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Description of Map Units and Discussion to Accompany Map Showing Quaternary Geology and Geomorphology of the Nankoweap Rapids area, Marble Canyon, Arizona

by

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Frontispiece

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 overlain by slope of Kaibab Formation. For scale, note 37-foot raft on river just downstream of Little Nankoweap Creek.

DESCRIPTION OF MAP UNITS

ALLUVIUM

ALLUVIAL DEPOSITS OF THE COLORADO RIVER

Post-dam channel-side bar deposits

mf

Moderated-flow sand (A.D. 1991-1995)--Very fine grained, light-gray (N7) (that is "Rock-Color Chart" code N7; Goddard and others, 1948) to very light gray (N8) sand; exposed thickness about 1 m. Maximum elevation of deposit downstream from Nankoweap Rapids is 848 m. Deposited by flows up to 570 m³/s (20,000 ft³/s)

ff

Fluctuating-flow sand (A.D. 1986-1991)--Very fine grained, light-gray (N7) to very light gray (N8) sand; exposed thickness about 1 m. Maximum elevation of deposit downstream from Nankoweap Rapids is 849 m. Deposited by flows as large as about 910 m³/s (32,000 ft³/s)

hf

High-flow sand (A.D. 1984-1986)--Very fine grained, light gray (N7) to very light gray (N8) sand; exposed thickness about 1 m. Downstream from Nankoweap Rapids, elevation of deposit ranges from 849-850 m; deposited by flows between about 910 to 1,400 m³/s (32,000 to 50,000 ft³/s)

fs

Flood sand of summer 1983 (June-August A.D. 1983)--Very fine grained, distinctive light gray (N8), well-sorted sand; silt and clay content less than 5 percent; exposed thickness about 1-1.5 m, well exposed along west side of river near south end of map. Elevation of deposit downstream from Nankoweap Rapids ranges from 850-851 m; deposited by flows ranging from about 1,400 to 2,700 m³/s (50,000 to 96,000 ft³/s)

Terrace and terrace-like features and deposits of pre-dam age

pda

Pre-dam alluvium (early A.D. 1920s to 1957-1958)--Very fine grained to fine-grained, light-gray (N7), silty sand; exposed thickness about 1-2 m. Large, mature saltcedar trees are partly buried in deposit; mesquite rare to absent. At Palisades Creek about 22-km downstream (Hereford, 1993; 1996), a tree-ring date from a partly buried saltcedar indicates germination in 1935. In mapped area, flood debris on surface contains cans and bottles that date from early to mid-A.D. 1950s and abundant cut wood. Elevation of deposit downstream of Nankoweap Rapids ranges from 851-852 m. Topographic position above the flood sand of June 1983 (fs) suggests deposition by flows larger than about 2,700 m³/s (96,000 ft³/s)

lmt

Lower mesquite terrace (A.D. 1884 to early 1920s)--Very fine grained to fine-grained, light-gray (N7), silty sand; exposed thick-

ness about 1-2 m. Typically has relatively small mesquite trees rooted on or beneath surface; saltcedar not present on terrace. Flood debris contains cut wood. Maximum elevation downstream of Nankoweap Rapids is 854 m. This terrace is present near Palisades Creek in a photograph taken in 1890, which suggests the alluvium was initially deposited in July 1884 by the largest flood of the historic record with estimated discharge of 8,500 ft³/s (300,000 ft³/s). Terrace was overtopped in 1921 by a flood of 6,200 m³/s (220,000 ft³/s; Hereford, 1993; 1996), the largest flood of the gaged record

umt

Upper mesquite terrace (A.D. 1400 to 1882-1883)--Very fine grained to fine-grained, light-gray (N7), silty sand; exposed thickness about 1-2 m. Typically has large, mature mesquite trees and shrubs rooted on or beneath surface, senescent or dead mesquite trees present locally. Flood debris not abundant, driftwood contains very little cut wood. Deposit generally has inset stratigraphic relation with alluvium of Pueblo-II age (ap). Elevation of top of deposit downstream of Nankoweap Rapids is 855-856 m. Deposit correlates by position in terrace sequence with upper mesquite terrace in the eastern Grand Canyon (Hereford, 1993; 1996), where age of the terrace is constrained by archeologic remains and radiocarbon dates. Radiocarbon date from near top of unit (no. 9, Table 1) gives A.D. 1450-1800. Terrace probably overtopped by floods larger than 6,200 to 8,500 m³/s (220,000 to 300,000 ft³/s)

Terrace-forming deposits of prehistoric age

ap

Alluvium of Pueblo-II age (A.D. 700 to 1200)--Very fine grained to fine-grained silty sand; exposed thickness about 1-6 m, well exposed in channel near drainage at south end of map. Contains Anasazi archeologic remains dated between A.D. 950-1200 near mouths of Little Nankoweap and Nankoweap Creeks (Helen C. Fairley, personal commun., 1994). Charcoal derived from burnt roots of large mesquite tree rooted on surface of unit give minimum age range of A.D. 1260-1380 (no. 5, Table 1). A roaster of probable Paiute affinity penetrates unit; charcoal in roaster gives modern date (nos. 6-7, Table 1). In southern portion of map, a disturbed charcoal horizon yielded radiocarbon date of A.D. 1330-1640 (no. 8, Table 1); charcoal probably contaminated and reworked by rodent burrowing. Unit correlates with alluvium of Pueblo-II age in eastern Grand Canyon (Hereford and others, 1995; 1996) based on archeologic remains and similar position in terrace sequence

sa

Striped(?) alluvium (before 770 B.C. to A.D. 300)--Very fine grained to fine-grained silty sand with minor interbedded sand and gravel. Tentatively correlated with striped alluvium present in Tanner Rapids area about 26-km downstream of map area (Hereford and others, 1995; 1996) based on topographic position above alluvium of Pueblo-II age (ap). In Tanner Rapids area, contains scattered archeologic remains from the late Archaic to early Basketmaker II

Gravel deposits

gv

Gravel deposits, undivided (prehistoric? to post-dam age)--

Unconsolidated, cobble to medium boulder-size gravel with coarse-sand matrix. Deposits consist of subrounded to rounded boulders of local Proterozoic and Paleozoic formations; exposed thickness up to 7-8 m. Mostly debris-flow deposits reworked by the Colorado River

gvY

Younger gravel deposits (late Pleistocene)--Weakly consolidated, cobble to small boulder-size gravel with coarse-sand matrix. Present only on south side of Little Nankoweap Creek. Deposit consists of subrounded to rounded boulders of local Paleozoic formations and widely scattered pebbles and small cobbles of very well rounded, far-travelled porphyritic rocks of Colorado River origin. Thickness about 8 m

gvo

Older gravel deposits (Pleistocene)--Weakly to moderately consolidated, subrounded to rounded, cobble to medium boulder-size gravel with coarse-sand matrix. Underlies west-half of high ridge on south side of Nankoweap Creek and low ridge on north side of creek. Deposit consists of boulders derived from local Proterozoic and Paleozoic formations eroded from Nankoweap Creek drainage basin; thickness greater than 35 m. Boulders of Proterozoic formations and Redwall Limestone comprise 22 and 63 percent of deposit, respectively; Kaibab Formation absent. Primarily stream-flow gravel with interbedded debris-flow gravel. Contact with underlying bedrock dips steeply toward river

TRIBUTARY STREAM DEPOSITS

Alluvial fans

afy

Younger alluvial-fan deposits (after A.D. 1400 to present-day)--

Pebble to cobble-size gravel grading downslope to poorly sorted fine to medium-grained sand which is characteristic of deposit; clasts blocky and angular; derived from reworking of talus (tl) and striped(?) alluvium (sa). Forms fan-shaped deposits on surface of upper mesquite terrace (umt); probably interfingers with alluvium of upper mesquite terrace in subsurface. Present on south side of high ridge south of Nankoweap Creek and at foot of talus-covered slope south of ridge

afo

Older alluvial-fan deposits (after A.D. 700 to present-day?)--

Poorly sorted fine- to medium-grained sand with minor pebble to small-cobble size gravel, derived from erosion of older gravel deposits (gvo) and breccia (bc). Probably younger than to contemporaneous with older eolian deposits (eo). Present at north side of high ridge south of Nankoweap Creek

COLLUVIUM

DEBRIS FLOWS

**Fan forming debris-flow deposits of large streams draining
from the rim of Marble Canyon and Walhalla Plateau**

dfy

Younger debris-flow deposits, undivided (after A.D. 1200 to early A.D. 1920s)--Small cobble to small boulder-size gravel with scattered boulders up to 1-2 m on an edge consisting of Paleozoic limestone and sandstone; breccia-like texture with mostly angular boulders; clast-supported fabric; matrix is clay, silt, and sand. Present on east side of Marble Canyon below cliff. Includes rock-fall deposits

dfyc

Unit c of younger debris-flow deposits (early A.D. 1920s)--Cobble to boulder-size gravel with scattered boulders larger than 1-2 m on an edge consisting mainly of Paleozoic limestone and sandstone. Pebble to cobble-size clasts are subangular to subrounded; granule to small pebble-size clasts are subangular. Includes interbedded streamflow gravel. Surface clasts have negligible rock varnish and limestone boulders are not pitted. Debris-flow was deposited on upper mesquite terrace (umt) and is overlain by younger sand dune (ey) that was reworked from alluvium of lower mesquite terrace (lmt); toe of debris flow on north side of Little Nankoweap Creek is truncated at level of lower mesquite terrace. Unit c is probably equivalent to uppermost lower mesquite terrace. Driftwood on surface of unit yields essentially modern radiocarbon date (nos. 1-2, Table 1). Present only in Little Nankoweap Creek where thickness is about 1-2 m

dfyb

Unit b of younger debris-flow deposits (after A.D. 1884 to before early A.D. 1900s)--Cobble to small boulder-size gravel with scattered boulders larger than 1 m on an edge consisting mainly of subangular to rounded boulders of Paleozoic limestone and sandstone and Proterozoic sandstone; clast-supported fabric. Includes interbedded streamflow gravel. Surface clasts lightly varnished; mean varnish darkness (Bull, 1991, p. 63-64; value + chroma / 2) is 4.6. Weathering pits in limestone boulders poorly developed; average depth 1.3 mm. Deposits of unit dfyb locally surround and partly bury large, older boulders having rock varnish and limestone boulders with well-developed weathering pits. Present only in Nankoweap Creek where exposed thickness is about 2 m. Unit dfyb post-dates upper mesquite terrace (umt); alluvium of lower mesquite terrace (lmt) deposited on lobes of unit b; probably equivalent to lower part of lower mesquite terrace (lmt)

dfya

Unit a of younger debris-flow deposits (after A.D. 1200 and before A.D. 1884)--Cobble to medium boulder-size gravel with scattered boulders larger than 1 m on an edge consisting mainly of angular clasts of Paleozoic limestone and sandstone; clast-supported fabric; matrix is coarse silt to very fine sand. Deposit composed of 33 per-

cent Redwall Limestone, 33 percent Supai Group sandstone, 18 percent Coconino Sandstone, and 8 percent Kaibab Formation. Weathering pits on surface of limestone boulders average 1.7 mm deep and mean varnish darkness is about 4. Beneath the surface, undersides of limestone boulders have thin, barely visible, very light gray (N8) to white (N9) coatings of calcium carbonate. Unit a has distinctive brecciated texture resulting from deposition by debris flow after free-fall of 330 m (1,000 ft) over nearby cliff of Redwall and Muav Limestones. Unit post-dates alluvium of Pueblo-II age and pre-dates lower mesquite terrace (lmt); probably equivalent to basal to middle part of upper mesquite terrace (umt)

dfi

Intermediate debris-flow deposits, undivided (A.D. 400 to around A.D. 1075)--Small cobble to large boulder-size gravel with scattered boulders up to 1-2 m on an edge consisting of Paleozoic limestone and sandstone; breccia-like deposit with angular to subangular clasts; clast-supported fabric; matrix is clay, silt, and sand. Present on east side of Marble Canyon below cliff. Includes rockfall deposits

dfic

Unit c of intermediate debris-flow deposits (around A.D. 1075)--Cobble to medium boulder-size gravel with scattered boulders larger than 1 m on an edge; consists mainly of subangular to subrounded clasts of Paleozoic limestone and sandstone eroded from Little Nankoweap Creek drainage basin; clast-supported fabric; matrix is coarse silt to sand. Redwall Limestone and Supai Group Sandstones comprise 33 and 37 percent of boulders, respectively; Kaibab Formation and Coconino Sandstone each comprise 8 percent of clasts. Includes interbedded streamflow gravel. On surface of unit, boulders have well-developed rock varnish; mean varnish darkness 3.7. Limestone boulders have weathering pits that average 2.4 mm deep. Limestone masonry in a Pueblo-II archeologic structure has similar average pit depth (Hereford and others, 1995; 1996), suggesting that unit c debris flow occurred in Pueblo-II time, with median date of A.D. 1075. Exposed thickness about 1 m along Little Nankoweap Creek

dfib

Unit b of intermediate debris-flow deposits (around A.D. 800)--Cobble to medium boulder-size gravel with scattered boulders larger than 1 m on an edge; consists mainly of Paleozoic limestone and sandstone in Nankoweap and Little Nankoweap Creeks with Proterozoic clasts in Nankoweap Creek; clast-supported fabric; matrix is coarse silt to sand. Clasts are angular to subangular in Little Nankoweap Creek and subangular, subrounded, and rounded in Nankoweap Creek. Deposit in Nankoweap Creek composed of 48 percent Redwall Limestone, 17 percent Supai Group sandstone, and 5 percent Coconino Sandstone; Kaibab Formation present in trace amounts only; 11 percent of clasts are Proterozoic sandstone. Includes interbedded streamflow gravel. Unit b deposits are overlain by upper part of alluvium of Pueblo-II age. Mean varnish darkness of surface boulders is 3.5 and pit depths on limestone boulders average 3.3-3.6 mm. Beneath the surface, undersides of clasts typically have Stage-I carbonate morphology of thin, discontinuous, very light gray (N8) to white (N9) coatings of calcium carbonate. A

debris flow dated at A.D. 660 in the Palisades Creek area 22-km downstream (Hereford and others, 1995; 1996) has limestone boulders with average pit depth of 4 mm, which suggests unit c is somewhat younger than A.D. 660. Thickness about 1-2 m at exposures along Little Nankoweap and Nankoweap Creeks

dfia

Unit a of intermediate debris-flow deposits (around A.D. 400)--

Cobble to medium boulder-size gravel with scattered boulders larger than 1 m on an edge; consists mainly of subangular, subrounded and rounded clasts of Paleozoic limestone and sandstone and Proterozoic sandstone; clast-supported fabric; matrix is coarse silt to sand. Includes interbedded streamflow gravel. Mean varnish darkness of surface boulders is 2.9 and pit depths on limestone boulders average 4.7 mm. Beneath the surface, undersides of clasts typically have Stage-I carbonate morphology of thin, discontinuous, very light gray (N8) to white (N9) coatings of calcium carbonate. Deposit present on south side of Nankoweap Creek where it is partly covered with older eolian sand (eo) derived from reworking of striped alluvium (sa) and alluvium of Pueblo-II age (ap)

dfo

Older debris-flow deposits (around 200 B.C.) --

Cobble to medium boulder-size gravel with scattered boulders larger than 1-2 m on an edge; consists mainly of angular to subangular clasts of Paleozoic limestone and sandstone; clast-supported fabric; matrix is coarse silt to sand. Deposit is brecciated resulting from deposition by debris flow after free-fall of 330 m (1000 ft) over nearby cliff of Redwall Limestone. Boulders on the surface of the older debris-flow deposits have well-developed rock varnish; mean varnish darkness 2.3. Limestone boulders have weathering pits that average 5.6 mm deep. Beneath the surface, clasts typically have weak Stage-II carbonate morphology of conspicuous thin, continuous, very light gray (N8) to white (N9) coatings of calcium carbonate. Present only on the north side of unnamed drainage at south end of map where exposed thickness is about 4 m. Part of the striped(?) alluvium (sa) was deposited against the older debris-flow deposits

Debris-flow deposits in entrenched channels of large streams draining from the rim of Marble Canyon and Walhalla Plateau

dcy

Younger channelized debris-flow deposits (present-day)--

Pebble to medium boulder-size gravel with scattered boulders up to 1 m on an edge that are unweathered and fresh appearing. Boulders are angular to subangular in Little Nankoweap Creek; mostly angular in unnamed drainage at south end of map and in east-side tributaries; subangular, subrounded, and rounded in Nankoweap Creek. In Nankoweap Creek, unit contains numerous Proterozoic sandstone clasts; Kaibab Formation present in trace amounts only. Mainly debris-flow and local streamflow deposits

dco

Older channelized debris-flow deposits (after A.D. 1957-1958 to

A.D. 1966)--Pebble to medium boulder-size gravel with scattered boulders up to 1 m on an edge composed of Paleozoic limestone and sandstone in Nankoweap and Little Nankoweap Creeks with

Proterozoic clasts present in Nankoweap Creek. Surface of unit is lightly vegetated with small cactus. In Nankoweap Creek, deposits probably accumulated during floods in December 1966 described by Cooley and others (1977, p. 25-28). Toe of unit appears to be truncated by the June 1983 flood sand (fs, part). In Little Nankoweap Creek, deposits post-date pre-dam alluvium (pda)

Debris-flow deposits of small tributary streams

da

Active small tributary debris-flow deposits (present-day)--Pebble to small-boulder size, angular to subangular gravel derived from reworking of nearby talus-covered hillslopes and Cambrian bedrock. Larger clasts are mainly Redwall Limestone. Surface of deposit is fresh appearing and unweathered. Probably interbedded locally with streamflow deposits

dy

Younger small-tributary debris-flow deposits (A.D. 700 to A.D. 1200)--Pebble to small boulder-size angular to subangular gravel with scattered boulders up to 1 m on an edge. Gravel derived from reworking of nearby talus-covered hillslopes and Cambrian bedrock. Larger clasts are mainly Redwall Limestone. Deposit typically has well-formed levees rising 0.5 to 1.5 m above channel. In southern part of mapped area on west side of river near radiocarbon sample locality 8 (no. 8, Table 1), deposit overlies and is interbedded with upper part of alluvium of Pueblo-II age. Surface has weathered limestone boulders with average pit depth of 2.8 mm, which is consistent for Pueblo-II age surfaces

do

Older small-tributary debris-flow deposits (before A.D. 300 to A.D. 600-700)--Pebble to small boulder-size angular to subangular gravel with scattered boulders up to 1 m on an edge. Gravel derived from reworking of nearby talus-covered hillslopes and Cambrian bedrock. Deposit typically has well-formed levees rising 0.5 to 1 m above channel. Surface limestone boulders are weathered with average pit depth of 3.8 to 4.1 mm, suggesting deposition around A.D. 600-700. Overlies and may interfinger with upper part of striped(?) alluvium (sa)

TALUS

ty

Talus deposits (present-day)--Pebble to very large boulder-size gravel consisting of angular, blocky boulders of Redwall Limestone; numerous blocks up to 5 m on an edge. Forms conspicuous light gray deposit on east side of river 0.6 km downstream of Nankoweap Creek. Recently active rockfall deposit

tr

Small-block red talus deposits (late Pleistocene? to early Holocene)--Small to medium boulder-size gravel consisting mainly of angular boulders of light-red Supai Group sandstone and minor Coconino Sandstone; scattered boulders up to 2-3 m on an edge; moderately to well consolidated; forms conspicuous, reddish talus cone at base of Redwall Limestone on east side of Marble Canyon

ts

Small-block talus deposits (late Pleistocene)--Small to large boulder-size gravel consisting of dark-gray, blocky boulders of Redwall Limestone as much as 2-5 m on an edge; moderately to well consolidated. On high ridge south of Nankoweap Creek, deposit is mainly slumps and small rock slides of coarse-grained breccia (bc) and older gravel (gvo)

tl

Large-block talus deposits (late Pleistocene)--Small to very large boulder-size gravel consisting of dark-gray, angular, blocky boulders of Redwall Limestone as much as 5-10 m on an edge; moderately to well consolidated. Cross-cuts older gravel deposits (gvo) on south side of high ridge south of Nankoweap Creek

to

Older talus deposits (Pleistocene)--Pebble to small boulder-size gravel consisting of angular, blocky boulders of Muav and Redwall Limestone; moderately to well consolidated. Overlies and may interfinger with older gravel deposits (gvo)

BRECCIA

bc

Coarse-grained breccia facies (late Pleistocene)--Small to very large boulder-size gravel consisting of angular, blocky boulders of Paleozoic limestone and sandstone; numerous boulders up to 2-7 m on an edge; poorly to moderately consolidated. Deposit composed of 88 percent Kaibab Formation, 8 percent Redwall Limestone, and 4 percent Coconino Sandstone; Supai Group sandstone present locally. Deposit cross-cuts and overlaps older gravel deposits (gvo); maximum thickness about 50 m; present on east-half of high ridge on south side of Nankoweap Creek. Coarse-grained breccia facies corresponds with rockfall deposit of Hereford (1978; 1984). Thin gravel on surface of deposit (stippled pattern) consists of widely scattered pebbles of very well-rounded quartzite, granite, and porphyry of Colorado River origin and subrounded cobbles of Proterozoic sandstone and Tapeats Sandstone derived from Nankoweap Creek; medium-size boulder of Tapeats Sandstone present at 875 m elevation on southeast portion of high ridge. Surface gravel corresponds with terrace level 3 and 4 of Machette and Rosholt (1991).

bf

Fine-grained breccia facies (late Pleistocene)--Pebble to small boulder-size gravel consisting of angular boulders of Paleozoic limestone and sandstone; edges of gravel-size boulders are angular with no evidence of rounding; fabric varies from clast-supported to weakly matrix-supported. Matrix is moderate orange pink (10R7/4) silt to medium sand; sand grains are angular and have low sphericity; grain surfaces are bright and appear fractured. Pebbles and small cobbles of very well rounded quartzite and porphyry similar to those carried by Colorado River are widely scattered throughout deposit. Deposit is massive without stratification or other discontinuities. Well exposed on ridge on north side of Nankoweap Creek at western boundary of mapped area; 20 to 25 m thick. At this locality, deposit unconformably overlies the older gravel deposits (gvo), which rest on Bright Angel Shale. Soil on fine-grained breccia facies has well developed Stage-III carbonate morphology and

truncated B horizon. Deposit is older than $210,000 \pm 25,000$ years based on Uranium-trend date of soil carbonate (Machette and Rosholt, 1991). On south side of Nankoweap Creek at western boundary of mapped area and immediately west of mapped area, deposit consists of two subunits. Basal subunit is pebble to cobble-size gravel with scattered small boulders composed of angular boulders of Redwall Limestone, Supai Group sandstone, and Coconino Sandstone with matrix-supported fabric; matrix is light red and imparts distinctive color to hillslope; 10-12 m thick. Upper subunit is light colored silty sand; well stratified in thin horizontal beds; contains sheetwash component of pebble-size Cambrian carbonate clasts and small, rotated slide blocks derived from nearby hillslope, 5-7 m thick

EOLIAN

SAND DUNES

Coppice sand dune deposits

ea

Coppice sand dunes (present-day)--Very fine grained, moderately well sorted sand; silt and clay content less than 6 percent; typically associated with mesquite shrubs. Forms lightly vegetated, active dune fields and isolated mounds or dune-like features having 1-2 m relief. Derived from reworking of lower mesquite terrace (lmt) and younger alluvial deposits

ey

Younger coppice sand dunes (after A.D. 1400 to A.D. 1920s)--Very fine grained, moderately well sorted sand; silt and clay content less than 6 percent; typically associated with mesquite shrubs and small trees. Forms lightly to moderately vegetated, locally inactive dune fields and dune-like features having 1-4 m relief. Derived mainly from reworking of alluvium of the upper and lower mesquite terraces (umt and lmt, respectively)

eo







Older sand dunes (after A.D. 300 to around A.D. 1200)--Very fine grained, moderately well sorted sand; silt and clay content less than 6 percent; typically associated with mesquite trees. Forms lightly to moderately vegetated, mostly inactive dune fields and sand sheets having less than 2 m relief. Derived mainly from reworking the striped(?) alluvium (sa) and alluvium of Pueblo-II age (ap)

BEDROCK

-Cba

Bright Angel Shale (Cambrian)--Greenish shale with interbedded gray platy siltstone, dark-magenta to pale-greenish or buff very-fine grained sandstone, and rusty-brown dolomite (Middleton and Elliot, 1990)

EXPLANATION

	Contact
	Outline of driftwood at level of upper mesquite terrace
	Lag deposit of Colorado River and Nankoweap Creek gravels
	Erosional scarp
	Foot trail
	Radiocarbon sample locality at point of arrow. Number refers to table 1

DISCUSSION OF QUATERNARY GEOLOGY AND GEOMORPHOLOGY

Introduction

The Nankoweap Rapids area along the Colorado River is near River Mile 52 (that is 52 miles 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, personal 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 gullyng 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

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 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 the mapped 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 age of the debris-flow deposits was calculated from the average depth of solution pits in limestone boulders on the fan surfaces using the methods and the approximately 2 mm per 1,000 years average rate of pit deepening reported by Hereford and others (1995; 1996).

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 m² segments until

Table1. Radiocarbon 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
No	Field ⁽¹⁾ number	Lab. number ⁽²⁾	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	ibid.	ibid.	Driftwood, bark	modern	modern	ibid.
3	LNRC 2-1	3569	36 18 30	111 52 00	Wood	235±35 ⁽⁶⁾	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	ibid.	ibid.	Wood	modern	modern	ibid.
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	ibid	ibid	Charcoal	240±30	A.D. 1520-1560 A.D. 1630-1680 A.D. 1740-1800	ibid.
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 30cm below top
10	NCRC 5	3570	36 18 18	111 51 49	Charcoal	modern ⁽⁹⁾	modern	Roaster associated with PII remains

⁽¹⁾ LN = Little Nankoweap Creek; NC = Nankoweap Creek⁽²⁾ U.S. Geological Survey Radiocarbon Laboratory, Menlo Park, California⁽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 ¹⁴C activity of dendrochronologically dated wood (Klein and others, 1982). Multiple dates are possible because of atmospheric ¹⁴C fluctuations⁽⁶⁾ Stratigraphically and analytically same as modern⁽⁷⁾ Burnt roots of mesquite; rooted in but slightly younger than terrace⁽⁸⁾ Date too young, charcoal from burnt mesquite root disturbed by burrowing⁽⁹⁾ Modern, probably from historic-age campfire

100 clasts were identified. The results indicate the relative proportion of bedrock units in the various deposits.

Geologic setting

Bedrock at river level is the Bright Angel Shale, 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 western, 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 sediment in the Quaternary deposits along the river, although trace amounts of far-travelled very 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 present-day.

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 eastern 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 the mapped area, west-side tributaries are Little Nankoweap Creek, Nankoweap Creek, and a relatively small, unnamed tributary near the southern boundary of the map 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. 1). 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. 1).

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

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:

Table 2. Drainage-basin characteristics and rounding of debris-fans clasts

Drainage basin	Area km ² mi ²	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



Figure 1. Mouth of Nankoweap Creek and reentrant of east wall of Marble Canyon, view east-south-east. 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).



Figure 2. Intermediate-age debris-flow deposits (dfib) on south side of Nankoweap Creek at 870 m contour, scale 15 cm long. 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.

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 rounding of debris-flow deposits

The debris-flow deposits are weakly stratified, poorly sorted mixtures of clay, silt, sand, and gravel (fig. 2). The fabric of the deposits ranges from clast to matrix supported, although

clast supported is typical. 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 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 rounding of deposits in Little Nankoweap Creek reflects the short transport

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

Debris-flow deposits of Nankoweap Creek (fig. 2) differ substantially in composition and 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. 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 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

The ages of fan-forming debris-flow deposits range from around 200 B.C. to as late as A.D. 1920. We differentiated the fan-forming deposits by topographic position and by degree of surface weathering, which is illustrated in figures 3-5. On any particular fan, the oldest surfaces have the highest elevation and are most intensely weathered. 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.

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 southern boundary of the map. 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. 3-4). 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, 3.3-3.6, 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 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 discon-



Figure 3. Surface weathering of debris-flow unit dfia on south side of Nankoweap Creek, scale 15 cm long. 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.



Figure 4. Surface weathering of debris-flow unit dfib on south side of Nankoweap Creek, scale 15 cm long. 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 3 and 5, which show more intense and very little weathering, respectively.



Figure 5. Surface of debris-flow unit dfyb on north side of Nankoweap Creek, scale 15 cm long. 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.

tinuous 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. 5).

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 southern 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 up to 3-4 m deep (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 $2,700 \text{ m}^3/\text{s}$ ($96,000 \text{ ft}^3/\text{s}$). 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-, 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 $14,100 \text{ m}^3/\text{s}$ ($500,000 \text{ ft}^3/\text{s}$) in A.D. 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 $6,200 \text{ m}^3/\text{s}$ ($220,000 \text{ ft}^3/\text{s}$) to $8,500 \text{ m}^3/\text{s}$ ($300,000 \text{ ft}^3/\text{s}$). These were the largest known floods between July 1884 and June 1921.

The pre-dam alluvium (pda) was deposited by spring floods after A.D. 1921. The largest of these was $3,600 \text{ m}^3/\text{s}$ ($127,000 \text{ ft}^3/\text{s}$) 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 $3,540 \text{ m}^3/\text{s}$ ($125,000 \text{ ft}^3/\text{s}$) and $3,050 \text{ m}^3/\text{s}$ ($107,700 \text{ ft}^3/\text{s}$), 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 $8,500\text{--}14,100 \text{ m}^3/\text{s}$ ($300,000\text{--}500,000 \text{ ft}^3/\text{s}$), 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 m³/s (96,000 ft³/s) and sustained flows were above 1,400 m³/s (50,000 ft³/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 m³/s (32,000 to 50,000 ft³/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 m³/s (1,400 ft³/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 m³/s (20,000 ft³/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 m³/s (45,000 ft³/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.

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. 6). 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



Figure 6. 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.

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 (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 rock-fall 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.

Composition and texture

Rock fragments in the coarse-grained breccia facies (bc) are mostly coherent blocks of Kaibab Formation. The Kaibab comprises 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 (43percent) 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 likely 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 three is relatively shallow compared with the

soil horizon of the breccia. The shallow soil dated at $40,000 \pm 24,000$ 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 western 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. 7). 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. 2, 5). Likewise, the older gravel (gvo) has abundant subrounded to rounded boulders (fig. 8). 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 the 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 the breccia

The massive, unstratified character of the breccia (fig. 9) 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 the slope are nearly vertical (fig. 1), 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 (bf) 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. 10) of the deposit is 0.46 km^2 (114 acres) and the volume, assuming an initial average thickness of 50 m (160 ft), is 23.2 hm^3 (18,240 acre-ft).



Figure 7. Fine-grained breccia facies (bf) on ridge on north side of Nankoweap Creek, scale 10-cm long. Angular boulders and cobbles are typical. Note very well rounded quartzite cobble in right-center.



Figure 8. Older gravel (gvo) on ridge on north side of Nankoweap Creek immediately west of mapped area, scale 140 cm long with 20 cm divisions. Subrounded to rounded cobbles and boulders are abundant.



Figure 9. 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 6, which shows surface of coarse-grained breccia (bc).

Late Pleistocene geomorphic development 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 10. 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. 1). 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 non-resistant sandstones and siltstones typically form a distinctive slope.

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 likely at about the same elevation as the rest of the breccia, as rock

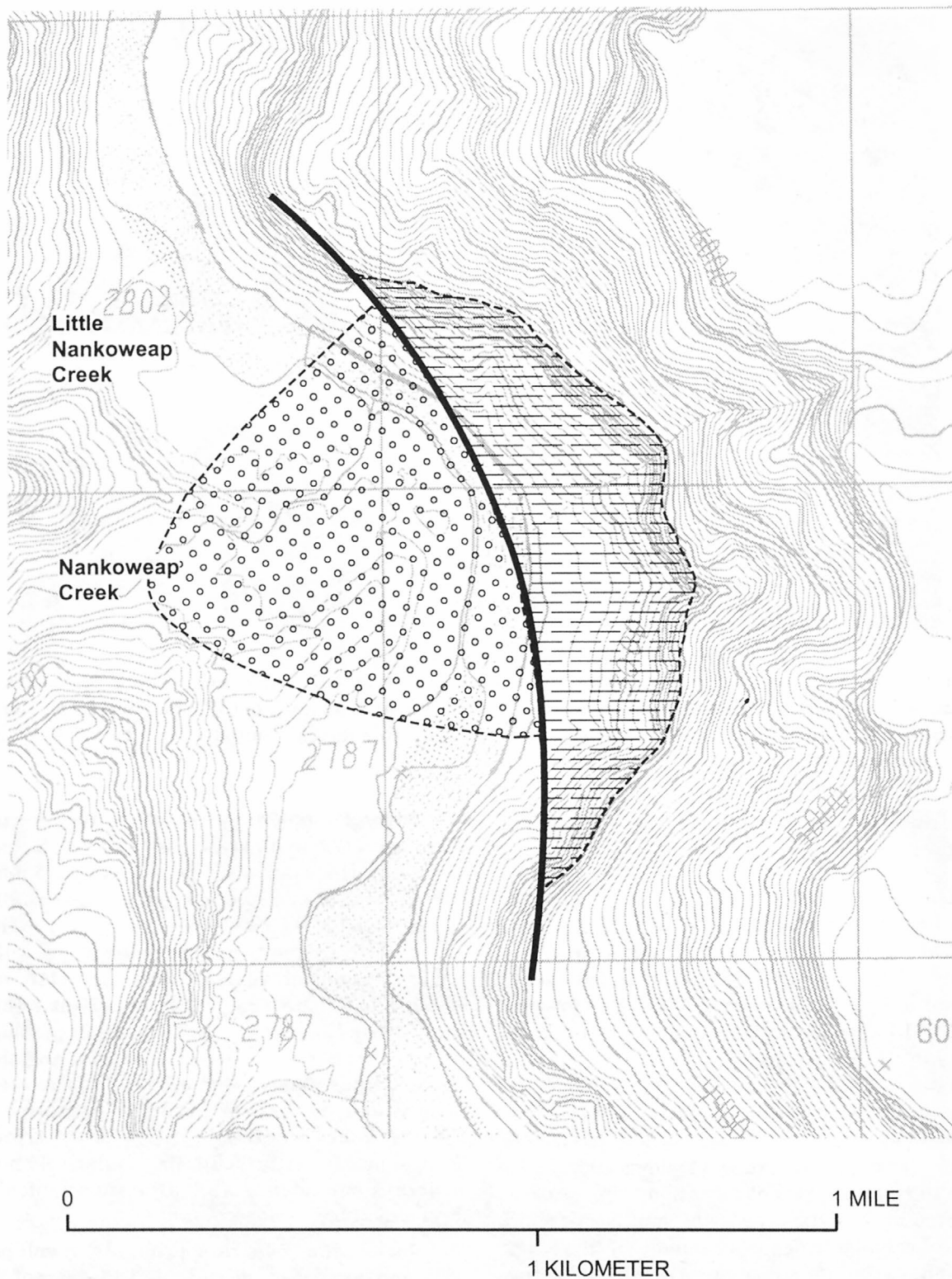


Figure 10. Topographic map (contour interval 40 ft or 12 m) showing reconstruction of Marble Canyon and distribution of rockfall that produced units bc and bf. Solid line is top of Redwall Limestone at time of rockfall; stippled pattern is rockfall breccia; dashed lines show retreat of Redwall Limestone cliff during and after rockfall. Topography from Nankoweap Mesa 7.5 ' quadrangle (1988).

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 Marble Canyon. 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 unnamed 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 (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; Hereford and others, 1996).

The intermediate and younger categories were further divided into three age categories each (dfia-c and dfya-c), totaling seven mappable surfaces among the three west-side tributaries. These surfaces range in age from about 200 B.C. to A.D. 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 comprise the west-side debris fans, except the unnamed tributary fan which has two main surfaces. Aggradation of the fans was probably from only 2-3 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 (sa, ap, umt, and lmt) that pre-date Glen Canyon Dam and four channel-side bar deposits (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 A.D. 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 A.D. 1884-1921. Even larger floods deposited the alluvium of the upper mesquite terrace (umt) between about A.D. 1400-1884. One of these floods, perhaps in A.D. 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. This occurs 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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References

- Andrews E.D., 1991, Sediment transport in the Colorado River basin, *in*, Colorado River ecology and dam management: Washington D.C., National Academy Press, p. 54-74.
- Bull, W.B., 1991, Geomorphic response to climatic change: New York, Oxford University Press, 326 p.
- Carothers, S.W., and Brown, B.T., 1991, The Colorado River through Grand Canyon: Natural history and human change: Tucson, University of Arizona Press, 235 p.
- Cooley, M.E., Aldridge, B.N., and Euler, R.C., 1977, Effects of the catastrophic flood of December 1966, North Rim area, eastern Grand Canyon, Arizona: U.S. Geological Survey Professional Paper 980, 43 p.
- Elston, D.P., 1989, Pre-Pleistocene (?) deposits of aggradation, Lees Ferry to western Grand Canyon, *in*, Elston, D.P., Billingsley, G.H., and Young, R.A., eds., Geology of Grand Canyon, northern Arizona (with Colorado River guides): Washington, D.C., American Geophysical Union, p. 175-185.
- Fairley, H.C., Bungart, P.W., Coder, C.M., Huffman, Jerry, Samples, T.T., and Balsom, J.R., 1994, The Grand Canyon river corridor survey project: Archaeological survey along the Colorado River between Glen Canyon Dam and Separation Canyon: Grand Canyon, Arizona, National Park Service, Coopera-

- tive Agreement No. 9AA-40-07920, 276 p.
- Ford, T.D., 1990, Grand Canyon Supergroup: Nankoweap Formation, Chuar Group, and Sixtymile Formation, *in*, Beus, S.S., and Morales, Michael, *eds.*, Grand Canyon Geology: New York, Oxford University Press, p. 49-70.
- Goddard, E.M., Overbeck, R.M., Rove, O.N., Singewald, J.T., Jr., and Trask, P.D., 1948, Rock-color chart: Washington, D.C., National Research Council, 6 p.
- Hereford, Richard, 1978, An ancient rockfall at Nankoweap Rapids, Marble Canyon, Grand Canyon National Park, Arizona (abs.): Geological Society of America Abstracts with Programs, v. 10, p. 109.
- _____, 1984, Driftwood in Stanton's Cave: The case for temporary damming of the Colorado River at Nankoweap Creek in Marble Canyon Grand Canyon National Park, Arizona, *in*, Euler, R.C., *ed.*, The archaeology, geology, and paleobiology of Stanton's Cave, Grand Canyon National Park, Arizona: Grand Canyon Natural History Association Monograph 6, p. 99-106.
- _____, 1993, Map showing surficial geology and geomorphology of the Palisades Creek archeologic area, Grand Canyon National Park, Arizona: U.S. Geological Survey Open-File Report 93-553, scale 1:2,000, 1 plate, 21 p.
- _____, 1996, Map showing surficial geology and geomorphology of the Palisades Creek area, Grand Canyon National Park, Arizona: U.S. Geological Survey Miscellaneous Investigations Map I-2499, scale 1:2,000, 26 p.
- Hereford, Richard, Fairley, H.C., Thompson, K.S., and Balsom, J.R., 1993, Surficial geology, geomorphology, and erosion of archeologic sites along the Colorado River, eastern Grand Canyon, Grand Canyon National Park, Arizona: U.S. Geological Survey Open-File Report 93-517, 4 plates, 46 p.
- Hereford, Richard, and Thompson, K.S., 1994, Topographic map of the Nankoweap Rapids area, Marble Canyon, Arizona: U.S. Geological Survey Open-File Report 94-564, scale 1:2,000.
- Hereford, Richard, Thompson, K. S., Burke, K. J., and Fairley, H. C., 1995, Late Holocene debris fans and alluvial chronology of the Colorado River, eastern Grand Canyon, Arizona: U.S. Geological Survey Open-File Report 95-57, 28 p.
- _____, 1996, Tributary debris fans and the late Holocene alluvial chronology of the Colorado River, eastern Grand Canyon, Arizona: Geological Society of America Bulletin, v. 108, p. 3-19.
- Howard, Alan, and Dolan, Robert, 1981, Geomorphology of the Colorado River in Grand Canyon: Journal of Geology, v. 89, p. 259-298.
- Huntoon, P.W., Billingsley, G.H. Jr., Breed, W.J., Sears, J.W., Ford, T.D., Clark, M.D., Babcock, R.S., and Brown, E.H., 1986, Geological map of the eastern part of Grand Canyon National Park, Arizona: Grand Canyon, Arizona, Grand Canyon Natural History Association, scale 1:62,500.
- Hyatt, M.L., 1990, Historic streamflows, water releases, and reservoir storage for Glen Canyon Dam and Lake Powell: Denver, Colorado, U.S. Department of Interior, Bureau of Reclamation, Water Management Section.
- Klein, Jeffry, Lerman, J.C., Damon, P.E., and Ralph, E.K., 1982, Calibration of radiocarbon dates: Radiocarbon, v. 24, p. 103-150.
- Machette, M.N., and Rosholt, J.N., 1989, Quaternary terraces in Marble Canyon and eastern Grand Canyon, *in*, Elston, G.H., Billingsley, G.H., and Young, R.A., *eds.*, Geology of Grand Canyon, northern Arizona (with Colorado River guides): Washington, D.C., American Geophysical Union, p. 205-211.
- _____, 1991, Quaternary geology of the Grand Canyon, *in*, Morrison, R.B., *ed.*, The geology of North America, vol. K-2, Quaternary non-glacial geology of the conterminous United States: Geological Society America, p. 397-401.
- Melis, T.S., and Webb, R.H., 1993, Debris flows in Grand Canyon National Park, Arizona: Magnitude, frequency, and effects on the Colorado River, *in*, Shen, H.W., Su, S.T., and Wen, Feng, *eds.*, Hydraulic engineering '93, Proceedings of the 1993 conference: Hydraulics Division, American Society of Civil Engineers, v. 2, p. 1290-1295.
- Middleton, L.T., and Elliot, D.K., 1990, Tonto



3 1818 00255307 9

- Group, *in*, Beus, S.S., and Morales, Michael, eds., Grand Canyon Geology: New York, Oxford University Press, p. 83-106.
- Péwé, T.L., 1968, Colorado River guidebook: Private Publication, 78 p.
- Potochnik, A.R., and Reynolds, S.J., 1990, Side canyons of the Colorado River, Grand Canyon, *in*, Beus, S.S., and Morales, Michael, eds., Grand Canyon geology: New York, Oxford University Press, p. 461-481.
- Schmidt, J.C., 1990, Recirculating flow and sedimentation in the Colorado River in Grand Canyon, Arizona: *Journal of Geology*, v. 98, p. 709-724.
- Schmidt, J.C., and Graf, J.B., 1990, Aggradation and degradation of alluvial sand deposits, 1965 to 1986, Colorado River, Grand Canyon National Park, Arizona: U.S. Geological Survey Professional Paper 1493, 74 p.
- U.S. Bureau of Reclamation, 1990, Colorado River basin probable maximum floods Hoover and Glen Canyon Dams: Denver, Colorado, U.S. Department of Interior, Bureau of Reclamation, 104 p.
- Webb, R.H., Pringle, P.T., Reneau, S.L., and Rink, G.R., 1988, Monument Creek debris flow, 1984: Implications for formation of rapids on the Colorado River in Grand Canyon National Park: *Geology*, v. 15, p. 50-54.
- Webb, R.H., Pringle, P.T., and Rink, G.R., 1989, Debris flows from tributaries of the Colorado River, Grand Canyon National Park, Arizona: U.S. Geological Survey Professional Paper 1492, 39 p.
- Yarnold, J.C., and Lombard, J.P., 1989, A facies model for large rock-avalanche deposits formed in dry climates, *in*, Colburn, I.P., Abbott, P.L., and Minch, John, eds., Conglomerates in basin analysis: A symposium dedicated to A.O. Woodford: Pacific Section, Society of Economic Paleontologists and Mineralogists, v. 62, p. 9-31.