interact. The section consists of four sand beds (fig 2, beds 1, 3, 5, and 6) of alluvial origin and one bed of possible eolian origin (bed 8). The alluvial deposits are mostly yellowish- gray (5Y 7/2), poorly sorted, very fine sand with an average silt and clay content of 15 percent. Sedimentary structures are poorly developed to absent in beds 1 and 3. Bed 5 is capped by a thin clay drape; bed 6 has well-developed climbing-ripple structure in the basal 18 cm that is overlain with apparent conformity by a moderately well sorted, fine-grained sand with large-scale, eastward-directed cross-stratification, which probably resulted from eolian reworking of the upper part of bed 6. The high silt and clay content of these beds and the sedimentary structures suggest that they are fluvial in origin. Bed 8 is probably eolian in origin, because it can be traced laterally to much thicker deposits of the coppice dune field (**ecs**), although diagnostic sedimentary structures were not observed.

The distal facies of debris-flow deposits at locality 2 are substantially thinner and finer grained than their counterparts near the apex of the fan (fig. 1). The color of the distal facies is a distinctive moderate orange pink (10YR 7/4) to moderate reddish orange (10R 6/6). From oldest to youngest, gravel content of the distal facies of the three debris-flow deposits is 29, 45, and 2 percent, respectively. With the exception of widely scattered boulders (clast in fig. 2), the gravels are typically granule to small-cobble size and the gravel clasts are matrix supported. The matrix is very poorly sorted medium sand with average silt and clay content of 25 percent.

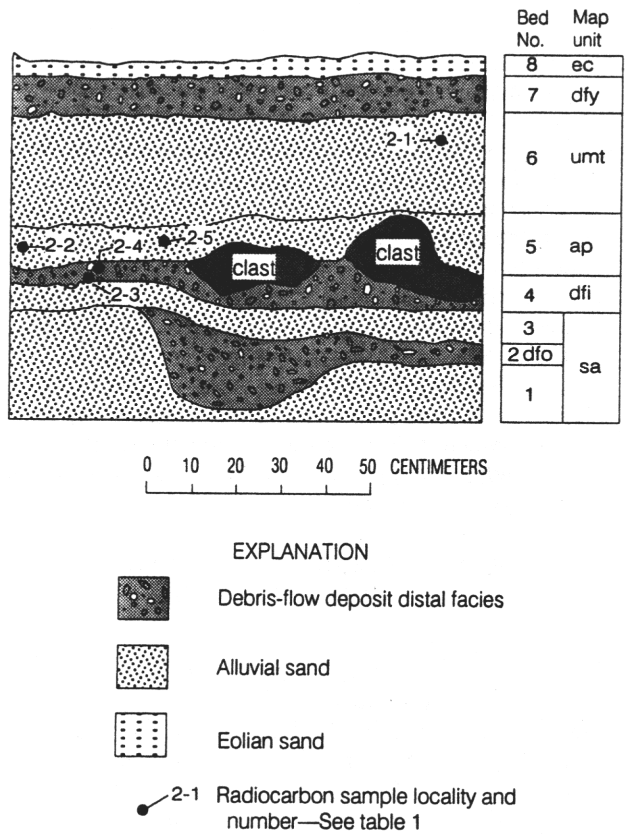


**Figure 2.** Stratigraphic cross section at locality 2 ( map sheet), showing alluvium interbedded with debris-flow deposit distal facies at margin of Palisades Creek debris fan. See Description of Map Units for explanation of map-unit symbols.

The age of the debris-flow deposit distal facies and alluvium is inferred from mapped relations, radiocarbon dates, and nearby archeologic remains. The debris-flow deposit of bed 4 (fig.2) traces 10–15 m to the west where it forms the occupation surface of a Pueblo II structure dated at A.D. 950–1100 using ceramics (Helen C. Fairley, 1990, oral commun.); this bed is probably the intermediate debris-flow deposit and it pre-dates A.D. 950. Radiocarbon dates from charcoal associated with bed 4 suggest that the deposit could be several hundred years older than A.D. 950. Sample 2–3 was collected immediately below bed 4 and sample 2–4 was collected from a hearth-like structure that penetrates the debris-flow deposit (table 1; fig. 2). The median date of the 2–3 sample is A.D. 640 and the median date of the 2–4 sample is A.D. 675. This suggests that the intermediate debris-flow was deposited sometime around A.D. 640–675, which predates the Pueblo period.

A date from the outer rings of driftwood in bed 5 (fig. 2; table 1, sample 2–5; ) agrees with another archeologic structure dated to A.D. 1030–1250, which falls largely within Pueblo II time. Sample 2–2 is charcoal collected from a hearth within bed 5. The calibrated dates range from A.D. 690–980 (table 1). This range lies within the Pueblo I to early Pueblo II periods, suggesting that the alluvium could in part predate the Pueblo II period. Archeologic evidence from the Upper Unkar area, about 9 km downstream from the Palisades Creek map area, indicates that the base of the alluvium of Pueblo-II age contains diagnostic Pueblo I ceramic material. Most of the section, however, is of Pueblo-II age.

The absolute age of the lowest debris-flow deposit (fig. 2, bed 2) is unknown, although it predates bed 4 and might correlate with one of the older debris-flow deposits (fig. 1). The uppermost debris-flow deposit (bed 7) forms the surface of the Palisades Creek fan and correlates with the younger debris-flow deposit (dfy). Stream-worn, fresh-appearing pine driftwood is present at the top of bed 6 (fig. 2); the outer rings were radiocarbon dated giving a minimum date of A.D. 1840–1880 (table 1, 2–1).

In summary, of the alluvial deposits at locality 2, beds 1 and 3 (fig. 2) probably pre-date most of the mapped alluvial deposits, except the local occurrences of the striped(?) alluvium (sa); bed 5 probably correlates with the alluvium of Pueblo-II age (ap), and bed 6 correlates with the alluvium of the upper mesquite terrace (umt). The debris-flow deposits, beds 2, 4, and 7 correlate with the older, intermediate, and younger debris-flow deposits (dfo, dfi, dfy), respectively.

At locality 1 (map), the inset stratigraphic relation between the alluvium of Pueblo-II age (ap) and the alluvium of the upper mesquite terrace (umt) is exposed. The disconformable stratigraphic relation between the two units is illustrated in figure 3. The contact between the two units is erosional, showing truncation of alluvium and debris-flow deposits of Pueblo-II age (ap) by sand and gravel deposits of the upper mesquite terrace. Additional evidence of nondeposition and exposure is the presence of thin, wispy, calcium carbonate filaments in the uppermost part of the alluvium of Pueblo-II age

The basal part of the alluvium of Pueblo-II age (ap) consists mainly of cobble to boulder gravel with a granule to pebble matrix. The clasts are subrounded and resemble Colorado River gravel deposits or reworked clasts from Pleistocene gravels that occur upstream in Lava Creek. Near archeologic feature 1 (F1 in fig. 3), the basal gravel grades laterally into alluvial sand interbedded with two beds of granule to small-pebble gravel. This basal sequence is overlain by a succession of thin-bedded gravelly sand of Colorado River origin and thicker- bedded gravel of debris-flow origin.

A stratigraphic section of the alluvium of the upper mesquite terrace in a slackwater setting is shown in figure 4. The section was measured at the right side (east side) of the cross section (fig. 3) where the alluvium is thickest. The alluvium is made-up of at least 17 distinct beds of alluvial, debris-flow or debris-flow related, eolian, and cultural origins. The alluvial deposits are typically very fine sand with silt and clay content averaging 18 percent. Color of the beds is very light gray (N8), light gray (N7), and yellowish gray (5Y 8/1). Although poorly preserved, sedimentary structures consist of ripple cross lamination, cross stratification, and thin silt and clay drapes. The cultural horizons consist mainly of carbonaceous sand that is medium dark gray (N4) to dark gray (N3) and massive; worked flakes of chert are present sparingly. Bed 11 (fig. 4) contains several flat boulders that are probably cultural in origin

The alluvial sand beds are flood deposits of the Colorado River that accumulated in this slackwater site at the mouth of Lava Creek, and the river flooded at this level at least nine times during accumulation of the upper mesquite terrace alluvium. The magnitude of these floods is unknown, but the slackwater deposits are topographically above the lower mesquite terrace. This suggests that the floods were as large or larger than those forming the lower mesquite terrace, which implies floods larger than 6,200 to 8,500 $m^3/s$ (220,000 to 300,000 $ft^3/s$). A paleoflood study at a site near the head of Marble Canyon found a sequence of flood deposits roughly similar to those of the upper mesquite terrace in terms size, number, and magnitude of floods (O'Connor and others, 1994).

Bed 16 (fig. 4), which contains historic artifacts (F3 in fig. 3) dating from about A.D. 1880, is probably eolian in origin, although this interpretation is somewhat equivocal. The bed is very fine grained to fine-grained sand with a silt and clay content of 14 percent. High-angle cross-stratification of the tabular planar variety is present locally, and the size grading of the laminae, which are as thick as 1 mm, appears to be inverse. This type of stratification with inversely graded laminae is diagnostic of eolian deposition (Hunter, 1977). In the map area, sand of known eolian origin generally contains less than 6 percent silt and clay—thus, the eolian origin of the bed is questionable.

The five beds of debris-flow or debris-flow related origin have distinctive color and grain size. Color of these beds is medium gray (N5) or grayish orange pink (5Y 8/2). The color reflects composition, such that gray beds contain dark, platy clasts of the Cardenas Lavas and the light-colored beds contain limestone and sandstone clasts derived from Paleozoic formations. The coarse fraction is granule to pebble size, and forms only a few percent of the total composition. The silt and clay averages 35 percent of the clay- to sand-size fraction. The debris flows originated upstream in the drainage of Lava Creek, where Webb and others (1989, p. 6–9) identified two debris-flow deposits of upper

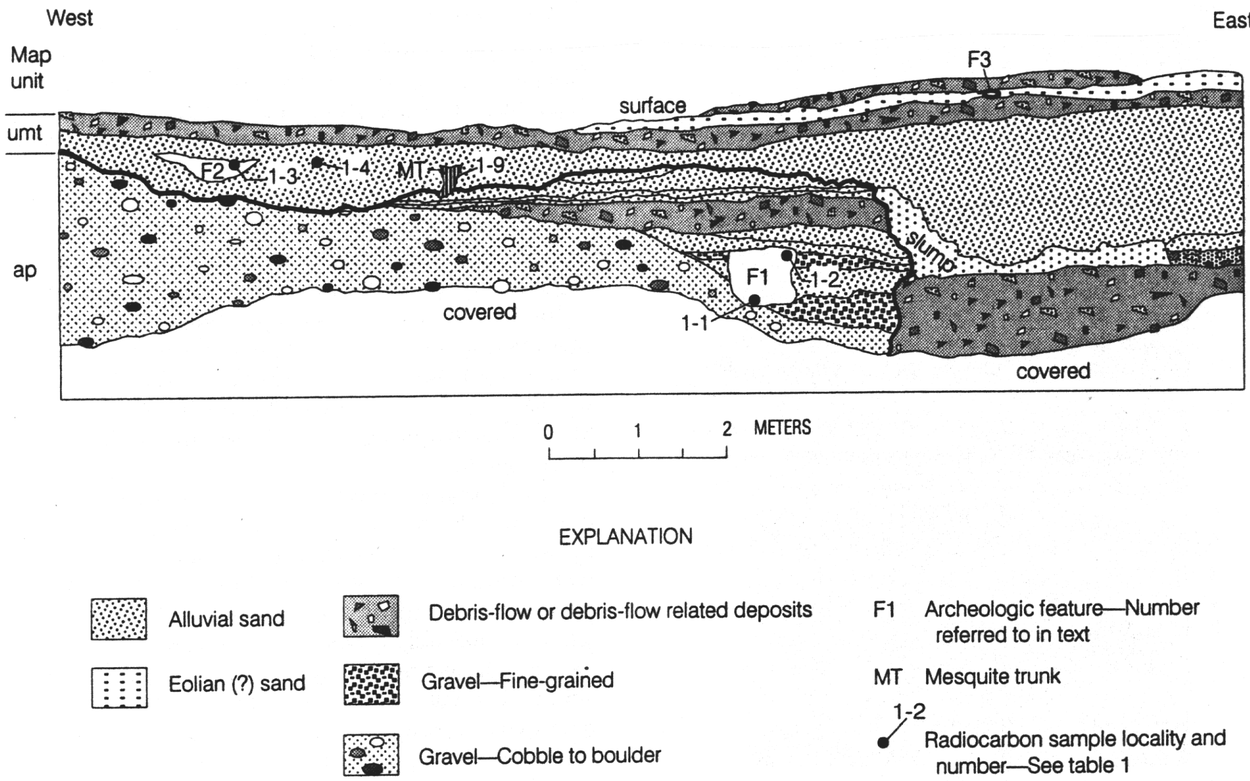


**Figure 3.** Stratigraphic cross section at locality 1 (map sheet), showing erosional relation between the alluvium of Pueble-II age and alluvium of upper mesquite terrace. See Description of Map Units (map sheet) for explanation of map-unit symbols.

mesquite terrace age.

Radiometric dating of archeologic remains and vegetation and archeologic dating of prehistoric and historic-age material was used to date the alluvium of Pueblo-II age and alluvium of the upper mesquite terrace.

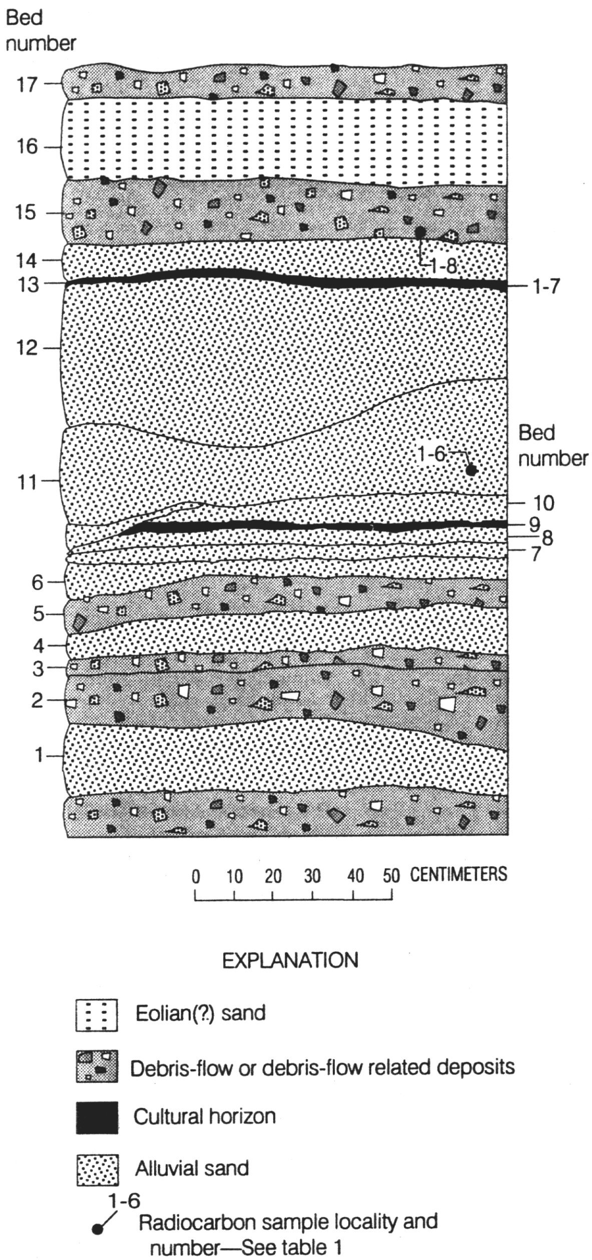


**Figure 4.** Stratigraphic cross section at locality 1 (map sheet), showing details of alluvium of the upper mesquite terrace.

Archeologic feature 1 (F1 in fig. 3) is a rock-lined hearth that contains abundant charcoal at the top and bottom of the feature. Radiocarbon dates of charcoal near the base and top of the hearth date to A.D. 900–1270 (table 1; fig. 3), using the maximum and minimum probable dates. An archeologic site 110 m east of locality 1 at elevation of about 826 m is on and just below the surface of the alluvium in a stratigraphic position well above the older hearth (F1 in fig. 3); this site dates to A.D. 1075–1200 (Euler and Taylor, 1966). Because the hearth is near the base of the alluvium, the probable range of A.D. 900–1270 is too large, and the early part of the range, perhaps to A.D. 900–1070, best fits the stratigraphy. Thus, the alluvium of Pueblo-II age at this locality dates from before about A.D. 900–1070 to A.D. 1075–1200.

The basal part of the alluvium of the upper mesquite terrace was dated radiometrically. Archeologic feature 2 (F2 in fig. 3) is an unlined, basin-shaped feature in sand that contains abundant charcoal; this charcoal dates to A.D. 1270-1460 (table 1, 1–3). The trunk and root collar of a mesquite bush (MT in fig. 3) are present at the contact between the two alluvial units, and the plant germinated on the contact. The innermost rings of the trunk date to A.D. 1280–1470 (table 1, 1–9). Deposition of the alluvium began between A.D. 1280 and 1470, assuming the date of the mesquite trunk is definitive.

Archeologic feature 3 (F3 in fig. 3) was used to infer the date of the upper part of the upper mesquite terrace. Feature 3 is an assemblage of historic artifacts consisting of a cylindrical metal object about 10 cm in diameter with an ornate design on its upper surface, which is probably a collapsible cup, and an engraved ceramic plate resembling a tea-cup saucer in size and shape. The style of the objects is Victorian, and they date from the late nineteenth century; collapsible cups came into use after the Civil War, and the saucer was manufactured by a company that was in business through the late 1800s (Janet R. Balsom, 1991, written commun.). Broadly speaking, the objects date from between A.D. 1870–90. As discussed below, they were probably lost or discarded by a group of government scientists who were present in the area during the winter of 1882–83.

The area surrounding locality 1 was a campsite used in historic times by prospectors and early government-sponsored scientific expeditions. The ostentatious style of the objects in feature 3 (F3 in fig. 3) suggests that they were not associated with prospecting activity, rather they were probably associated with early scientific work. In the winter of 1882–83, Charles D. Walcott lead an expedition equipped with nine pack mules and provisions for three months to study the Proterozoic stratigraphy in the eastern Grand Canyon (Rabbitt, 1980, p. 71–72). A well-equipped expedition of government scientists might have carried elegant china utensils and collapsible cups. The conclusion is that the objects probably date to the occupation of the area by the Walcott expedition, and the deposits of the upper mesquite terrace, therefore, are mostly older than A.D. 1882–83.

## SUMMARY AND CONCLUSIONS

The mapped area is near the mouths of Lava and Palisades Creeks along the Colorado River in eastern Grand Canyon. Deposits of late Holocene age record the interaction between fluvial processes of the Colorado River and debris-flow processes of large tributary streams during the past 2,000 years. Wind activity is a secondary process, which erodes and redistributes the alluvium, forming sand dunes that cover the older deposits.

The topography of the mapped area is dominated by two debris fans, which formed during prehistoric to historic time. Each fan is composed of the deposits of at least three large debris flows; the age of the oldest debris flow is about 2,000 years, and the youngest is slightly more than 100 years old. Because the fans are composed of very coarse, bouldery, sedimentary material which the river is unable to remove, the fans control the position of the river and rapids as well as sites of alluvial deposition.

Alluvium of prehistoric to historic age forms terraces and terrace-like features that are closely associated spatially with the debris fans. For the most part, these alluvial units result from Colorado River floods, although they are interbedded with the debris-flow deposits. The oldest and most widespread prehistoric alluvial unit contains abundant archeologic remains of Anasazi affiliation; it was deposited from sometime before A.D. 950 until A.D. 1075–1200. After perhaps several centuries of erosion and nondeposition, three alluvial units, which form successively lower terraces, were deposited between about A.D. 1270–1470 until A.D. 1957.

Three levels of channel-side bars have been deposited since the closure of Glen Canyon Dam in 1963. The three levels resulted from erosion followed by deposition as the river adjusted to a pattern of declining maximum water releases that began in 1983. Flow regimen during 1983–89 includes the largest post-dam release of June–August 1983, the second largest seasonal runoff of May–June of 1984–86, and the lower, strongly fluctuating flows after 1986. As defined by the channel-side bars, the post-dam depositional level of the river is 3–4 m below the level of the lowest pre-dam terrace, the result of regulated flows with substantially reduced flood peaks and sediment loads.

The alluvial deposits are dissected and eroded by small, ephemeral tributary streams with entrenched channels similar to arroyos or gullies. Dissection of prehistoric alluvium by these streams has exposed and partially destroyed archeologic remains. Erosion was particularly active between 1973 and 1984. This increased erosion occurred when the streams regraded to the post-dam depositional level of the Colorado River.

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