QUATERNARY GEOLOGY AND GEOMORPHOLOGY OF THE NANKOWEAP RAPIDS AREA, MARBLE CANYON, ARIZONA

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INTRODUCTION

The Nankoweap Rapids area along the Colorado River (fig. 1) is near River Mile 52 (that is 52 mi or 83 km downstream of Lees Ferry, Arizona) in Grand Canyon National Park (west bank) and the Navajo Indian Reservation (east bank). Geologic mapping and related field investigations of the late Quaternary geomorphology of the Colorado River and tributary streams were undertaken to provide information about the age, distribution, and origin of surficial deposits. These deposits, particularly sandy alluvium and closely related debris-flow sediment, are the substrate for riparian vegetation, which in turn supports the ecosystem of the Colorado River (Carothers and Brown, 1991, p. 111–167).

Closure of Glen Canyon Dam (109 km or 68 mi upstream of the study area) in 1963 and subsequent regulated streamflow lowered the sediment load downstream. Floods were virtually eliminated and the sediment load was reduced to about 13 percent of pre-dam levels (Andrews, 1991), which resembles clear-water discharge. These changes reduce the ability of the river to remove bouldery sediment deposited in the channel by tributaries and curtail channel and floodplain aggradation. Information about past geomorphic activity in the near-river environment is necessary to understand the rates, magnitude, and processes of environmental change along the river today and to evaluate the consequences of regulated streamflow. The map is a baseline against which future geomorphic changes resulting from natural conditions and regulated streamflow can be judged.

Aside from understanding the Quaternary history of the area, the geomorphic information is necessary to understand how archeologic sites are affected by erosion in the near-river environment. The wide alluviated debris fan of Nankoweap Creek and nearby prehistoric cross-canyon foot trails favored human habitation of the area (Fairley and others, 1994, p. 18). Archeologic sites of Anasazi and Paiute affinity are relatively abundant in the mapped area (Helen C. Fairley, oral commun., 1994). Some of these sites have recently been eroded and damaged by floods in large tributary streams (Cooley and others, 1977). In addition, arroyo cutting or gullying in small tributary streams of the type present in the Nankoweap Rapids area is associated with archeologic site erosion elsewhere in Grand Canyon (Hereford and others, 1993; Fairley and others, 1994, p. 147–150).

METHODS

[See map sheet for Description of Map Units]

A variety of methods were used to date the deposits. Radiocarbon dates were obtained from charcoal and wood recovered from several of the mapped units (table 1). Several of these dates are not definitive as they are affected by extensive animal burrowing in the alluvial deposits that redistributed burnt roots of mesquite trees, giving anomalous dates. The late Pleistocene breccia (units bc and bf) and related terraces were dated by Machette and Rosholt (1989; 1991) using the uranium-trend method. Although experimental, this method produced dates that are consistent with mapped stratigraphy in this map area as well as in the eastern Grand Canyon where the method was used to date a sequence of Pleistocene terraces. These dates, however, are provisional and subject to revision. Other dating methods should be used to confirm the age of the Pleistocene deposits.

Alluvial deposits of the Colorado River were dated by archeologic context and by correlation with the terrace sequence of eastern Grand Canyon (Hereford, 1993; 1996; Hereford and others, 1995; 1996). Likewise, the fan-forming debris-flow deposits were correlated with debris fans of the eastern Grand Canyon using the degree of surface weathering. The numerical ages of the debris-flow deposits were calculated from the average depth of solution pits in limestone boulders on the fan surfaces using the methods and the 2.54 mm per 1,000 years average rate of pit deepening reported by Hereford and others (1997).

Lithologic composition of the older gravel (gvo), coarse-grained breccia facies (bc), and the debris-flow deposits at each west-side tributary was determined quantitatively. On the debris fans and the surface of the coarse-grained breccia facies, clast lithology was identified every 1 m along 100-m transects. Clasts in the older gravel were identified in 2 m^2 segments until 100 clasts were identified. The results indicate the relative proportion of bedrock units in the various deposits.
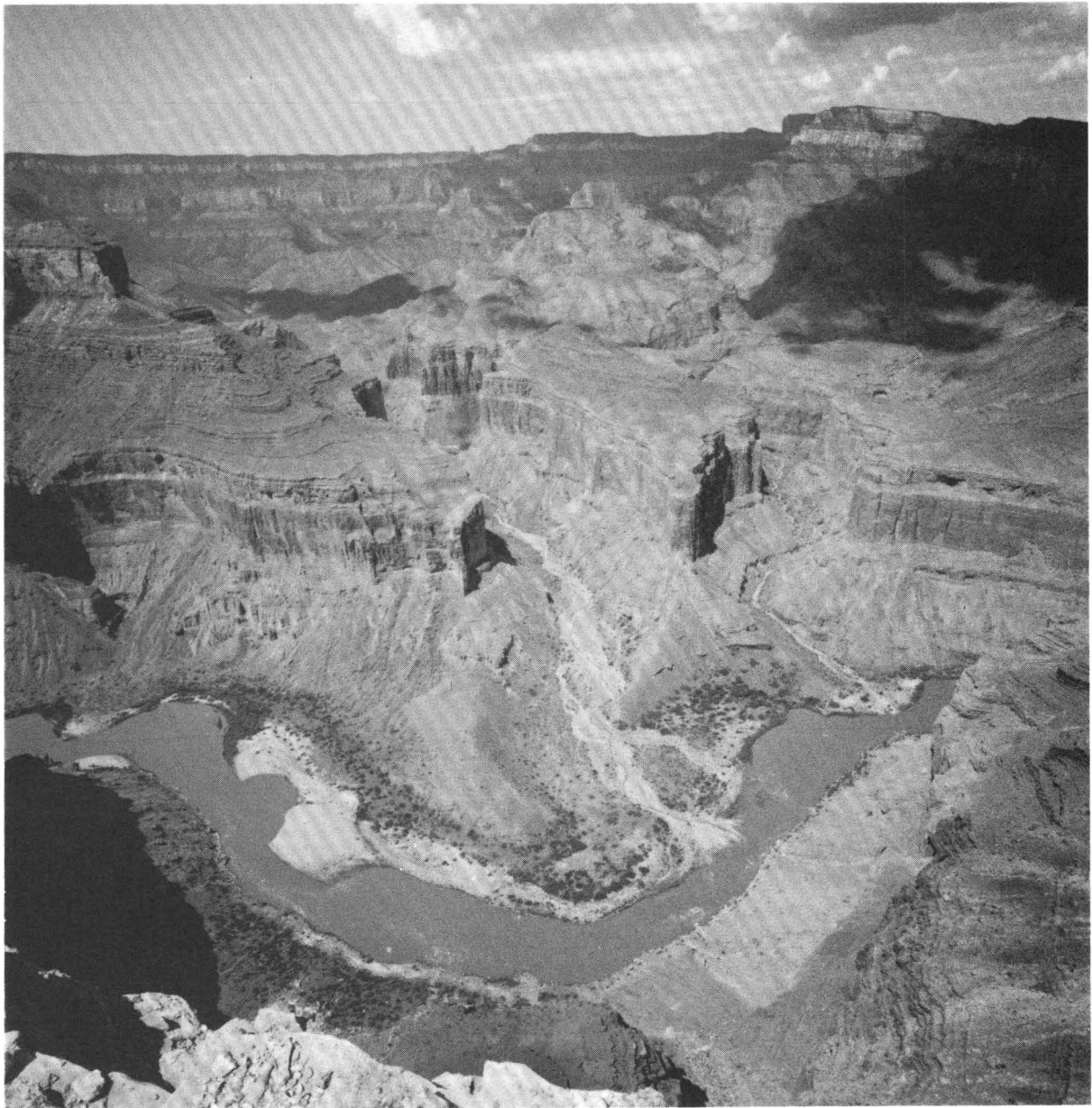
Figure 1. View to the west of the Colorado River and Nankoweap Rapids area, river flows from right-to-left. Nankoweap Creek and rapids just below and right of center; Little Nankoweap Creek at right center; unnamed west-side tributary at left center. Cliff in near skyline on extreme left is Coconino Sandstone at north end of Nankoweap Mesa. From left-to-right, distant skyline is Walhalla Plateau (headwaters of Nankoweap Creek), Saddle Mountain, and Boundary Ridge (headwaters of Little Nankoweap Creek). Distinctive light-colored formation in cliff just below distant skyline is Coconino Sandstone.

GEOLOGIC SETTING

Bedrock at river level is the Bright Angel Shale (€ba), an easily eroded unit that forms a distinctive, mostly talus-covered slope above the Colorado River. Exposed in the steep walls of Marble Canyon above the shale are the Muav Limestone (Cambrian), Redwall Limestone (Mississippian), sandstone, siltstone, and shale of the Supai Group (Pennsylvanian to Permian), Hermit Shale, Coconino Sandstone, Toroweap Formation, and Kaibab Formation (all of Permian age).

These Paleozoic strata dip gently to the northeast. Cambrian Tapeats Sandstone and the Proterozoic Chuar Group consisting of the Galleros, Kwagunt, and Sixtymile Formations (Huntoon and others, 1986; Ford, 1990) are exposed along Nankoweap Creek on the west, upthrown side of the Butte Fault and East Kaibab Monocline 3.7 km (2.3 mi) upstream of Nankoweap Rapids.

These bedrock units are the source of most boulder-size sediment in the Quaternary deposits along the river, although trace amounts of far-travelled very

Table 1. *Radiocardon dates of alluvium, debris-flow related deposits, and archeologic features, Nankoweap Rapids area, Marble Canyon, Arizona*

Sample number			Location[3]		Material	Date, in years B.P.	Calendar date[5]	Description
Map No.	Field[1] number	Lab. number	Latitude DMS[4]	Longitude DMS[4]				
1	LNRC 1-1	3566	36 18 35	111 51 51	Driftwood, outer rings	280±30[6]	A.D. 1510–1610 A.D. 1610–1660	Driftwood, dfyc surface
2	LNRC 1-2	3567	do	do	Driftwood, bark	modern	modern	Do.
3	LNRC 2-1	3569	36 18 30	111 52 00	Wood	235±35	A.D. 1520–1600 A.D. 1620–1680 A.D. 1740–1810	Twigs in debris flow mudline west of map area
4	LNRC 2-2	3568	do	do	Wood	modern	modern	Do.
5	LNRC 3	3564	36 18 39	111 51 54	Charcoal	700±30	A.D. 1260–1300 A.D. 1360–1380	Burned zone 2 m below ap surface[7]
6	LNRC 4A	3571	36 18 29	111 51 49	Charcoal	modern	modern	Roaster in ap, 34–42 cm below surface
7	LNRC 4B	3572	do	do	Charcoal	240±30	A.D. 1520–1560 A.D. 1630–1680 A.D. 1740–1800	Do.
8	NCRC 1	3565	36 17 51	111 51 39	Charcoal[8]	440±60	A.D. 1330 A.D. 1400–1530 A.D. 1550–1640	Unit ap
9	NCRC 3	3633	36 18 03	111 51 30	Charcoal	290±60	A.D. 1450–1670 A.D. 1750–1800	Roaster in umt alluvium 30 cm below top
10	NCRC 5	3570	36 18 18	111 51 49	Charcoal	modern[9]	modern	Roaster associated or fire pit with Pueblo-II remains

[1] LN = Little Nankoweap Creek; NC = Nankoweap Creek
[2] U.S. Geological Survey Radiocarbon Laboratory, Reston, Virginia
[3] Latitude and longitude from Hereford and Thompson (1994)
[4] DMS = Degrees, minutes, seconds
[5] 95 percent confidence interval in calendar years of the radiocarbon date which was calibrated to calendar years using relations developed through measurement of ^{14}C activity of dendrochronologically dated wood (Klein and others, 1982). Multiple dates are possible because of atmospheric ^{14}C fluctuations
[6] Stratigraphically and analytically same as modern
[7] Burnt roots of mesquite; rooted in but slightly younger than terrace
[8] Charcoal from burnt mesquite root disturbed by burrowing, date too young
[9] Modern, probably from historic-age campfire

well rounded pebbles and small cobbles of Colorado River origin are present locally. The dominant rock types in the deposits of the large tributaries are Redwall Limestone and Supai Group sandstones. Kaibab Formation is essentially absent in the deposits of Nankoweap Creek and is present only sparingly in the deposits of the other tributaries.

GEOMORPHOLOGY OF THE NANKOWEAP RAPIDS AREA

The principal geomorphic elements along the river are (1) debris fans and channels of large tributary streams with headwaters on the rim of Marble Canyon and Walhalla Plateau, (2) small tributary streams with headwaters along the river corridor, (3) alluvial terraces and deposits of the Colorado River, (4) sand dunes, and (5) the high ridge on the south side of Nankoweap Creek. These geomorphic features range in age from older than about 210,000 years (Machette and Rosholt, 1989; 1991) to A.D. 1995.

The Nankoweap Rapids area is in Marble Canyon, a name applied to Grand Canyon from just downstream of Lees Ferry to just downstream of the Little Colorado River near River Mile 61. The mapped area is in the "Lower Marble Canyon" of Schmidt and Graf (1990, table 2) and the "Chuar Segment" of Grand Canyon defined by Potochnik and Reynolds (1990). Large tributaries heading on the west side of the canyon on the east escarpment of the Walhalla Plateau (one of the plateaus forming the Kaibab Plateau) and relatively short tributaries on the east side of the canyon are characteristic of the Chuar Segment.

In this map area, west-side tributaries are Little Nankoweap Creek, Nankoweap Creek, and a rela-

Table 2. *Drainage-basin characteristics and rounding of debris-fan clasts, Marble Canyon, Arizona*

Drainage basin	Area km² mi²	Channel length km mi	Channel relief m ft	Channel slope	Clast rounding
Nankoweap Creek	84.630 32.68	14.27 8.869	1,370 4,490	0.10	Subrounded to rounded
Little Nankoweap Creek	10.780 4.162	5.97 3.71	702 2,300	0.12	Subangular to subrounded
Unnamed east side	2.9480 1.138	2.53 1.57	983 3,220	0.39	Angular
Unnamed west side	1.3596 0.5250	1.54 0.956	589 1,930	0.38	Angular

tively small, unnamed tributary near the south boundary of the map area that drains the northeast side of Nankoweap Mesa. The east-side tributaries, which are unnamed, drain the Blue Moon Bench of the Marble Platform. These tributaries are of widely differing basin size (table 2). Nankoweap Creek is the largest basin and the unnamed west-side tributary is the smallest. Channel length is directly related to drainage basin area, whereas area is inversely related to channel slope.

The nearly vertical east wall of Marble Canyon towers over the spectacular scenery of the Nankoweap Rapids area (fig. 2). The east rim of Marble Canyon rises 1,000 m (3,280 ft) above the Colorado River, and the horizontal distance from rim-to-river is only 700 m (2,300 ft). This results in the steepest topography in Marble Canyon. The Supai Group typically forms a distinctive stepped-slope profile throughout Grand Canyon, but the exposures are nearly vertical in the reentrant above Nankoweap Rapids (fig. 2).

The Colorado River flows south-southwest into the Nankoweap area. Just upstream of Little Nankoweap Creek, the river bends sharply 80 degrees to the southeast. The river is deflected to the southeast into the cliff face by the high ridge of breccia (bc) and gravel (gvo) along the south side of Nankoweap Creek.

DEBRIS FANS AND DEBRIS-FLOW DEPOSITS

Debris fans are the conspicuous, roughly fan-shaped landforms at the mouths of Little Nankoweap Creek, Nankoweap Creek, and the unnamed west-side drainage near the south boundary of the mapped area. The fans developed by relatively large, infrequent debris flows during the past several thousand years. Sandy alluvial deposits of the Colorado River encircle the toes of the fans, outlining the fan shape.

Debris fans consist of two main elements: the inactive surface of the fan itself and the active, entrenched debris-flow channel. Deposits forming the surface of the fans are called fan-forming, because the primary fan surfaces are developed on these deposits; deposits in the channel are called channelized debris-flow deposits (Hereford, 1993, 1996; Hereford and others, 1993; 1995; 1996). Although the two types differ in age and surface area, both are similar sedimentologically to tributary debris-flow deposits described elsewhere in Grand Canyon (Webb and others, 1989; Melis and Webb, 1993). The texture and composition of the deposits in the study area, however, depend on which drainage they originate from.

COMPOSITION AND CLAST ROUNDING OF DEBRIS-FLOW DEPOSITS

The debris-flow deposits are weakly stratified, poorly sorted mixtures of clay, silt, sand, and gravel (fig. 3). The fabric of the deposits ranges from clast to matrix supported, although clast supported is typical. Clast rounding (table 2) and clast composition vary among the several drainage basins.

Deposits of Little Nankoweap Creek and the unnamed west-side drainage are similar in composition, although they differ substantially in degree of clast rounding. The main rock types are Redwall Limestone (33 percent) and Supai Group sandstones (33–37 percent) along with substantially smaller amounts of Kaibab and Toroweap formations (8 percent) and Coconino Sandstone (8–18 percent), rocks derived from the west rim of the canyon. Boulders in Little Nankoweap Creek are subangular to subrounded, whereas in the unnamed drainage boulders are angular to subangular. Angularity in deposits of the unnamed tributary results from break-up of the debris after free-fall over the 330 m (1,000 ft) cliff of Redwall and Muav Limestones and short transport distance. The relatively poor clast rounding of deposits in Little Nankoweap Creek reflects the short

Figure 2. Mouth of Nankoweap Creek and reentrant of east wall of Marble Canyon, view east-southeast. Cliff at skyline is Kaibab Formation and Coconino Sandstone; massive cliff above river is Redwall Limestone. Note truncation at south end of reentrant of relatively gentle, talus-covered slope extending from top of Redwall Limestone to near base of Coconino Sandstone in upper right of photograph. Nankoweap Creek debris fan is flat area extending from lower right to near left center; light-colored area is recently active channel of Nankoweap Creek with debris-flow units dco and dcy. Ridge on right side of Nankoweap Creek composed of older gravel (gvo) and coarse-grained breccia facies (bc) near river. Ridge extending through foreground on left side of creek exposes older gravel overlain by fine-grained breccia facies (bf). See map sheet for Description of Map Units.

transport distance from the source area of this small basin (table 2).

Debris-flow deposits of Nankoweap Creek (fig. 3) differ substantially in composition and clast rounding from those of the other west-side tributaries. Almost half (48 percent) of the boulders are Redwall Limestone derived from Nankoweap Canyon. Rocks from the distant escarpment of the Walhalla Plateau are absent to rare; limestone of the Kaibab Formation is present in trace amounts and only 5 percent of the boulders are Coconino Sandstone. Proterozoic rocks derived from the middle and upper parts of the basin constitute 11 percent of the deposits. Clast rounding is substantially improved over the two smaller tributaries. Rounded and subrounded boulders are abundant, although subangular boulders are present.

These differences in composition and rounding between Nankoweap Creek and the other west-side tributaries are mainly a function of drainage-basin geology and geomorphology (table 2). Generally, the larger drainages with long, low-gradient channels produce boulders that are subrounded to rounded; whereas the small drainages with short, steep channels produce angular to subangular boulders.

The virtual absence of Kaibab Formation and the improved clast rounding of debris-flow deposits in Nankoweap Creek result from the relatively long transport distance; Kaibab Formation is present in the headwaters of Nankoweap Creek 10–14 km (6–8.5 mi) upstream of the debris fan. The nearest outcrops of Kaibab in Little Nankoweap Creek and the unnamed debris fan are only 4–6.4 km (2.5–4 mi) and 1.6 km (1 mi) upstream of the river, respectively.

AGE AND CORRELATION OF FAN-FORMING DEBRIS-FLOW DEPOSITS

[All ages are anno Domini (A.D.) unless otherwise noted]

The ages of fan-forming debris-flow deposits range from around 210 B.C. to as late as 1920. We differentiated the fan-forming deposits by topographic

Figure 3. Intermediate-age debris-flow deposits (dfib) on south side of Nankoweap Creek at 870 m contour, scale 15 cm. Abundant subrounded to rounded boulders are typical. Grain size ranges from silt to small boulder and stratification is lacking, typical characteristics of debris-flow deposits in the mapped area. Note Stage-I carbonate accumulation beneath surface on large boulder in upper center of photograph. See map sheet for Description of Map Units.

position and by degree of surface weathering, which is illustrated in figures 4–6. On any particular fan, the oldest surfaces have the highest elevation and are most intensely weathered. The numerical age of the deposits was estimated from measurement of surface roughness or pitting of limestone boulders, which is related to exposure time of the fan surface (Hereford and others, 1996; 1997).

Debris-fan surfaces and deposits in the Nankoweap Rapids area are correlated with those in eastern Grand Canyon by surface weathering characteristics. Three age categories are recognized (Hereford and others 1993; 1995; 1996); these are the older, intermediate, and younger fan-forming debris-flow deposits and surfaces. In the Nankoweap Rapids area, the younger and intermediate-age surfaces are further divided into three categories, each based on degree of weathering.

The older deposits (dfo) are present only at the unnamed drainage near the south boundary of the map area. The surface of these deposits is not well exposed because of heavy sand cover by the striped (?) alluvium (sa). Nevertheless, the surface has well-developed rock varnish and limestone boulders have weathering pits that average 5.6 mm deep. Beneath the surface, the undersides of boulders have weak Stage-II carbonate morphology (Bull, 1991). This

degree of weathering is typical of the older debris-fan surfaces of eastern Grand Canyon.

Three intermediate-age surfaces (dfia, dfib, and dfic), each with different weathering characteristics, are present on the Little Nankoweap and Nankoweap Creek debris fans. Generally, surfaces of intermediate age are distinctly patinated, limestone boulders are rough and thoroughly pitted, and sandstone boulders show some degree of splitting, spalling, and granular disintegration (figs. 4–5). Chert on the surface of limestone boulders weathers differentially, producing several millimeters of relief between chert and surrounding limestone. Average depth of weathering pits are 4.7 mm, 3.3–3.6 mm, and 2.4 mm for units dfia, dfib, and dfic, respectively. The undersides of boulders have weak to moderately developed Stage-I carbonate morphology (Bull, 1991).

Pueblo-II archeologic sites are present on these surfaces at the Nankoweap Creek debris fan. The sites demonstrate that the intermediate-age surfaces mostly pre-date Pueblo-II occupation. The relation to Pueblo-II archeologic sites is similar to those on intermediate-age debris fans in eastern Grand Canyon.

Three younger fan surfaces were mapped (dfya, dfyb, and dfyc). Although subtle, the surfaces differ in degree of weathering and relation to progressively

Figure 4. Surface weathering of debris-flow unit dfia on south side of Nankoweap Creek, scale 15 cm. Note deeply pitted limestone boulder to left of scale and partly decomposed sandstone boulders in upper foreground. Surface is probably about 1,500 years old. See map sheet for Description of Map Units.

Figure 5. Surface weathering of debris-flow unit dfib on south side of Nankoweap Creek, scale 15 cm. Note relatively shallow pits on limestone boulder in mid-ground to right of scale and spalling of sandstone boulder at right side of photograph. Surface is probably about 1,200 years old. Compare this illustration with figures 4 and 6, which show more intense and very little weathering, respectively. See map sheet for Description of Map Units.

Figure 6. Surface of debris-flow unit **dfyb** on north side of Nankoweap Creek, scale 15 cm. Most boulders are fresh appearing with incipient rock varnish on 20–40 percent of boulders; limestone boulders are mostly fresh with only poorly developed weathering pits. Surface is probably about 90–110 years old. See map sheet for Description of Map Units.

older alluvial terraces. The oldest of the younger fan surfaces (**dfya**) is present only on the fan of the unnamed west-side tributary. Boulders are lightly patinated, limestone boulders are slightly pitted, and the undersides of boulders have barely visible, very thin discontinuous coatings of calcium carbonate. This deposit is younger than the alluvium of Pueblo-II age (**ap**) and pre-dates the lower mesquite terrace (**lmt**). Unit **dfya** is equivalent to the upper mesquite terrace (**umt**), and the weakly developed soil and pitting further suggest that the unit is probably equivalent to the lower or early part of the upper mesquite terrace (**umt**).

The youngest of the three surfaces (**dfyc**), present on Little Nankoweap Creek fan, has essentially no rock varnish and limestone boulders are fresh without surface roughening. Mapped relations indicate this debris flow is younger than the upper mesquite terrace (**umt**) and older than the pre-dam alluvium (**pda**). On Nankoweap Creek fan, the younger surface (**dfyb**) is somewhat older than at Little Nankoweap Creek as suggested by very lightly patinated boulders and weakly developed, incomplete pitting of limestone boulders (fig. 6).

EROSION OF ARCHEOLOGIC SITES BY LARGE TRIBUTARY STREAMS

Archeologic sites are present on the debris fans and adjacent alluvium of Nankoweap and Little Nankoweap Creek. Sites near the active debris-flow channels are subject to erosion and damage during runoff. The channel of Nankoweap Creek widened and shifted in December 1966 (Cooley and others, 1977) and again during floods of March 5–6, 1995, when the channel widened 10 m (30 ft) near the upper trail crossing.

The channel of the unnamed west-side tributary near the south boundary of the map is deep and steep-walled where it crosses the alluvium of Pueblo-II age (**ap**). This suggests that the channel recently deepened and widened. This channel incision resulted from diversion of an earlier channel by deposits of the younger fan-forming debris flow (**dfya**). Although floods large enough to cause noticeable shifting of the active debris-flow channels are relatively infrequent, such floods widen and deepen the channel, eventually removing or damaging near-channel archeologic sites.

SMALL TRIBUTARY STREAMS

Small tributary streams drain the hillslopes along the Colorado River. These streams head in talus, on the slope of Bright Angel Shale, and on the alluvial terraces and debris fans. Several of the small tributary streams have mappable deposits. We identified two types of deposits and surfaces: alluvial fans and debris fans.

The alluvial fans are mainly sand with pebble- and cobble-size gravel on the slopes at the head of

the fans. Most of the older alluvial fan deposits (afo) are on the north side of the high ridge, where the alluvium was deposited on the Nankoweap Creek debris fan. The deposits appear stabilized and largely inactive. The younger alluvial fans (afy) are on the south side of the high ridge. These deposits appear relatively fresh and the topography resembles small, coalescing alluvial fans on the surface of the upper mesquite terrace (umt). The sand is probably reworked from the striped (?) alluvium (sa) in the area and from sand deposits too thin to show at map scale on the basal slope of the small-block talus (ts).

The debris-flow deposits of small tributaries (do, dy, and da) are mainly gravel derived from reworking of talus. The deposits resemble debris flows because of poor sorting and abundant small boulder-size clasts. Paired debris-flow levees on relatively steep slopes and small debris fans on gentler slopes characterize these deposits. The older small-tributary debris-flow deposits (do) overlie the striped (?) alluvium (sa); field relations indicate these older deposits probably interfinger with the upper part of the striped (?) alluvium in the subsurface. Weathering of the older deposits (do) resembles the surface weathering characteristics of debris-flow unit dfib. South of the high ridge, the younger small-tributary deposits (dy) overlie and interfinger with the alluvium of Pueblo-II age (ap). The youngest small-tributary debris-flow deposits (da) appear fresh and were deposited in relatively small channels incised into older deposits.

EROSION OF TERRACES AND DEBRIS FANS BY SMALL TRIBUTARY STREAMS

Elsewhere in Grand Canyon, small tributary streams are associated with erosion of archeologic sites where the streams flow across terraces (Hereford and others, 1993). In the Nankoweap Creek area, several of these small streams have channels entrenched or eroded into the alluvial terraces. On the north side of the debris fan of the unnamed west-side tributary, the banks of the small tributary streams are steep and as deep as 3–4 m (9–12 ft). This suggests that the channels are actively eroding by deepening and widening. In other places, such as near the toe of the Nankoweap Creek debris fan at the 860 m contour, the banks of the channel are gently sloping, suggesting that the channels are relatively stable and that widening and deepening are not a problem.

ALLUVIAL TERRACES AND DEPOSITS OF THE COLORADO RIVER

A stepped sequence of terraces parallels the Colorado River on the west side of the Nankoweap Rapids area. The full sequence is present on the north side of Little Nankoweap Creek debris fan, in the wide area between Little Nankoweap Creek and Nankoweap

Creek debris fans, and in the wide area south of the high ridge. Elevation of the sequence and post-dam deposits from water level to the upper contact of the alluvium of Pueblo-II age ranges from 851–862 m north of the high ridge to 846–857 m downstream of Nankoweap Rapids south of the high ridge. About the lower 5 m of this 11-m elevation range is occupied by the post-dam deposits.

The number of terraces is identical to the number in eastern Grand Canyon (Hereford and others, 1993; 1995; 1996). This similarity and the relation of terraces to dated archeologic sites, debris fans, and flood debris suggest the alluvial sequence in the Nankoweap Rapids area correlates with the eastern Grand Canyon terrace sequence. This correlation seems reasonable because the terraces and related alluvium are modified and deposited by floods of the Colorado River, which are continuous through Marble Canyon and Grand Canyon.

PRE-DAM TERRACES

The pre-dam terraces are present on the west side of the river. They were not mapped on the east side south of Little Nankoweap Creek debris fan; the terraces in this area are poorly developed and terraces or terrace-like features older than the pre-dam alluvium (pda) were not found. Although sandy deposits are present above the level of the pre-dam alluvium, they were not mappable as distinct landforms on the steep talus slopes and debris fans that are typical of the east side south of Nankoweap Creek.

The alluvial deposits of pre-dam age aggraded by overbank deposition during floods, which in time built a floodplain-like surface along the channel margin. Abandonment of the floodplain by shifting of the channel forms a terrace. Over the past several thousand years, the Colorado River has shifted course and cut through pre-existing floodplains four times, forming the terraces of the striped (?) alluvium (sa), alluvium of Pueblo-II age (ap), alluvium of the upper and lower mesquite terraces (umt and lmt), and the terrace of the pre-dam alluvium (pda). Each downcutting, except the most recent, was followed by floodplain deposition of the various alluvial deposits. Several repetitions of this cut-and-fill process produced the inset terrace stratigraphy that is typical of alluvial deposits in the mapped area as well as eastern Grand Canyon (Hereford, 1993; 1996; Hereford and others, 1993; 1995; 1996). The most recent channel adjustment was incision of the pre-dam alluvium, which happened after 1958.

The historic or systematic flood record suggests the size of floods forming the younger pre-dam terraces (umt, lmt, and pda). These terraces and related alluvial deposits resulted from floods substantially larger than the post-dam maximum of 2,700 m^3/s (96,000 ft^3/s). Because the terraces are inset, flood levels may have been progressively lower through time, assuming the channel has not deepened.

The uppermost alluvium of the upper mesquite terrace (umt) was probably deposited by a flood in the late 1800s, as shown by studies in eastern Grand Canyon (Hereford, 1993; 1996). In the mapped area, a large driftwood pile on the east side of the river at the same elevation as the terrace contains only beaver-cut cottonwood. This lack of milled, saw-cut, and ax-cut wood suggests the flood occurred before widespread Anglo settlement of the river basin. According to reconstructions by the U.S. Bureau of Reclamation (1990, p. 8), peak flow of the Colorado River in Grand Canyon was 14,100 m^3/s (500,000 ft^3/s) in 1862. This was probably the last flood to overtop the upper mesquite terrace. Although the flow rate and the 1862 date of the flood are only estimates, the flood level is above the level of the lower mesquite terrace (lmt). Floods during deposition of the alluvium of the lower mesquite terrace probably ranged from 6,200 m^3/s (220,000 ft^3/s) to 8,500 m^3/s (300,000 ft^3/s). These were the largest known floods between July 1884 and June 1921.

The pre-dam alluvium (pda) was deposited by spring floods after 1921. The largest of these was 3,600 m^3/s (127,000 ft^3/s) in July 1927. Flood debris on the surface of the alluvium dates from the 1950s; this debris was probably deposited during floods in June of 1957 and 1958 with flow rates of 3,540 m^3/s (125,000 ft^3/s) and 3,050 m^3/s (107,700 ft^3/s), respectively. These were the last floods to overtop the pre-dam alluvium.

If inset terraces indicate progressively higher flood levels back through time, floods during deposition of the striped alluvium (sa) and alluvium of Pueblo-II age (ap) would be the largest of the past 2,000 years. The relation of these terraces, however, to younger flood levels is uncertain, as the channel was substantially wider than during deposition of the two younger alluviums (umt, lmt). Thus, the present relation between elevation and discharge (or flood stage) may not apply to these oldest terraces. If the present relation of stage to discharge applies, then the striped (?) alluvium and alluvium of Pueblo-II age were deposited by floods larger than 8,500–14,100 m^3/s (300,000–500,000 ft^3/s), which were presumably the largest floods during deposition of the upper and lower mesquite terraces.

POST-DAM CHANNEL-SIDE BAR DEPOSITS

The post-dam channel-side bar deposits (fs, hf, ff, and mf), referred to as beaches by river runners, occupy four progressively lower and narrower topographic levels adjacent to the river. The deposits are well developed on the north side of Little Nankoweap Creek debris fan, the wide area between Nankoweap and Little Nankoweap Creeks, and south of the high ridge in the two wide areas defined by the arcuate pattern of the 848 m contour. In these places, deposition results from sedimentation in zones of recirculating flow, where the flow separates from the main current and moves upstream, rejoining the main flow at the head of the recirculation zone. This type of deposition was studied recently by Schmidt (1990) who developed a detailed sedimentologic classification of recirculating-zone deposits. For the most part, the deposits record the depositional activity of the Colorado River since 1983. The lack of post-dam deposits between 1963–1983 suggests either little deposition in the period or erosion during the flood of 1983.

Generally, deposition of the channel-side bars at progressively lower levels is related to the declining pattern of maximum water releases from Glen Canyon Dam since 1983 (Hyatt, 1990) that culminated in the moderated flow regimen beginning August 1991. The largest flows of the post-dam era were in June–August 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). These flows resulted in erosion of the terrace of the pre-dam alluvium (pda) and deposition of the flood sand (fs). During May–June of 1984–1986, sustained flows were the second largest of the post-dam era, ranging from about 900 to 1,400 m^3/s (32,000 to 50,000 ft^3/s). This discharge regimen produced the high-flow sand (hf). From late 1986 through 1991, seasonal variation was largely eliminated and daily flows fluctuated up to a maximum of 910 m^3/s (1,400 m^3/s). This strongly fluctuating flow regimen resulted in deposition of the fluctuating-flow sand (ff). From August 1991 until late 1996, flows have generally not exceeded 570 m^3/s (20,000 ft^3/s), and the moderated-flow sand (mf) was deposited immediately adjacent to the river in the lowest level of the channel margin.

Between March 22 and April 8, 1996, flow rates were increased to 1,270 m^3/s (45,000 ft^3/s) in an experimental, controlled-flood release designed to reposition sand submerged in the channel onto subaerial river banks. The flood stage of the experimental flood should have been near the upper limit of the high-flow sand (hf). Although we have not visited the map area since the flood release, we anticipate that sand from the experimental flood was deposited at the level of the moderated-flow, fluctuating-flow, and high-flow sands (mf, ff, hf).

SAND DUNES

Sand dunes are widespread on the debris fans of Little Nankoweap Creek, Nankoweap Creek, the unnamed west-side debris fan, and in the wide area south of the high ridge. These are mainly coppice dunes forming sand hummocks and mounds around mesquite trees, although sand sheets are present locally. Sand in the dunes is derived entirely from eolian reworking of alluvial deposits. The Colorado River is the only important source of eolian sand in the mapped area.

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The dunes are classified as active (ea), moderately active to inactive (ey), and largely inactive (eo). The degree of eolian activity coincides with vegetation cover and topographic relief of the dune. Active dunes (ea) are lightly vegetated and have relatively high relief. Vegetation is more abundant and relief is relatively subdued on the less active dunes (ey and eo).

Dunes and alluvial terraces are collocated, suggesting they develop in many cases where a terrace rise is exposed to prevailing winds. On the south side of the Little Nankoweap Creek debris fan, the older sand dunes (eo) originate from the steep southeast facing terrace rise of the alluvium of Pueblo-II age (ap). The active dunes are reworked from pre-dam alluvium (pda) and alluvium of the upper and lower mesquite terraces (umt and lmt). Most of the sand probably originated from wind deflation along the terrace rises separating the alluviums. The linear dune (ey) south of the high ridge is probably developed along the terrace rise separating the upper and lower mesquite terraces.

THE HIGH RIDGE SOUTH OF NANKOWEAP CREEK

The largest and perhaps most interesting landscape element of the Nankoweap Rapids area is the high ridge on the south side of Nankoweap Creek debris fan. The ridge is about 50 m (160 ft) high and is conspicuous because of the numerous large, angular blocks of Kaibab Formation on the top and sides (fig. 7). Most rafters and hikers notice these

deposits, and their age and origin intrigue the specialist and layman alike.

The ridge developed on highly eroded deposits of the older gravel (gvo) and coarse-grained breccia (bc). These deposits are topographically the highest and oldest Quaternary units in Marble Canyon. The breccia is probably at least 210,000±25,000 years old (Machette and Rosholt, 1989; 1991), and the gravel is older, probably substantially older. The breccia deposits are related geologically to almost identical deposits on the somewhat lower ridge on the north side of Nankoweap Creek that extends several hundred meters west of the mapped area. The crests of the two ridges are the drainage divide of Nankoweap Creek, indicating the ridges are geomorphically old.

How the breccia was deposited is especially interesting, and several hypotheses have been presented. Péwé (1968) suggested the deposits are a dissected mudflow or debris flow of Nankoweap Creek. Unpublished observations by Andre Potochnik (written commun., 1995) suggest that the breccia was derived from Tilted Mesa (2.4 km (1.5 mi) west of the mouth of Nankoweap Creek) as a catastrophic debris flow emanating from Little Nankoweap Creek. In contrast, other studies suggest the rubbly sediment was a rockfall originating nearly 1 km (0.6 mi) above the river on the steep east wall of Marble Canyon (Hereford, 1978; 1984; Elston, 1989; Machette and Rosholt, 1989, 1991). These explanations involve different depositional processes and opposing directions of sediment movement. We examine the problem of a rockfall from the east versus a debris flow from the west by comparing the composition, texture, and distribution of breccia with the older gravel and deposits of known debris-flow origin.

Figure 7. Coarse-grained breccia facies on high ridge south of Nankoweap Creek, background is east side of Marble Canyon. Large blocks are predominantly Kaibab Formation. Block behind person is typical of largest blocks, which show as closed contours and crenulations on topographic base map (map sheet).

COMPOSITION AND TEXTURE

Rock fragments in the coarse-grained breccia facies (bc) are mostly coherent blocks of Kaibab Formation. The Kaibab makes up about 90 percent of the clasts on the surface of the high ridge. In contrast, Holocene deposits of Nankoweap Creek debris fan have essentially no Kaibab Formation, and late Holocene deposits of Little Nankoweap Creek and the unnamed west-side tributary generally contain less than 10 percent Kaibab clasts.

One might expect the composition of the older gravel (gvo) to closely resemble the breccia if both were derived from Nankoweap Creek. This is not the case, however, as the gravel contains abundant boulders of Redwall Limestone (43 percent) and Proterozoic sandstone (22 percent), but no Kaibab Formation. Thus, the abundant Kaibab Formation in the coarse-grained breccia facies is peculiar compared with Holocene or Pleistocene deposits of Nankoweap Creek or Little Nankoweap Creek.

Subrounded to rounded cobbles and small to medium-size boulders of Tapeats Sandstone and Proterozoic formations as well as very well rounded pebbles and small cobbles of Colorado River origin are widely scattered on the surface of the high ridge near the northeast end. The Tapeats Sandstone and Proterozoic-type clasts were probably derived from the upper portion of Nankoweap Creek basin. The area corresponds approximately with terrace levels 3 and 4 of Machette and Rosholt (1991), although the topography does not resemble a terrace. This area is shown with a stippled pattern on the geologic map.

These "terraces" and associated thin deposits are likely erosional remnants that developed when the Colorado River and Nankoweap Creek flowed over the ancestral ridge after deposition of the breccia. The carbonate soil horizon of level 3 is relatively shallow compared with the soil horizon of the breccia. The shallow soil was dated at 40,000±24,000 years B.P. by the uranium-trend method (Machette and Rosholt, 1991), which is significantly younger than the underlying breccia.

The fine-grained breccia facies (bf) also contains widely scattered very well rounded pebbles and small cobbles of Colorado River origin (Hereford, 1984) near and beyond the west boundary of the mapped area on both sides of Nankoweap Creek. Clasts of this type are not present in Nankoweap Creek basin, nor are they present in the older gravel (gvo) at this locality or in the Holocene debris-flow deposits. The only source of the clasts was the bed of the river, as they are not found elsewhere.

Deposition of the breccia evidently incorporated or entrained sediment from the river bed. This entrainment process and the thin deposits on the surface of the breccia derived from the Colorado River and Nankoweap Creek explain the inclusion of rock types in and on the surface of the breccia that could not have originated from the east side of Marble Canyon. The composition of the breccia, therefore, is not exactly the composition expected of an east-side source area, because the breccia is contaminated with a small number of clasts derived from the bed of the Colorado River and Nankoweap Creek.

The texture of the breccia contrasts sharply with the texture of the Holocene debris flows and Pleistocene gravel. Texture of the breccia ranges from angular to subangular, with angular clasts dominant (fig. 8). Boulders in the late Holocene debris-flow deposits of Nankoweap and Little Nankoweap Creeks are more or less rounded. Debris-flow deposits of Nankoweap Creek range from subangular to rounded, although subrounded to rounded is typical (figs. 3, 6). Likewise, the older gravel (gvo) has abundant subrounded to rounded boulders (fig. 9). Transport of sediment to the mouth of Nankoweap Creek evidently results in substantial rounding of cobble- and boulder-size sediment. The lack of rounding in the gravel-size component of the breccia is difficult to reconcile with a debris flow originating in either Nankoweap Creek or Little Nankoweap Creek.

Distribution of breccia

The distribution of the coarse- and fine-grained breccia (bc and bf) shows that the deposits become substantially finer grained from east to west, or from the Colorado River to the mouth of Nankoweap Canyon. In about 400 m, the maximum dimension of Kaibab Formation blocks decreases from 7 m to less than 1 m, as measured from the east-facing side of the high ridge to the outcrop of fine-grained breccia on the south side of Nankoweap Creek. The fine-grained breccia has only a few large boulder-size clasts of Kaibab Formation and the percentage of sand-size matrix is much larger than in the coarse-grained breccia. At the westernmost outcrop on the south side of Nankoweap Creek west of the mapped area, the fine-grained breccia is mostly cobble- and small boulder-size gravel with abundant reddish sand matrix. This east to west decrease of clast size is not expected of a deposit originating in Nankoweap Creek, which should become finer grained from west to east as slope and velocity decrease from the mouth of Nankoweap Creek to the Colorado River.

ORIGIN AND DEPOSITION OF BRECCIA

The massive, unstratified character of the breccia (fig. 10) suggests that deposition was a single event. In contrast, the Holocene debris fans were formed from multiple debris flows. It seems unlikely that a single debris flow could deposit as much as 50 m (160 m) of sediment across the entire mouth of Nankoweap Creek.

The above evidence indicates that the breccia was derived from the east. The present average slope of the east side is 55 degrees and long segments of
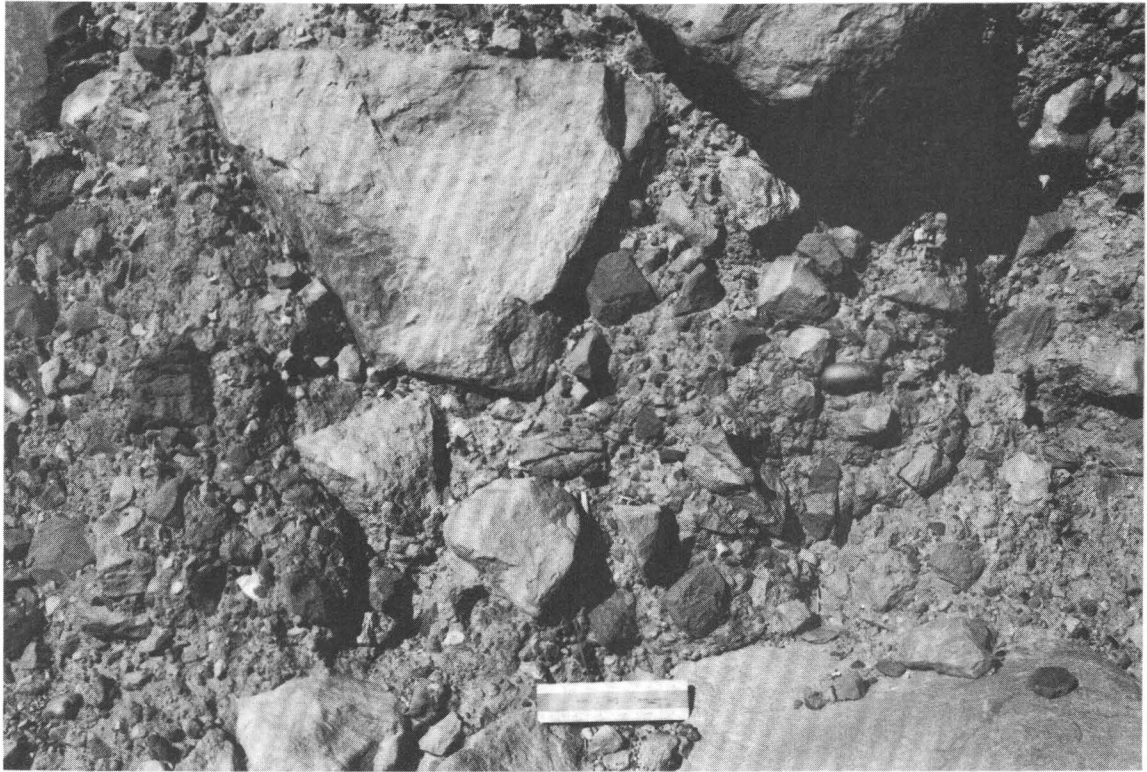
Figure 8. Fine-grained breccia facies (bf) on ridge on north side of Nankoweap Creek, scale 10-cm. Angular boulders and cobbles are typical. Note very well rounded quartzite cobble in right-center.

Figure 9. Older gravel (gvo) on ridge on north side of Nankoweap Creek immediately west of mapped area, scale 140 cm with 20 cm divisions. Subrounded to rounded cobbles and boulders are abundant.

Figure 10. Fine-grained breccia (bf) exposed on ridge on north side of Nankoweap Creek. Note lack of stratification in breccia. Contact with underlying gravel (gvo) is about 1 m (3 ft) below person. Large clast of Kaibab Formation (above person) is not typical of this facies. Compare with figure 7, which shows surface of coarse-grained breccia (bc).

the slope are nearly vertical (fig. 2), a likely configuration when the breccia formed. Thus, we conclude that the breccia originated as a rockfall or rock avalanche resulting from catastrophic failure of the east wall of Marble Canyon.

The former extent of the breccia is uncertain because subsequent erosion has removed much of the deposit. The coarse-grained remnants on the high ridge (bc) and the fine-grained remnants (bc) on the north and south side of Nankoweap Creek suggest that the deposit initially extended over 600 m (1,970 ft) from the Colorado River to the mouth of Nankoweap Canyon. At the base of the east wall, the deposit may have extended more than 700 m (2,300 ft) along the river. Our reconstructed area (fig. 11) of the deposit is 0.46 km² (114 acres) and the volume, assuming an initial average thickness of 50 m (160 ft), is 23.2 hm³ (18,240 acre-ft).

LATE PLEISTOCENE GEOMORPHIC DEVELOP-MENT OF MARBLE CANYON

The older gravel (gvo) and breccia (bf and bc) record the late Pleistocene geomorphic development of Marble Canyon in the Nankoweap Rapids area. The older gravel is probably part of an ancient debris fan or alluvial fan of Nankoweap Creek. The

deposits no longer resemble a fan, as they have been extensively eroded before and after the rockfall. This ancient fan resulted from more than 50 m (160 ft) of aggradation by Nankoweap Creek and the Colorado River. Following this deposition, the river downcut at least 50 m to near its present elevation. This erosion removed most of the gravel; the southeast-facing slope of the high ridge is a remnant of this early erosion. Although subsequently buried by the rockfall, this slope probably extended upstream where it was east-facing and parallel with the river. The extensive downcutting of the river suggests that the gravel is substantially older than the rockfall.

At the time of the rockfall, the Colorado River was close to its present elevation. The east wall of Marble Canyon, however, was probably farther west than at present, by as much as 300–400 m (980–1,300 ft), as shown in figure 11. This is suggested by the truncated talus slope at the top of the Redwall Limestone at the north and south end of the east-wall reentrant above Nankoweap Rapids (fig. 2). The rockfall probably resulted from failure at some point along this ancient talus slope. Geomorphically, the reentrant is unusual in Grand Canyon, because it is the only place where the entire Supai Group forms a nearly vertical cliff; these relatively nonresistant sandstones and siltstones typically form a distinctive slope.

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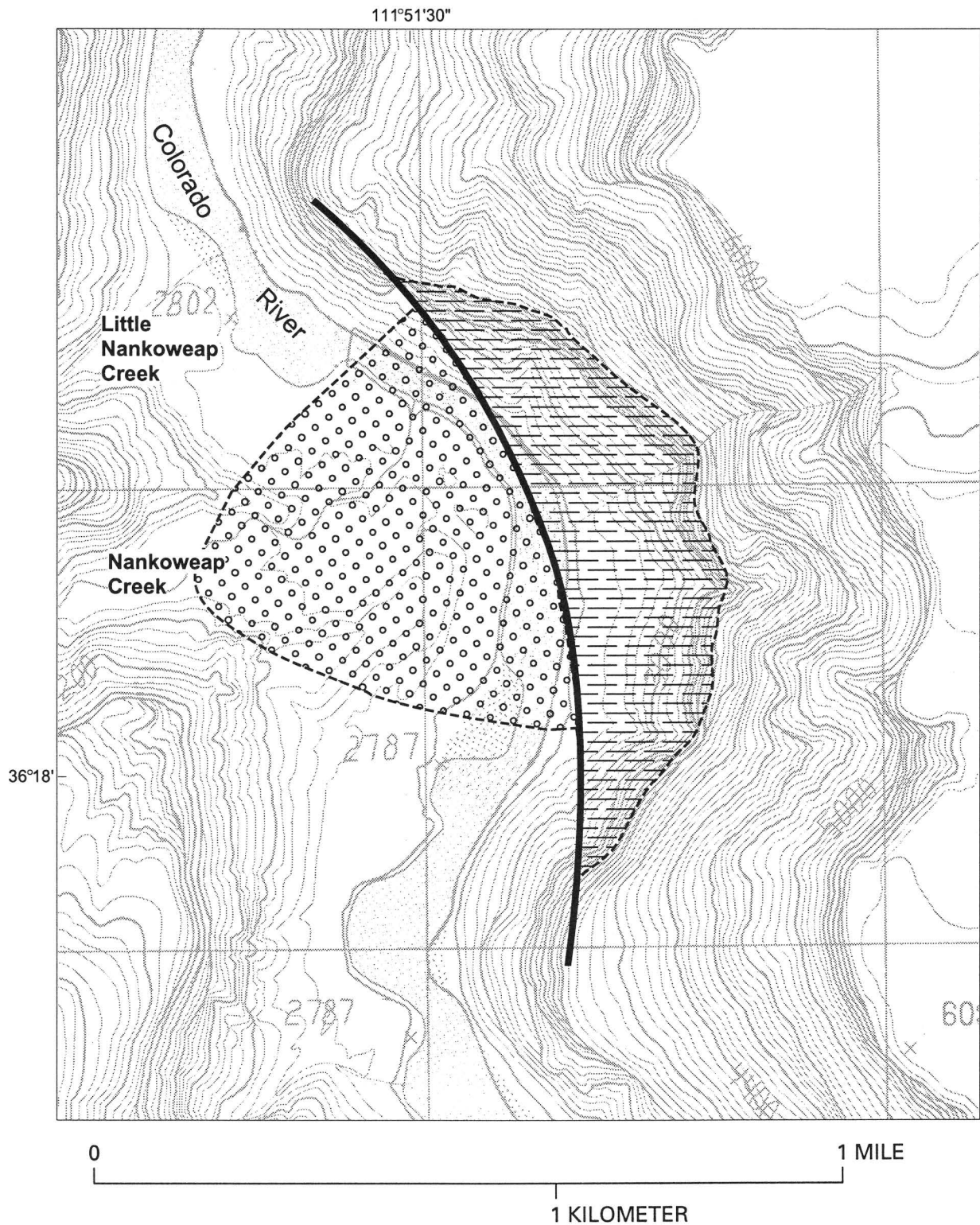
Figure 11. Topographic map (contour interval 40 ft (12 m)) showing reconstruction of Marble Canyon and distribution of rockfall that produced units **bc** and **bf**. Solid line is top of Redwall Limestone at time of rockfall; stippled pattern is rockfall breccia; dashed lines show retreat of Redwall Limestone cliff during and after rockfall. Topography from USGS Nankoweap Mesa 7.5' quadrangle (1988).

Most of the reentrant probably developed after and because of the rockfall. Clast size of the breccia was largest near the base of the ancient east wall of Marble Canyon. These extremely large clasts formed a major obstacle for the Colorado River. The clasts were probably at about the same elevation as the rest of the breccia, as rock avalanches typically have gentle surface slopes (Yarnold and Lombard, 1989). The river was forced around the east margin of the breccia, where it eroded the soft Bright Angel Shale; this eastward shift of the river resulted in oversteepening of the Supai and east wall of MarbleCanyon. Ultimately, the Colorado River and Nankoweap Creek removed most of the breccia, but not without a major shift of the river and reshaping of Marble Canyon.

CONCLUSIONS

Deposits of late Holocene age dominate the surficial geology of the Colorado River in the Nankoweap Rapids area, although late Pleistocene deposits are present as well. Sand dunes, debris fans of large tributary streams, and alluvial terraces of the Colorado River occupy most of the mapped area. The sand dunes are secondary deposits resulting from eolian reworking of sandy alluvium of the Colorado River.

Debris fans formed at the mouths of Little Nankoweap Creek, Nankoweap Creek, and the un-named west-side tributary by relatively large, infrequent debris flows that deposited coarse-grained sediment on the debris fans and in the channel of the Colorado River. Debris flow is the main process of sediment transport in almost every tributary stream in Grand Canyon, including those of the Nankoweap Rapids area (Webb and others, 1989; Melis and Webb, 1993). Alluvial terraces of several ages line the west side of the river and encircle the near-channel margins of the debris fans. Terraces and debris fans are closely related, as emplacement of the fans forms alluvial depositional sites, as noted throughout Grand Canyon by Howard and Dolan (1981) and Schmidt (1990).

Debris fans consist of an active debris-flow channel and the inactive surface of the fan itself. The active channel is entrenched into the fan and the deposits are referred to as the channelized debris-flow deposits. These deposits partly fill the channels and form small, eroded debris fans at the river. Channelized debris flows have occurred at least twice in the past 40 years (map units dco and dcy). A debris flow in Nankoweap Creek in December 1966 deepened and widened the channel, damaging near-channel archeologic sites.

The surfaces of the debris fans are underlain by relatively old debris-flow deposits with large surface area compared with the active channels. The deposits are called fan-forming debris-flow deposits, as they form the primary fan surfaces. Three broad age categories were identified: the older (dfo), intermediate

(dfi), and younger (dfy) fan-forming debris-flow deposits and surfaces; these correlate with and are similar in age to debris fans in eastern Grand Canyon (Hereford and others, 1995, 1996).

The intermediate and younger debris-flow deposit categories were further divided into three age categories each (dfia, dfib, dfic, and dfya, dfyb, dfyc), totaling seven mappable surfaces among the three west-side tributaries. These surfaces range in age from about 200 B.C. to 1920. Their relative ages were established from topographic position and weathering characteristics; the absolute ages were estimated from the measured depth of solution pits in limestone boulders. The degree of weathering and the depth of solution pits are similar to dated late Holocene debris fans in eastern Grand Canyon.

Three fan-forming debris flows make up the west-side debris fans, except the unnamed tributary fan which has two main surfaces. Aggradation of the fans was probably from only two or three debris flows in about the past 1,500 to 2,200 years, depending on the particular fan. This implies that fan-forming debris flows large enough to cover the fan surface do not occur often. One might expect a debris flow of this size to deposit a large quantity of sediment in the Colorado River, substantially altering the channel and forming new rapids. A modern analogue for development of rapids by debris flow sediment was discussed by Webb and others (1988).

The terraces and related alluvial deposits record the depositional and erosional history of the Colorado River during the past several thousand years. The terraces are identified by their height above the river. The number and relative height of terraces and channel-side bars are identical to a dated sequence in eastern Grand Canyon described by Hereford (1993; 1996) and Hereford and others (1995; 1996). The sequence is four terraces and terrace-like features (map units sa, ap, umt, and lmt) that pre-date Glen Canyon Dam and four channel-side bar deposits (map units fs, hf, ff, and mf) that post-date closure of the dam. The post-dam deposits are closest to the channel and resulted from the operation of Glen Canyon Dam since 1983. The oldest and topographically highest of these post-dam deposits is the flood sand (fs) of June–August 1983, which resulted from a flood release of 2,700 m³/s (96,000 ft³/s), the largest release of the post-dam era. An experimental flood release in late March and early April 1996 of 1,270 m³/s (45,000 ft³/s) should have reworked and covered with sand all the post-dam units except the flood sand.

The four pre-dam terraces were former floodplains of the Colorado River; floods during alluviation of the pre-dam deposits were larger than 2,700 m³/s (96,000 ft³/s). Deposition of the pre-dam alluvium (pda) between 1922–1958 was from floods up to 3,600 m³/s (127,000 ft³/s). Floods as large as 6,200 to 8,500 m³/s (220,000 to 300,000 ft³/s) resulted in deposition of the alluvium of the lower mesquite

terrace (umt) between 1884–1921. Even larger floods deposited the alluvium of the upper mesquite terrace (umt) between about 1400–1884. One of these floods, perhaps in 1862, may have discharged 14,100 m³/s (500,000 ft³/s).

Early and middle Holocene deposits were not found in the Nankoweap Rapids area. Older deposits were evidently not preserved, suggesting the Colorado River eroded and removed tributary and mainstem deposits. This erosion and channel flushing could be the cumulative effect of multiple episodes of cut-and-fill in which cutting and erosion remove more sediment than is deposited during filling episodes. Alternatively, a period of unusually large floods several thousand years ago could have scoured Marble Canyon removing middle and perhaps early Holocene debris fans and mainstem alluvium, assuming these older deposits are not simply buried beneath younger alluvium.

Archeologic sites of mostly Pueblo-II age are present in and on the alluvium of Pueblo-II age (ap), in the striped (?) alluvium (sa), and on the surfaces of the intermediate-age debris fans (dfi). Sites near the margins of the active large tributary debris-flow channels (dco and dcy) are subject to erosional damage mainly by shifting of the channels during runoff. The alluvium of Pueblo-II age is dissected locally by short tributary streams of the Colorado River, for example, north of Little Nankoweap Creek and on the debris fan of the unnamed west-side tributary. Although archeologic sites are not presently exposed at these localities, continued erosion by these short tributary streams could expose and damage buried sites.

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