Geochemical Discrimination of Five Pleistocene Lava-Dam Outburst-Flood Deposits, Western Grand Canyon, Arizona

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ABSTRACT

Pleistocene basaltic lava dams and outburst-flood deposits in the western Grand Canyon, Arizona, have been correlated by means of cosmogenic ^3He (^3He_c) ages and concentrations of SiO_2, Na_2O, K_2O, and rare earth elements. These data indicate that basalt clasts and vitroclasts in a given outburst-flood deposit came from a common source, a lava dam. With these data, it is possible to distinguish individual dam-flood events and improve our understanding of the interrelations of volcanism and river processes. At least five lava dams on the Colorado River failed catastrophically between 100 and 525 ka; subsequent outburst floods emplaced basalt-rich deposits preserved on benches as high as 200 m above the current river and up to 53 km downstream of dam sites. Chemical data also distinguishes individual lava flows that were collectively mapped in the past as large long-lasting dam complexes. These chemical data, in combination with age constraints, increase our ability to correlate lava dams and outburst-flood deposits and increase our understanding of the longevity of lava dams. Bases of correlated lava dams and flood deposits approximate the elevation of the ancestral river during each flood event. Water surface profiles are reconstructed and can be used in future hydraulic models to estimate the magnitude of these large-scale floods.

Online enhancements: appendix tables.

Introduction

The Uinkaret volcanic field in the western Grand Canyon region of northwestern Arizona (fig. 1) erupted many times in the Tertiary and particularly in the late Quaternary. Billingsley and Hamblin (2001) mapped the distribution of basalt flows in this field but recognized only select Quaternary flows. Hamblin (1994) mapped at least 13 lava dams between river miles (RM) 179 and 189 on the Colorado River in western Grand Canyon, with K-Ar ages that ranged from 100 ka to 1.8 Ma (McKee et al. 1968; Dalrymple and Hamblin 1998); however, nine of these ages are between 430 and 600 ka (Dalrymple and Hamblin 1998), and all of the measured dam remnants exhibit normal paleomagnetic polarity (Hamblin 1994). New ^3He_c (table 1; Fenton et al. 2001) and $^{39}Ar/^{40}Ar$ ages (Lucchitta et al. 2000; McIntosh et al. 2002) show that volcanism and lava damming in this region occurred between 1 and 630 ka, rather than between 10 ka and 1.8 Ma as previously reported (Damon et al. 1967; Hamblin 1994). In the Uinkaret volcanic field, cosmogenic ^3He dating provides an alternative to K-Ar dating and, in certain cases, $^{39}Ar/^{40}Ar$ dating, particularly for relatively young basalts that have documented problems with excess Ar resulting from abundant glassy groundmass and magmatic fluid inclusions in phenocrysts (Damon et al. 1967; Dalrymple and Hamblin 1998; Fenton et al. 2001).

Dams were formed by lava flows that mostly erupted from the North Rim of Grand Canyon, although at least one lava dam was produced by flows from the south (fig. 1). Lava cascaded over the rim either through sheet flow or within existing tributary canyons created by the tectonically active Toroweap and Hurricane faults (fig. 1; Jackson 1990; Fenton et al. 2001) near RM 179 and 188, respec-

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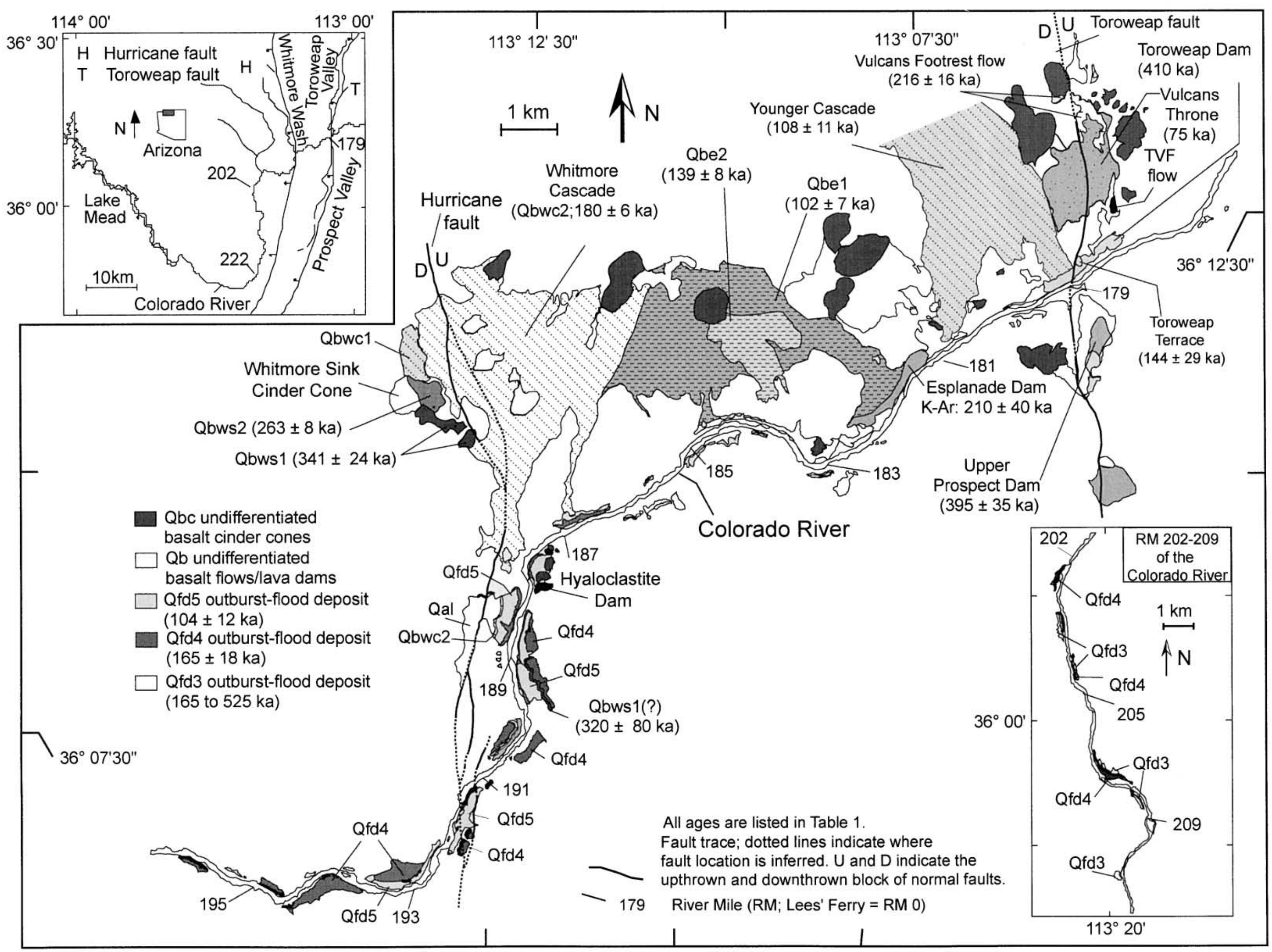

114° 00'
113° 00'
36° 30'
36° 00'
H Hurricane fault
T Toroweap fault
H
T
Whitmore Wash
Toroweap Valley
Prospect Valley
179
N
Arizona
202
222
Lake Mead
10km
Colorado River
113° 12' 30"
113° 07'30"
36° 12'30"
36° 07'30"
36° 00'
113° 20'
1 km
N
D U
Toroweap fault
Toroweap Dam
(410 ka)
Vulcans Footrest flow
(216 ± 16 ka)
Vulcans
Throne
(75 ka)
TVF
flow
Younger Cascade
(108 ± 11 ka)
Qbe2
(139 ± 8 ka)
Qbe1
(102 ± 7 ka)
Whitmore
Cascade
(Qbwc2;180 ± 6 ka)
Hurricane
fault
Toroweap
Terrace
(144 ± 29 ka)
Esplanade Dam
K-Ar: 210 ± 40 ka
Upper
Prospect Dam
(395 ± 35 ka)
Qbwc1
Whitmore Sink
Cinder Cone
Qbws2 (263 ± 8 ka)
Qbws1 (341 ± 24 ka)
179
181
183
185
187
189
191
193
195
Colorado River
Hyaloclastite
Dam
Qfd5
Qal
Qbwc2
Qfd4
Qfd5
Qbws1(?)
(320 ± 80 ka)
Qfd4
Qfd5
Qfd4
Qfd4
Qfd5
Qbc undifferentiated
basalt cinder cones
Qb undifferentiated
basalt flows/lava dams
Qfd5 outburst-flood deposit
(104 ± 12 ka)
Qfd4 outburst-flood deposit
(165 ± 18 ka)
Qfd3 outburst-flood deposit
(165 to 525 ka)
All ages are listed in Table 1.
Fault trace; dotted lines indicate where
fault location is inferred. U and D indicate the
upthrown and downthrown block of normal faults.
179 River Mile (RM; Lees' Ferry = RM 0)
RM 202-209
of the
Colorado River
202
Qfd4
Qfd3
Qfd4
205
Qfd3
Qfd4
209
Qfd3

tively. The bases of most lava dams are at, near, or below current river level; after the destruction of each lava dam, the Colorado River eroded down to its original profile but no farther (Hamblin 1994). Between RM 188 and 208, the bases of lava dams that once filled the channel are 511 ± 63, 296 ± 57, and 97 ± 32 ka ($^{39}Ar/^{40}Ar$; Pederson et al. 2002) and are 36, 7, and 14 m, respectively, above current river level. This may reflect long-term incision that was perturbed by the presence of lava dams. Incision rates reportedly range from 70 to 90 m/Ma downstream of the Hurricane/Toroweap fault zone (Lucchitta et al. 2000; Pederson et al. 2002).

Fenton et al. (2002) presented a conceptual model for lava-dam instability and failure that suggests at least two lava dams failed catastrophically, releasing high-magnitude floods into the narrow canyon downstream, which resulted in thick outburst-flood deposits that are composed of >80% basalt boulders and cobbles. These deposits were previously mapped as basalt-rich terrace gravels (Huntoon et al. 1981; Lucchitta et al. 2000). Whether any of the lava dams lasted long enough to allow the deposition of lacustrine deposits in their upstream reservoirs is uncertain, since deposits from deepwater lakes linked to lava dams have not yet been verified in Grand Canyon (Kaufmann et al. 2002). Dalrymple and Hamblin (1998) propose that each dam lasted no longer than 20 ka.

Western Grand Canyon outburst-flood deposits are very similar in appearance and cannot be distinguished on the basis of stratigraphy and appearance alone. Fenton et al. (2002) identified two outburst-flood events on the basis of $^{3}He_{c}$ ages and chemical compositions of basalt glasses and whole rock basalts in the flood deposits. They further suggested that individual basalt flows in the Uinkaret volcanic field should have distinct chemical signatures that would allow correlation of clasts between lava flow and outburst-flood deposit. New mapping and chemical data provide strong evidence for at least five lava-dam outburst-flood events preserved in terraces throughout western Grand Canyon (fig. 2).

In this article, we document the extent of deposits resulting from five lava-dam failures and suggest correlations between these flood deposits and lava flows and dam remnants on the basis of field evidence, cosmogenic ^{3}He ($^{3}He_{c}$) ages, and concentrations of SiO_2, Na_2O, K_2O, and rare earth elements (REE) in basalt glass and whole rock basalt. We demonstrate that REE patterns can be used to (1) help separate and reclassify lava-dam outburst-flood deposits that have similar major-element compositions, (2) identify common sources for glass and boulders in a given deposit, (3) distinguish or suggest correlations among lava flows of similar ages, and (4) suggest source-product relations between lava-dam remnants and outburst-flood deposits. These geochemical tools greatly improve the correlation and interpretation of late Quaternary basalt flows, lava-dam remnants, and lava-dam outburst-flood deposits in western Grand Canyon.

Methods

We mapped and investigated 49 discontinuous lava-dam outburst-flood deposits between RM 185 and 222. Because these deposits are very similar in appearance and cannot be distinguished on the basis of stratigraphy and appearance alone, we collected rock samples for geochemical analyses and $^{3}He_{c}$ dating. In this study, we focus on the geochemical and cosmogenic data that permitted us to distinguish five individual lava-dam failures and their related floods. We have provided generalized stratigraphic sections at five different localities between RM 185 and 222 (fig. 2) to illustrate the relations among the deposits and underlying lava-dam remnants. Fenton et al. (2002) provide detailed sedimentological descriptions of the outburst-flood deposits. Point counts were conducted on the surfaces and natural vertical exposures, where possible, of Holocene Colorado River gravels and Pleistocene outburst-flood deposits (fig. 3) using the sampling method of Wolman (1954). The 10 largest boulders and/or megaboulders (>10-m *b*-axis diameter; Sundell and Fisher 1985) in each deposit were also measured. The megaboulder data and the basalt content of the outburst-flood deposits and Holocene river gravels are published in Fenton et al. (2002).

Figure 1. Geologic map of volcanic landforms and outburst-flood deposits associated with basaltic lava dams in western Grand Canyon, Arizona (adapted from Huntoon et al. 1981). *Qbws1* = older Whitmore Sink lava flow; *Qbws2* = younger Whitmore Sink lava flow; *Qbwc1* = older Whitmore Cascade lava flow; *Qbwc2* = younger Whitmore Cascade lava flow; *Qbe1* = older Esplanade lava flow; *Qbe2* = younger Esplanade lava flow; *TVF* = Toroweap Valley Fill lava flow. Patterns on map are used only to distinguish map units from one another on a gray color scale map.

Table 1. $^{3}He_{c}$ and Other Ages of Lava Dams and Lava Flows in Western Grand Canyon

Name of volcanic unit[a]	$^{3}He_{c}$ age (ka)	$^{40}Ar/^{39}Ar$ age (ka)	K-Ar age (ka)	TL age (ka)[b]	Age estimate (ka)
Qfd5 outburst-flood deposit	**104 ± 12**[c]	…	…	…	…
Younger Cascade	**108 ± 11**[c]	…	**110 ± 53**[d]	…	…
Esplanade Cascade (Qbe1)	102 ± 7[e]	…	210 ± 40[f]	…	…
Younger Esplanade Cascade (Qbe2)	**139 ± 8**[e]	…	…	…	…
Gray Ledge Dam:					
Younger unit	…	**110 ± 30**[g,h]	140[i]	…	…
		97 ± 32[g,h]	788 ± 128[j]		
Older unit	…	193 ± 46[g,h]	…	…	…
Toroweap Valley Fill	125 ± 3[e]	…	776 ± 138[j]	…	…
Massive Diabase lava dam	…	296 ± 57[k]	174 ± 39[l]	…	…
			443 ± 41[j]		
			140[j]		
Toroweap Terrace	144 ± 29[e]	…	…	…	…
Qfd4 outburst-flood deposit	**165 ± 18**[e]	…	…	…	…
Whitmore Cascade:					
Qbwc2	**180 ± 6**[e]	220 ± 120[m]	993 ± 97[j]	**203 ± 24**	600
Qbwc2	**180 ± 6**[e]	150 ± 220[m]		88 ± 15	
Basalt flow north of Vulcans Throne	**208 ± 14**[c]	…	…	**201 ± 34**	…
Vulcans Footrest flow	**220 ± 20**[e]	…	…	…	…
Whitmore Sink:					
Qbws2	**263 ± 8**[e]	…	…	…	…
Qbws1	**341 ± 24**[e]	**315 ± 81**[h]	…	…	…
Toroweap Dam (flow A)	…	…	1160 ± 18[n]	…	**410**[o]
Upper Prospect flow	**395 ± 35**[c]	**509 ± 27**[g]	**500 ± 47**[j]	…	…
Lower Prospect flow	…	**630 ± 70**[g]	**657 ± 52**[j]	…	…
		600 ± 60[g]	1860 ± 300[j]		
			869 ± 52[j]		
			946 ± 74[j]		
			745 ± 103[j]		
Black Ledge lava dam	…	**480 ± 80**[m]	**549 ± 32**[p]	…	…
		511 ± 63[g]			
		524 ± 7[q]			
		603 ± 8[q]			

Note. Ellipsis indicates no data. The authors accept boldfaced ages as reliable.
[a] All locality names are informal unless otherwise noted. See figure 1.
[b] All thermoluminescence (TL) ages are from Holmes et al. (1978).
[c] Reported in Fenton et al. (2001, 2002).
[d] This age is reported for an Esplanade lava-dam remnant at RM 181L (Dalrymple and Hamblin 1998), but it is part of the Younger Cascade.
[e] See apps. C and D for details of $^{3}He_{c}$ analyses.
[f] This age is reported for an Esplanade lava-dam remnant at RM 182L (Hamblin 1994).
[g] McIntosh et al. (2002). Black Ledge sample was collected at RM 208.
[h] W. C. McIntosh (pers. comm., 2001) and Pederson et al. (2002). Samples collected from the Gray Ledge flow were collected near RM 188. The Toroweap Dam (flow A) $^{40}Ar/^{39}Ar$ age estimate comes from a sample that was collected from a lava flow at RM 177L whose base is 31.2 m above river level, roughly the same elevation as Toroweap flow A at RM 179; these two flows are probably equivalent.
[i] Hamblin (1989). Sample location is given as RM 192. No specific basalt unit is specified, but it may be the Gray Ledge on the basis of Hamblin's (1994) mapping.
[j] Dalrymple and Hamblin (1998).
[k] Sample collected from a Massive Diabase unit (RM 195; W. C. McIntosh, pers. comm., 2001).
[l] No specific basalt unit was specified, but the sample may have been collected from the Massive Diabase dam at RM 206 (Wenrich et al. 1995).
[m] $^{39}Ar/^{40}Ar$ ages analyzed at the New Mexico Geochronological Research Laboratory. Whitmore Cascade data reported in Fenton et al. (2002). Black Ledge sample was collected at RM 189.5L.
[n] McKee et al. (1968).
[o] Age estimate based on 44 m of vertical displacement and an average displacement rate of 110 m/m.yr. or the Toroweap fault (Fenton et al. 2001).
[p] Hamblin (1994).
[q] Lucchitta et al. (2000). Black Ledge samples collected in Granite Park (RM 207–209).

On the basis of the conceptual model of lava-dam failure proposed by Fenton et al. (2002), we hypothesize that outburst-flood deposits related to a specific lava-dam failure should contain basalt clasts and vitroclasts that have chemical signatures similar to one another and to the source dam, within the uncertainty of the technique and allowing for natural chemical variations within a lava flow. Fenton et al. (2002) illustrated that vitroclasts collected from different vertical and lateral locations within a given flood deposit exhibited identical SiO_2, Na_2O, and K_2O concentrations. Likewise, discontinuous deposits with similar ^3He_c exposure ages also exhibit similar chemical signatures. These geochemical techniques are used to classify 49 discontinuous flood deposits into separate map units. Contacts of flood deposits were first mapped, where possible, in the field in a downstream direction starting at the dam sites. Initial field relations were then tested using geochemical signatures, ^3He_c ages of the deposits, and K-Ar and/or $^{39}Ar/^{40}Ar$ ages of underlying and overlying lava-dam remnants. Flood deposits with similar ages and similar chemical signatures are grouped as one map unit. At least five units (Qfd1, Qfd2, Qfd3, Qfd4, and Qfd5) that we attribute to lava-dam outburst floods are preserved between RM 179 and 222 of the Colorado River through western Grand Canyon (figs. 1, 2).

All ^3He_c, REE, and electron microprobe samples were collected, prepared, and analyzed as described in Fenton et al. (2002). Samples were taken from stable, level surfaces in outburst-flood deposits and lava flows that exhibit well-developed desert pavement and varnish, features that indicate surface stability (Wells et al. 1995). ^3He_c samples were collected from exposed basalt boulder surfaces, primary flow structures, and/or desert pavements from outburst-flood deposits and lava-dam-forming basalt flows. Deposits that were covered with alluvium from adjacent hillslopes or adjacent outburst-flood deposits were not sampled for ^3He_c dating because burial affects exposure ages.

^3He_c Dating Techniques. ^3He_c is ideal for dating young basalts because it is a stable isotope with the highest production rate of any cosmogenic nuclide (Kurz 1986; Cerling 1990) and leakage of ^3He_c from olivines is minimal at surface temperatures (Cerling 1990). This method is particularly useful for dating basalt flows in western Grand Canyon because they contain abundant olivine phenocrysts (Cerling et al. 1999; Fenton et al. 2002). ^3He_c has been used extensively to determine exposure ages of a variety of Quaternary surfaces, including basalt flows, flood deposits, and associated desert pavements (Cerling 1990; Anthony and Poths 1992; Poreda and Cerling 1992; Cerling and Craig 1994; Laughlin et al. 1994; Wells et al. 1995; Cerling et al. 1999; Fenton et al. 2001).

The amount of in situ ^3He_c is directly related to the length of time a rock has been exposed to cosmic rays (Craig and Poreda 1986; Kurz 1986; Lal 1987). The production rate of ^3He_c is controlled by elevation, latitude, and shielding of a sample. Shielding results from surrounding topography (i.e., hillslopes, cliff ledges), burial of a surface by sediment, or self-shielding. Production of ^3He_c decreases exponentially with depth but is thought to be relatively constant in the top 4 cm of a surface (Cerling and Craig 1994). As elevation and latitude increase and as shielding decreases, the production rate of in situ ^3He_c increases. Variations in the geomagnetic field also affect the production rate; the production rate is higher during periods of a weaker magnetic field (Cerling and Craig 1994). Four main processes contribute to the total helium mass in a rock: (1) air contamination, (2) radioactive decay and associated nuclear reactions, (3) mantle-gas contamination, and (4) cosmic-ray interaction (Mamyrin and Tolstikhin 1984).

The cosmogenic component is calculated by subtracting the mantle, air, and radiogenic values from the total ^3He in a sample using

$$^3He_c = {}^3He_{tot} - {}^3He_m - {}^3He_a - {}^3He_r, \qquad (1)$$

where the subscripts c, tot, m, a, and r refer to the cosmogenic, total, mantle, air, and radiogenic ^3He components, respectively. The contribution of radiogenic $^3He/^4He$ is significant in old rocks with young exposure ages (<10–20 ka) but is not significant for young basalts from the Uinkaret volcanic field (Cerling et al. 1999).

Olivine separates from rock samples were analyzed for $^3He/^4He$ content on the noble gas mass spectrometers at the University of Utah (MAP 215–50) and the University of Rochester (VG 5400). Cerling and Craig's (1994) absolute production rate of 115 ± 4 atoms/g/yr for ^3He_c in olivine corrected to high latitude and sea level was used to calculate ^3He_c ages in this study. Details of new ^3He_c analyses for this article are presented in appendixes A and B in the online edition of the *Journal of Geology* and also from the Data Depository at the *Journal of Geology* office. All K-Ar, $^{39}Ar/^{40}Ar$, and ^3He_c ages discussed in this article are listed in table 1 with their respective authors.

Electron Microscope Analyses of Basalt Glass. Glass was collected from pillow basalts at the base of two lava dams and from hyaloclasites in 49 individual sites in discontinuous outburst-flood deposits. The glass samples were analyzed on the Cameca SX-50 electron microprobe at the University of Utah for Si, K, and Na (table 2). Glasses were collected from various vertical and lateral locations in each outburst-flood deposit. Appendix C in the online edition of the *Journal of Geology* and from the Data Depository at the *Journal of Geology* office lists the locations and elevations where basalt

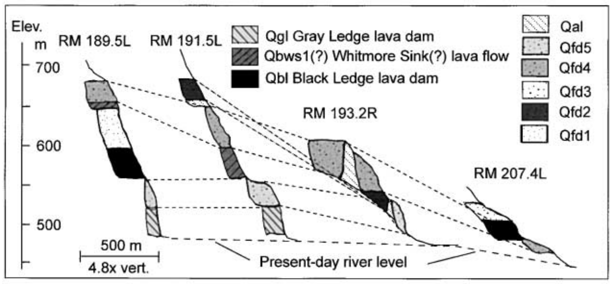


Figure 2. Select profiles and relative stratigraphic positions of outburst-flood deposits and lava-dam remnants.

glasses were collected. Table 2 lists average chemical data.

ICP-MS Analyses of Basalt Samples. REE concentrations of whole rock basalt and basalt glass samples (table 2; app. D in the online edition of the *Journal of Geology* and from the Data Depository at the *Journal of Geology* office) were measured at the University of Rochester ICP-MS using BCR-2 as a standard. Results for the standard were within 5% of the reported values (Wilson 1997). All REE values are normalized to chondrite values reported in Taylor and McClennan (1985).

The Black Ledge, Gray Ledge, Massive Diabase, Upper Prospect, Whitmore, Toroweap, Toroweap Valley Fill, and Esplanade lava flows and lava dams were mapped and named by Hamblin (1994). We have informally named the outburst-flood deposits and other lava flows and lava dams not previously named. Locations of these volcanic landforms are given by RM according to Stevens (1983) and are designated as either river left (L) or river right (R) facing downstream.

Sedimentology of Lava-Dam Outburst-Flood Deposits

Outburst-flood deposits are found only downstream of lava dams in western Grand Canyon (Lucchitta et al. 2000; Fenton et al. 2002) and are significantly different from typical Pleistocene and Holocene Colorado River gravels. Fenton et al. (2002) used the following criteria to distinguish between lava-dam outburst-flood deposits and typical Holocene and Pleistocene river gravels. The latter have a quartz-sand matrix and contain sandstone and limestone clasts from local Paleozoic rock sections and clasts of a variety of quartzite, porphyritic, and other igneous clasts from extralocal origin. Clasts, including sand grains, are rounded to well rounded and moderately to well sorted (fig. 3*a*). Holocene river gravels have a maximum of 60% basalt, and the amount of basalt decreases in a downstream direction away from the dam sites (Fenton et al. 2002). Point data do not show any significant difference in clast size between Holocene gravels and outburst-flood deposits other than the degree of sorting. Holocene gravels exhibit better sorting and have a smaller percentage of fine-grained ($\phi \leq 4$) material (fig. 3*a*). Outburst-flood deposits contain boulders ranging in size from 5- to 35-m *b*-axis diameter (Fenton et al. 2002). The largest clasts found in western Grand Canyon Holocene gravels were 5 m or less in diameter and were likely contributed to the mainstem river by nearby tributary canyons (Fenton et al. 2002).

Outburst-flood deposits (1) are 82%–98% basalt boulders and cobbles; (2) lack quartz river sands but contain hyaloclastite (basalt glass) matrix and hyaloclastite tuffs indicative of lava-water interaction; (3) are coarse with subangular to rounded clasts that are poorly to moderately sorted (fig. 3*a*, 3*c*); and (4) have clast sizes, elevation, and thicknesses that decrease with increasing distance downstream of the lava dams (figs. 3, 4). Deposits are typically preserved on benches provided by older lava-dam remnants (figs. 5*a*, 6) but are also found as slack water deposits at the mouths of tributary canyons, as well as interbedded lenses in slope colluvium, and as channel fill in preexisting Colorado River channels (fig. 5*b*). Some deposits exhibit foresets >45 m in height (fig. 5*a*), imbricated limestone blocks and basalt boulders (up to 8 and 35 m in *b*-axis diameter, respectively; fig. 7), and/or water surface profiles that exponentially decay in elevation downstream from the dam site (fig. 4). All of these features are indicative of large-scale floods with large unsteady discharges. Deposits are found between 53 and 200 m above current river level and are 20–110 m thick (figs. 4, 5*b*). These characteristics distinguish the deposits from typical Colorado River gravels or basalt-rich channel fill. The monolithological nature of the deposits strongly suggests that the basalt clasts in each flood deposit had a lava-dam point source; it is unlikely normal watershed processes would concentrate abundant basalt clasts (>82%) in a basalt-glass matrix yet exclude other Colorado River watershed lithologies, including quartz river sands.

Other basalt-rich gravels in western Grand Canyon appear to be related to normal streamflow processes and are different from gravels we recognize as being related to lava-dam failures. For example, at RM 188 under the Gray Ledge lava flow (fig. 5*a*), gravels contain as much as 83% basaltic clasts and possess strong imbrication and well-

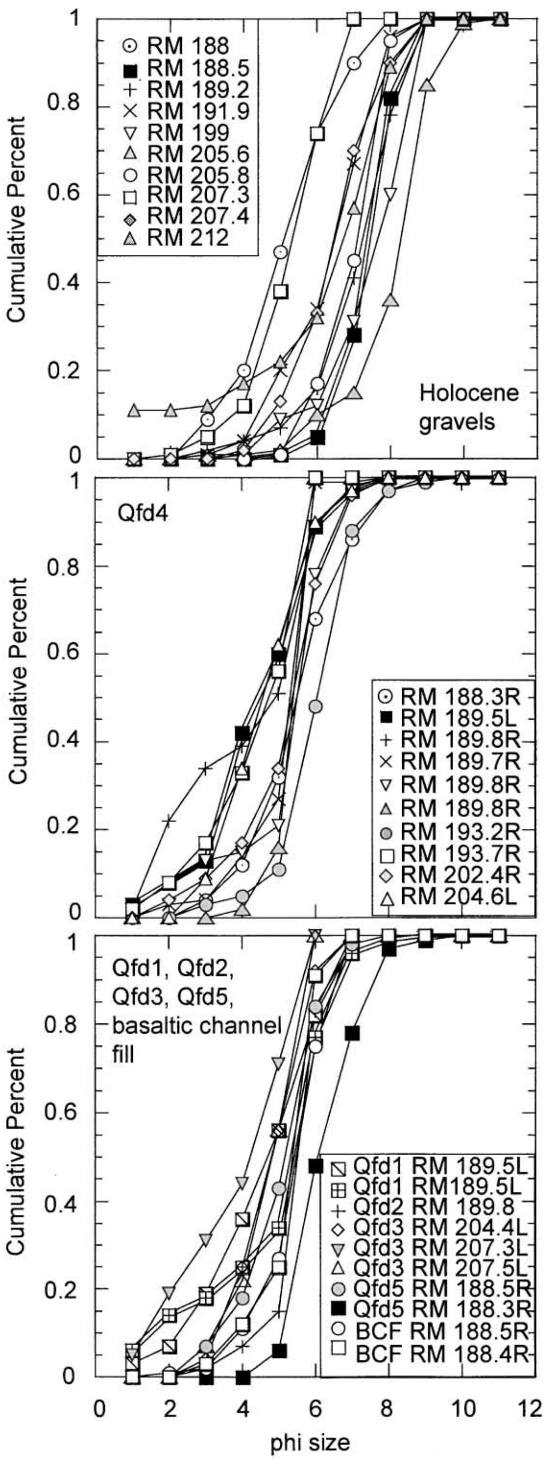


Figure 3. Cumulative percent of grain-size data from point counts conducted on Holocene river gravels and Pleistocene outburst-flood deposits in the method described by Wolman (1954).

sorted, well-rounded cobbles to small boulders with a quartz-sand matrix. The base and top of the gravels are 7 and 14 m above current river level. These gravels lack most of the aforementioned features found in lava-dam outburst-flood deposits and were likely deposited in the Colorado River channel bed as the free-flowing river excavated lava flows, lava-dam remnants, and/or preexisting outburst-flood deposits.

Geochemical Signatures of Lava-Dam Outburst-Flood Deposits

Total alkali ($K_2O + Na_2O$) and silica (SiO_2) concentrations in glass in hyaloclastites initially classify all outburst-flood deposits into groups of alkali olivine basalt (AOB I and AOB II) and tholeiitic basalt (THOL I; table 2; fig. 8), regardless of initial designation of map units in the field. The AOB I group has the highest average total alkali content (8.14% ± 0.71%) and lowest average silica content (46.64% ± 0.92%) of the three groups. On average, glasses in group AOB II contain 5.20% ± 0.44% and 50.22% ± 0.57% total alkali and total silica content, respectively, whereas glasses in tholeiitic basalts contain 4.26% ± 0.42% total alkali and 52.87% ± 0.74% silica.

Total alkali and silica concentrations of basalt glasses in chemical group AOB I have indistinguishable major element chemical signatures (fig. 8). Samples in group AOB I were collected from three depositional units. Two of these had been recognized in the field as distinctly different units. It was difficult to determine in the field whether the third unit was conclusively related or unrelated to one of the former two units. We relied on REE concentrations of clasts in these deposits to aid us in our correlation efforts. REE data and age constraints further divide group AOB I into subgroups AOB Ia, Ib, and Ic (figs. 5, 6; table 2).

REE contents illustrate that vitroclasts and whole rock basalt clasts in given depositional units are chemically related and permit us to assign discontinuous flood deposits to specific depositional units. REE concentrations of hyaloclastites and boulders in Qfd1, Qfd4, and Qfd5 indicate chemical similarities between the vitroclasts and basalt cobbles and boulders within each unit. In addition to ubiquitous SiO_2, Na_2O, and K_2O concentrations in vitroclasts in a given unit, REE data indicate that whole rock basalt clasts and hyaloclastites in a flood deposit could have had the same lava-dam source (fig. 10). These chemical data strongly suggest that the lava-dam sources for each flood deposit had identifiable chemical signatures that are

Table 2. Average Total Alkalies and Silica of Basalt Glasses, Average Select Ratios, and Total REE Concentrations of Basalt Glasses and Whole Rock Basalt Collected from Outburst-Flood Deposits and Lava Dams in Western Grand Canyon

Stratigraphic unit and sample type	Chemical group	n_{MIC}[a]	Total $K_2O + Na_2O$ (wt% ± 1σ)	SiO_2 (wt% ± 1σ)	n_{REE}[a]	La/Sm (±1σ)	Gd/Lu (±1σ)	La/Lu (±1σ)	Total REE (±1σ)[b]
Qfd1:									
Glass	AOB Ia	67 (6)	8.36 ± .62	46.69 ± .93	2	4.1 ± .1	2.6 ± .1	10.5 ± .8	355 ± 1
Boulder	AOB Ia	…	…	…	2	4.3 ± .0	2.6 ± .0	11.4 ± .1	322 ± 1
Average	AOB Ia	67 (6)	8.36 ± .62	46.69 ± .93	4	4.2 ± .1	2.6 ± .1	10.9 ± .7	339 ± 19
Qbup:									
Flow	…	…	…	…	1	5.0	1.9	9.6	335
Qfd2:									
Glass	AOB II	136 (13)	5.20 ± .44	50.22 ± .57	0	…	…	…	…
Qfd3:									
Glass	AOB Ib1	162 (15)	8.07 ± .58	46.51 ± .95	6	5.3 ± .5	4.7 ± .5	25.0 ± 3.5	496 ± 61
Qbtda:									
Flow	AOB I	7 (1)	9.27 ± .33	47.89 ± .48	1	4.4	4.3	18.7	194
Qfd3:									
Boulder	AOB Ib2	…	…	…	4	6.7 ± .1	4.3 ± .6	28.5 ± 4.8	198 ± 28
Qbwc2:									
Flow	…	…	…	…	3	4.6 ± .2	4.1 ± .4	19.0 ± 2.3	100 ± 11
Qfd4:									
Glass	THOL I	358 (22)	4.26 ± .42	52.87 ± .74	7	2.7 ± .1	2.2 ± .2	5.9 ± .7	167 ± 66
Boulder	THOL I	…	…	…	7	2.8 ± .3	1.9 ± .4	5.2 ± 1.3	199 ± 26
Average	THOL I	358 (22)	4.26 ± .42	52.87 ± .74	14	2.7 ± .2	2.0 ± .4	5.6 ± 1.1	182.9 ± 50.6
Qbhd:									
Flow	THOL I	…	…	…	2	2.7 ± .0	1.7 ± .0	4.6 ± .1	198 ± 3
Glass	THOL I	67 (5)	4.42 ± .15	51.85 ± .52	4	3.3 ± .7	1.6 ± .0	5.5 ± 1.2	311 ± 21
Average	THOL I	67 (5)	4.42 ± .15	51.85 ± .52	4	3.1 ± .6	1.7 ± .1	5.2 ± 1.1	274 ± 61
Qfd5:									
Glass	AOB Ic	31 (4)	7.68 ± 1.08	46.93 ± .48	2	4.9 ± .3	2.5 ± .1	12.1 ± .9	750 ± 61
Boulder	AOB Ic	…	…	…	5	5.6 ± .6	2.7 ± .6	15.3 ± 4.2	493 ± 259
Average	AOB Ic	31 (4)	7.68 ± 1.08	46.93 ± .48	7	5.4 ± .6	2.6 ± .5	14.4 ± 3.8	567 ± 247
Qbyc:									
Flow	…	…	…	…	1	5.7	3.4	19.7	407

Note. Ellipsis indicates no data. K_2O, Na_2O, and SiO_2 values were obtained from electron microprobe analyses of basalt glasses, and REE values were obtained from ICP-MS analyses of whole rock basalt boulders and basalt glasses within outburst-flood deposits and lava dams; n_{REE} and n_{MIC} indicate the number of values used in the calculation of average and standard deviation values for REE and electron microprobe analyses, respectively. Qbup = Upper Prospect flow; Qbtda = Toroweap Dam (flow A); Qbwc2 = Whitmore Cascade; Qbhd = Hyaloclasite Dam; Qbyc = Younger Cascade.

[a] First number indicates the number of electron microprobe analyses of specified number of basalt glass samples (in parentheses).

[b] Total REE values are chondrite normalized. Chemical groups AOB Ia, Ib, and Ic are classified on the basis of REE data.

reflected in the chemical concentrations of the flood deposits.

Outburst-flood deposits are assigned to one of the following depositional units: Qfd1, Qfd2, Qfd3, Qfd4, and Qfd5. These units correspond to chemical groups AOB Ia, AOB II, AOB Ib, THOL I, and AOB Ic, respectively. Total alkali and silica concentrations of basalt glasses collected from Qfd2 (AOB II) and Qfd4 (THOL I) deposits are distinctly different from one another and from units Qfd1, Qfd3, and Qfd5 in chemical group AOB I (fig. 8). Likewise, clasts from these units have different REE signatures (figs. 9, 10*a*). Basalts with common magma sources have overlapping or parallel REE patterns; parallel patterns occur as a result of fractionation (Humphris 1984). REE patterns that cross, such as those belonging to clasts collected from units Qfd1 and Qfd3 (fig. 10*a*), indicate the basalts are chemically unrelated. In addition, the age of the Qfd1 unit is constrained by lava flows between 315 and 480 ka (fig. 11), and Qfd3 deposits are between 165 and 525 ka. Clasts from Qfd1 and Qfd5 have similar La/Sm and Gd/Lu ratios (fig. 9); however, field evidence and distinct age differences indicate that Qfd1 and Qfd5 are unrelated. The youngest outburst-flood deposits (Qfd5) yielded an average ^3He_c age of 104 ± 12 ka. La/Sm and Gd/Lu ratios reflect the slopes of REE patterns such as those illustrated in figure 10.

Qfd1 Outburst-Flood Deposit. The only Qfd1 lava-dam outburst-flood deposit in western Grand Canyon is exposed at RM 189.5L (figs. 1, 2, 6). It is preserved between a Black Ledge lava-dam remnant whose $^{39}Ar/^{40}Ar$ age is 480 ± 80 ka and a basalt flow

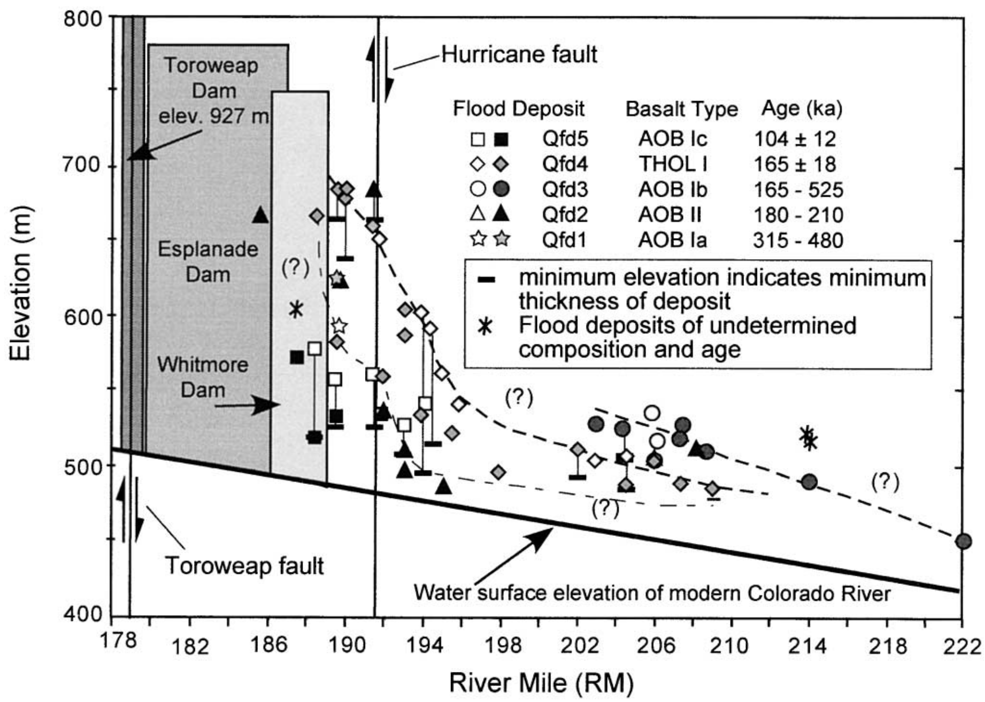


Figure 4. Elevations of lava-dam outburst-flood deposits between RM 185 and 222 (modified from Fenton et al. 2002). Solid markers represent deposits that have been correlated on the basis of chemical data and field evidence; open markers indicate no chemical data. Dashed lines connecting deposits are arbitrarily drawn. The modern Colorado River elevations are taken from Stevens (1983). Toroweap, Esplanade, and Whitmore Dams of Hamblin (1994) are schematically represented by the shaded rectangles. The Toroweap fault displaces the Toroweap Dam by 44.5 m, and the Hurricane fault displaces the Qfd4 deposit at RM 191.5 by 13 m. The authors have yet to find well-preserved displacements in the Qfd2 and Qfd5 deposits near RM 191.5L, but the Hurricane fault crosses the river at this point.

whose $^{39}Ar/^{40}Ar$ age is 315 ± 81 ka (table 1), mapped by Hamblin (1994) as part of the Whitmore Dam complex (fig. 11); we have informally named this basalt flow the Qbws1 (?) lava. Clasts in the deposit are 92% basalt, and the base and top are at 110 and 170 m above current river level, respectively. Clast size ranges from hyaloclastite ash and lapilli to a 6-m *b*-axis diameter limestone block; the largest basalt clast is 1.5 m in the b-axis diameter.

Whole rock basalt ($n = 1$) and vitroclasts ($n = 2$) collected from the Qfd1 deposit have identical REE patterns (fig. 9). La/Sm and Gd/Lu values for these clasts range from 4.0 to 4.3 and from 2.5 to 2.6, respectively (fig. 10*a*). This strongly indicates that all the clasts came from the same lava-dam source on its failure.

Qfd2 Outburst-Flood Deposit. Qfd2 deposits are located between RM 185.7 and 193.2. Greater than 90% of the clasts are basalt cobbles and boulders as much as 1 m in *b*-axis diameter together with lesser limestone blocks. At RM 185.7L, a Qfd2 deposit is juxtaposed against an Esplanade lava-dam remnant whose K-Ar age is 210 ± 40 ka, and another deposit is overlain by the Whitmore Cascade, whose $^{3}He_{c}$ age is 180 ± 6 ka at RM 189.8R. The few Qfd2 deposits that are exposed do not provide surfaces stable enough for $^{3}He_{c}$ dating. The stratigraphic relation between Qfd2 and Qfd3 deposits is not clear, but Qfd4 deposits commonly unconformably overlie Qfd2 deposits (fig. 2). Qfd2 deposits are between 10 and 20 m thick and are preserved at elevations ranging from 204 to 15 m above current river level. Clasts from Qfd2 have not been analyzed for REE content.

Qfd3 Outburst-Flood Deposit. Qfd3 deposits are preserved at maximum elevations of 74 and 89 m above current river level between RM 203 and 222. These gravels were mapped as part of a downcutting-aggradation cycle involving catastrophic volcanic events upstream that occurred between 525 and 600 ka (Lucchitta et al. 2000). The gravels are 9–20 m thick and overlie a younger lava flow ($^{39}Ar/^{40}Ar$ age = 511 ± 63 ka) that is mapped as part of the Black Ledge Dam (figs. 1, 4). The largest clasts are 50 cm in *b*-axis diameter. Extralocal Colorado River gravels and quartz-rich river sands are found intermittently in Qfd3 deposits between RM 204.4L and 207.3L but no higher than 87 m above current river level. This indicates the presence of a free-flowing Colorado River, but a contact could not be found in naturally occurring vertical exposures. The gravels may be inset against or within the lower section of the Qfd3 gravels.

^3He_c ages for Qfd3 terraces at RM 204.4L and RM 207.3L range from 59 to 155 ka and are considered age minima because these deposits are stratigraphically older than the Qfd4 flood (^3He_c age = 165 ± 18 ka; Fenton et al. 2002). In addition, other age controls suggest that the deposits are older than 100 ka. Lucchitta et al. (2000) report stage III (100–250 ka) and V (~525 ka) soil carbonates that are developed in locally derived limestone talus overlying parts of Qfd3 flood deposits between RM 207.3L and 208.7R. Three basalt boulders that yielded the youngest ^3He_c ages—59 ± 4, 68 ± 5, and 71 ± 5 ka—were collected from a Qfd3 deposit at RM 204.4 deposit. There is a Quaternary landslide upslope of the RM 204.4 deposit; the minimum exposure ages may result from burial by landslide material and then reexhumation, but there is very little landslide material found in desert pavement on the surface of the deposit. It is more likely that the young ages are a result of degradation of the Qfd3 deposit possibly because of slopewash eroding away fine-grained material. Exposure ages of deposits between RM 206L and 207.3L are between 110 and 155 ka. The surfaces from which these samples were collected have subhorizontal surfaces with well-developed desert pavements and desert varnish; however, it is likely these age minima also represent degradation of Qfd3 deposits.

Boulders and glasses within Qfd3 deposits do not appear to be related magmatically (figs. 10, 11*a*; table 2; Fenton et al. 2002). Although the boulders and glasses have similar Gd/Lu ratios, their La/Sm ratios are significantly different. Samples from Qfd3 deposits were collected in an area where the elevations of Qfd3, Qfd4, and Qfd2 deposits converge (fig. 4). It may be that two separate outburst-flood deposits are mixed in what we have designated as Qfd3 deposits, or, alternatively, one Qfd3 flood tapped separate basalt-clast sources along route. The presence of extralocal gravels in Qfd3 deposits supports the former hypothesis.

Qfd4 Outburst-Flood Deposit. Qfd4 deposits between RM 189.5 and 209 overlie Massive Diabase Dam remnants (140–440 ka), Whitmore Cascade flow remnants (^3He_c age = 180 ± 6 ka), and a lava-dam remnant whose $^{39}Ar/^{40}Ar$ age is 315 ± 81 ka. A Qfd4 deposit at RM 209R is preserved within a reworked debris fan 23 m above current river level. Clasts in the deposits are >82% basalt. Deposits are preserved between 13 and 200 m above current river level and are between 20 and 110 m thick. Clast size ranges from hyaloclastite ash and lapilli to 5-m boulders (*b*-axis). The Qfd4 deposit contains the most continuous, extensively preserved record, between RM 188.5 and RM 209 (fig. 4), of a catastrophic lava-dam outburst flood in western Grand Canyon.

^3He_c ages of Qfd4 surfaces range from 115 to 216 ka (n = 15), with an average exposure age of 165 ± 18 ka (table 1). Six cosmogenic samples are between 157 and 161 ka (app. A). Six samples yielded the youngest ages ranging from 115 to 144. The remaining three samples yielded ages of 189 ± 13, 201 ± 14, and 216 ± 15 ka. The youngest exposure ages are attributed to degradation and erosion of Qfd4 surfaces, although all samples were collected from horizontal to subhorizontal surfaces with well-developed desert varnish and desert pavements. The oldest age (216 ± 15 ka) was rejected because a duplicate sample yielded an age of 161 ± 11 ka (app. A), and the younger of these two ages agrees with five other samples of similar exposure age. On the basis of the oldest exposure ages, it is possible that Qfd4 deposits are closer to 200 ka in actual depositional age and that the average exposure age is a minimum reflecting erosion and degradation of Qfd4 surfaces; however, Qfd4 deposits are inset against Whitmore Cascade lava flows and, thus, must be older than 180 ± 6 ka.

Seven of 10 basalt boulders and seven glass samples collected from Qfd4 deposits are tholeiite (figs. 8, 10), and three of boulders are alkali olivine basalt (fig. 10). Fenton et al. (2002) identified two Qfd4 alkali olivine basalt boulders at RM 189.5L and 202R but identified a tholeiite glass sample in a Qfd4 outburst-flood deposit at RM 202R. They suggested that the boulders and glass were emplaced by separate, chemically unrelated events; however, the data in this study strongly suggest that Qfd4 basalt boulders and hyaloclastites are dominated by tholeiites and that the three alkali olivine boulders are older clasts that were incorporated into the Qfd4 outburst flood. One tholeiitic boulder was collected from the Qfd4 deposit at RM 204.6 that has the 100-ka-old strath terrace cut into it; hyaloclastites from this deposit are also tholeiitic (fig. 9). This is consistent with the hypothesis that the outburst-flood deposit at RM 204.6L is related to other Qfd4 deposits that were emplaced at 165 ka (Fenton et al. 2002). The strath terrace is preserved as a prominent, flat surface occurring at 36 m above current river level in the Qfd4 deposit, whose maximum elevation is 52.4 m above current river level.

The 100-ka terrace at RM 204.6L may have been cut into the Qfd4 deposit during the Qfd5 outburst flood (at 104 ± 12 ka), but no alkali olivine basalt Qfd5 material is preserved at this location.

Qfd5 Outburst-Flood Deposit. Qfd5 deposits (^3He_c age = 104 ± 12 ka) overlie Massive Diabase lava-dam remnants (140–440 ka) and the youngest ($^{39}Ar/^{40}Ar$ ages = 110 ± 30 and 97 ± 32 ka) of two flows mapped as the Gray Ledge lava dam between RM 187 and 194. Qfd5 deposits preserved between RM 188 and 190 are up to 45 m thick. Exposure ages for the Qfd5 flood deposit (^3He_c age = 89–125 ka) overlap exposure ages of a strath terrace cut into a Qfd4 deposit (^3He_c age = 100 ± 6 ka) at RM 204.6 (Fenton et al. 2002). Three ^3He_c samples collected at RM 188R yielded exposure ages of 110 ± 8 ka ($n = 2$) and 125 ± 9 ka, whereas five ^3He_c samples collected at RM 189.5L yielded ages ranging from 89 to 108 ka. All samples were collected from horizontal surfaces with well-developed desert pavements and desert varnish. The variation in ages likely represents erosion or degradation of Qfd5 deposits since deposition.

Several basalt glass samples from Qfd5 deposits yielded more scattered REE ratios than other depositional units, likely suggesting reworking of older alkalic-basalt clasts into the deposits. Only six glass samples yielded useful major element basalt-glass data (fig. 9). Qfd5 hyaloclastites are more scoriaceous and contain more olivine, pyroxene, and/or plagioclase crystals than hyaloclastites in other flood deposits, making it difficult to analyze interstitial glass without contamination from surrounding minerals. This characteristic of the Qfd5 hyaloclastites distinguishes them from other deposits. Five of seven boulders collected from Qfd5 deposits between RM 188.5R and RM 189.5L are alkali olivine basalts and exhibit similar La/Sm and Gd/Lu ratios and total REE concentrations (fig. 9; app. D). The data suggest the boulders likely came from the same lava dam. Of the other two boulders, one is tholeiite and the other alkali olivine basalt, although it has a significantly higher total REE content (fig. 9; app. D); these two boulders are likely older clasts that were incorporated into the Qfd5 flood.

Western Grand Canyon Lava Dams

Whitmore Dam Complex. At least two vents, now covered by cinder cones near Whitmore Wash, produced lavas that flowed out of Whitmore Canyon into the mainstem Colorado River (fig. 1), forming lava dams that Hamblin (1994) mapped collectively as the Whitmore Dam complex. Dalrymple and Hamblin (1998) report one "unreliable" K-Ar age of 993 ± 97 ka for this complex. Within this complex, Hamblin (1994) described river gravels and laminated deposits of tephra between RM 188.7L and 189.6L; we distinguish these gravels and tephra as Qfd1 and Qfd4 outburst-flood deposits that are interlayered with Whitmore flows. We differentiate at least five lava flows within this complex that have different ages and different chemical signatures, including the Qbwc1 flow, Whitmore Cascade (Qbwc2), Whitmore Sink lava flows (Qbws1 and Qbws2), and the Hyaloclastite Dam (fig. 1).

The Qbwc1 flow was incorrectly mapped as part of the Whitmore Cascade (Qbwc2, fig. 1) by Fenton et al. (2002). Qbwc1 unconformably underlies the Whitmore Cascade and caps several thin basalt flows that overlie the Qbws2 Whitmore Sink lava flow (^3He_c age = 263 ± 8 ka). Three samples of the Qbwc1 lava flow (99-AZ-924-WC, 99-AZ-925-WC, and 99-AZ-926-WC) yielded ^3He_c ages of 125 ± 9000, 176,000 ± 12,000, and 161 ± 11 ka, respectively (Fenton et al. 2002). These are minimum exposure ages that represent surfaces affected by either sediment burial or erosion, on the basis of the stratigraphic position of the Qbwc1 flow. Two of these ages were used in an average ^3He_c age of 177 ± 9 ka ($n = 10$) of the Whitmore Cascade (Fenton et al. 2002); by removing these two ages from the calculations, we find that the Whitmore Cascade has an average exposure age of 180 ± 6 ka. Stratigraphic relations limit the age of the Qbwc1 flow to between 174 and 271 ka.

The two Whitmore Sink lava flows, Qbws1 and Qbws2, are alkali olivine basalts that erupted at the Whitmore Sink cinder cone (fig. 1). They are not stratigraphically correlative, are separated by a thick volcaniclastic tuff, and have different ^3He_c ages. The older Qbws1 unit yields ^3He_c ages of 248 ± 18 ka and 341 ± 24 ka; the former age most likely represents the exposure age of an eroded surface. There were no primary flow surfaces present on Qbws1, only a desert pavement. The latter age overlaps an $^{39}Ar/^{40}Ar$ age of 315 ± 81 ka (table 1) of a basalt flow mapped as part the Whitmore Dam complex at RM 189.5L (mapped as Qbws1 [?]; fig. 6). The Qbws1 flow caps at least five massive basalt flows that fill an ancestral Whitmore Canyon. The Qbws2 flow is stratigraphically below the older Whitmore Cascade (Qbwc1) flow but overlies a volcaniclastic tuff that separates the two Whitmore Sink lava flows. Qbws2 is covered in a desert pavement, and primary flow surfaces are rare. Two ^3He_c ages from the desert pavement are 257 ± 18 and 268 ± 19 ka, which yield an average age of 263 ± 8 ka. Desert pavements reflect the age of the un-

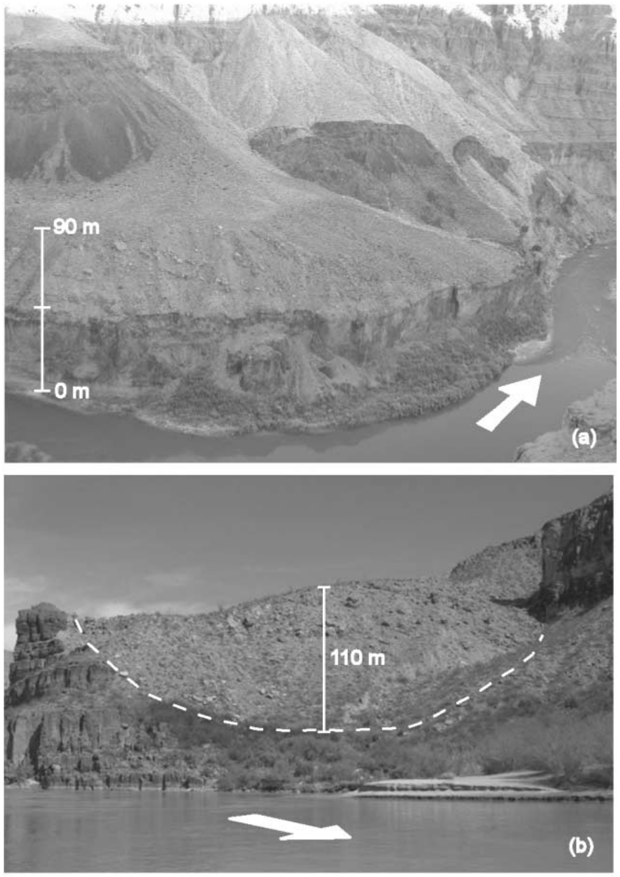


Figure 5. *a*, Photograph of Qfd5 outburst-flood deposit preserved on a bench created by a Gray Ledge lava-dam remnant at RM 188L. *b*, Upstream view of a paleo–Colorado River channel filled with a Qfd4 deposit that is 110 m thick at RM 194L. The white arrows indicate the direction of flow of the present-day Colorado River.

derlying lava flow (Wells et al. 1995; Fenton et al. 2002).

Different eruptive sources, La/Sm and Gd/Lu ratios (fig. 10), and $^{3}He_{c}$ ages (table 1) distinguish the Whitmore Cascade from the Whitmore Sink lava flows. The Whitmore Cascade has smaller La/Sm ratios and larger Gd/Lu ratios, and its exposure age is approximately 80 ka younger than the Qbws2 flow ($^{3}He_{c}$ = 263 ± 8 ka). The cinder cone marking the source of the Whitmore Cascade is east of the Whitmore Sink cinder cone and on the upthrown block of the Hurricane Fault (fig. 1; Fenton et al. 2001). Although it cannot be distinguished either in the field or through aerial photography, there must be a contact (arbitrarily assigned; fig. 1) between the Whitmore Cascade and Esplanade lava cascades (Qbe1; fig. 1) on the Esplanade platform between Toroweap Valley and Whitmore Wash.

At RM 188L, a slump block containing a remnant of the Hyaloclastite Dam (fig. 1) is composed of interfingering layers of hyaloclastites, pillow basalts, and lava flows. No absolute ages exist for the Hyaloclastite Dam, and the stratigraphic position of the slump block is difficult to discern, but the dam appears to be inset against and younger than other lava flows (180–315 ka) also mapped in the Whitmore Dam complex. The Hyaloclastite Dam is tholeiitic and is not related to the Whitmore Cascade or Whitmore Sink lava flows of alkali olivine basalt. Whole rock and glass samples taken from the dam yielded La/Sm ratios of 2.4–3.9 and Gd/Lu ratios of 1.6–1.7 (fig. 10). Variable La/Sm ratios may have resulted from palagonitization of basalt glass, which enriches light REE (Humphris 1984).

On the basis of $^{3}He_{c}$ ages, $^{39}Ar/^{40}Ar$ ages, and stratigraphy, it is apparent that the Whitmore Sink lava flows (Qbws1 and Qbws2), Qbwc1, Whitmore Cascade (Qbwc2), and the Hyaloclastite Dam did not construct one large, long-lived Whitmore Dam complex as described by Hamblin (1994). These lava flows represent eruptions that may have formed individual lava dams, but potential dams formed by Qbws1 ($^{3}He_{c}$ = 341 ka), Qbws2 ($^{3}He_{c}$ = 263 ka), and Qbwc2 ($^{3}He_{c}$ = 180 ka) lava flows occurred approximately 80 ka apart (table 1). On the basis of Niagara Falls headword-erosion rates, the maximum lifetime of a stable western Grand Canyon lava dam would have been 20 ka (Dalrymple and Hamblin 1998).

Esplanade Cascades and Dam. At RM 182L, the Esplanade lava dam has a K-Ar age of 210 ± 40 ka (fig. 1; table 1). Esplanade lava cascades (Qbe1; fig. 1) that flowed down and cap the Esplanade Dam at RM 182 have an average $^{3}He_{c}$ age of 101 ± 5 ka. A smaller lava flow (Qbe2; fig. 1) overlying the Qbe1 cascades yielded an average $^{3}He_{c}$ age of 139 ± 8 ka (table 1). The Qbe1 flow appears to be stratigraphically below the Qbe2 flow but yields a younger $^{3}He_{c}$ age. Either this may be a result of erosion of the Qbe1 basalt flow surfaces that were dated or the Qbe1 flow is actually younger and juxtaposed against the Qbe2 flow in a drainage. Neither of these flows has been analyzed for REE.

Toroweap Valley Lava Flows and Lava Dams. Whole rock basalt samples were collected from several alkali-olivine basalt flows in or near Toroweap and Prospect Valleys (fig. 1). These flows include the Upper Prospect flow ($^{3}He_{c}$ = 395 ka), Vulcans Footrest flow ($^{3}He_{c}$ = 220 ka), an unnamed basalt flow ($^{3}He_{c}$ = 208 ka) north of Vulcans Throne, Toroweap Terrace ($^{3}He_{c}$ = 144 ka), Toroweap Valley Fill ($^{3}He_{c}$ = 125 ka), and the Younger Cascade ($^{3}He_{c}$ = 110 ka). These basalts have similar and

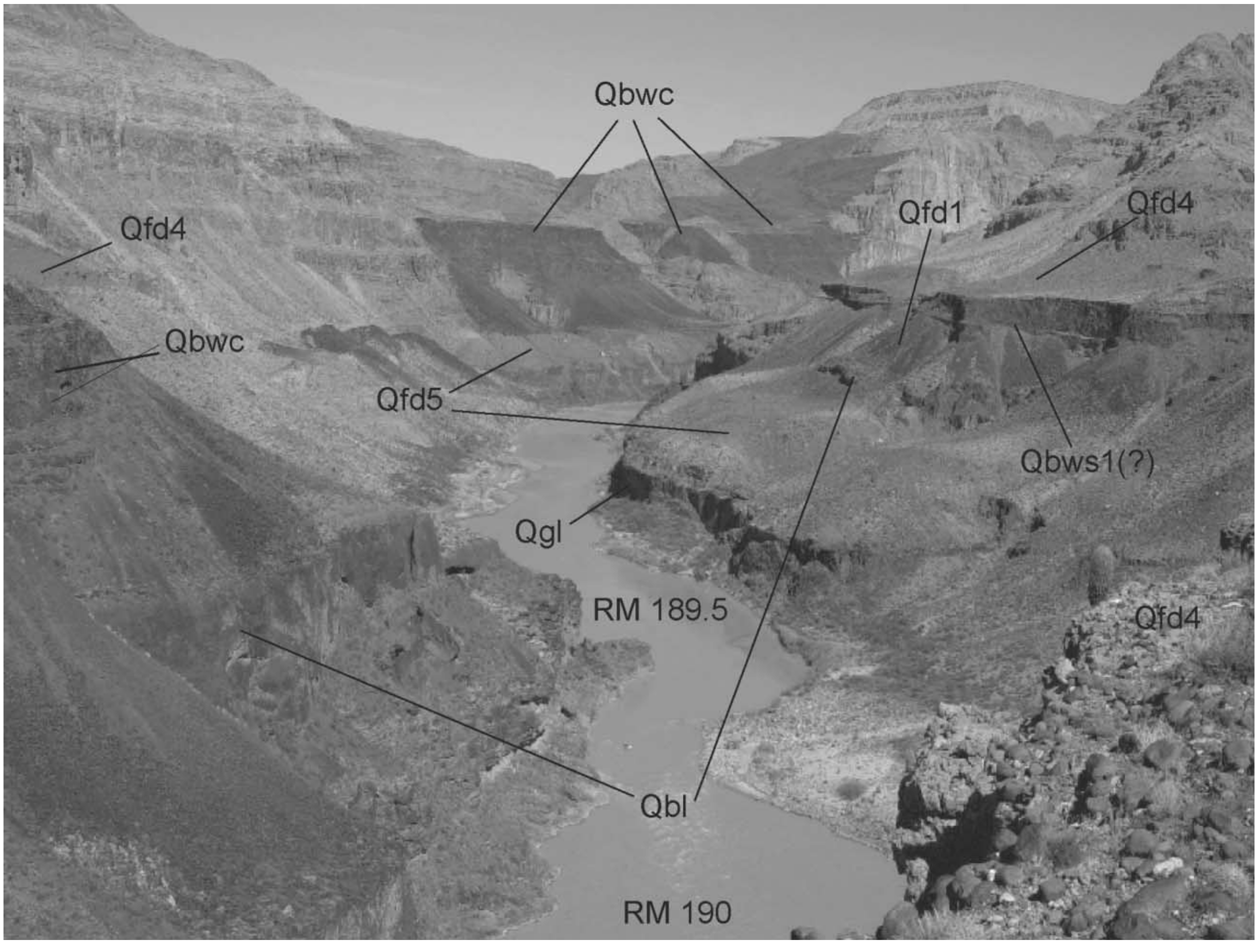


Figure 6. Upstream view of the Colorado River between RM 188 and 190 from 200 m above the river. Qfd5, Qfd4, and Qfd1 outburst-flood deposits are shown in this view. *Qbwc*, *Qbl*, and *Qgl* = Whitmore Cascade, Black Ledge, and Gray Ledge lava flows. The Qbws1 (?) flow may be equivalent to the Qbws1 Whitmore Sink lava flow.

sometimes indistinguishable REE values (fig. 12) and are correlated and distinguished on the basis of field evidence, $^{3}He_{c}$ exposure ages, and REE data.

Vulcans Footrest. A flow that erupted from the Vulcans Footrest cinder cone (fig. 1) and an unnamed basalt flow north of Vulcans Throne have near-identical REE patterns (fig. 12) and indistinguishable $^{3}He_{c}$ ages of 208 ± 14 and 220 ± 20 ka, respectively (table 1). It is likely that the Vulcans Footrest vent erupted at approximately 200 ka and lava flowed east and south down the drainage at the mouth of Toroweap Valley. Over time, the basalt flow was subsequently displaced 14 m by the Toroweap fault (Fenton et al. 2001). The upthrown lava flow blocked the drainage and allowed the accumulation of lake sediments west of the fault (Jackson 1990), thus making the upthrown and downthrown sections of the basalt flow appear separate and unrelated. On the basis of their proximity to one another, the similarities in their REE signatures (fig. 12), and their near-identical $^{3}He_{c}$ ages, the unnamed basalt flow north of Vulcans Throne and the basalt flow preserved near the Vulcans Footrest cinder cone are correlated here as the Vulcans Footrest basalt flow. It has not been determined whether the lava flow formed a lava dam.

Upper Prospect Toroweap Valley Fill Lava Flows. The Upper Prospect flow lies on the south rim in Prospect Valley (fig. 1). Fenton et al. (2001) report an average $^{3}He_{c}$ age for this flow of 395 ± 35 ka on the basis of the exposure ages of seven samples. Pederson et al. (2002) report an average age for the same flow of 509 ± 27 ka on the basis of five $^{39}Ar/^{40}Ar$ determinations for the Upper Prospect flow. Dalrymple and Hamblin (1998) also report a K-Ar age of 500 ± 47 ka for this basalt. Seven $^{3}He_{c}$ ages for the Upper Prospect flow range from 356 ± 18 to 450 ± 22 ka (Fenton et al. 2001). The

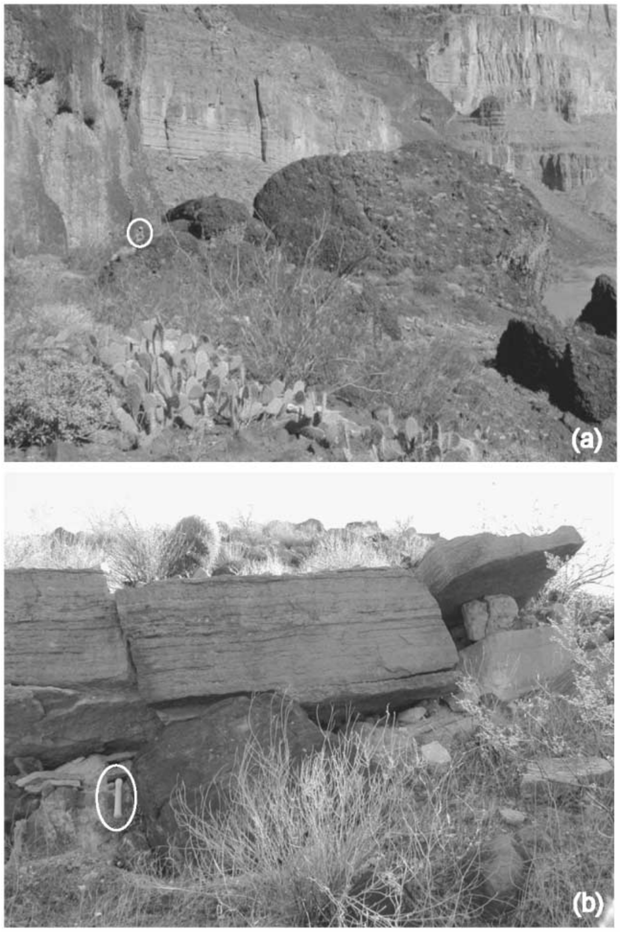


Figure 7. *a*, Photograph of megaboulders preserved in a Qfd5 deposit at RM 188.4R. The white circle on the left side of the picture indicates a person for scale. *b*, Imbricated limestone blocks preserved in a Qfd4 deposit at RM 194. A hammer is circled in white for scale.

average ^3He_c and $^{39}Ar/^{40}Ar$ ages are inconsistent, but the average ^3He_c and K-Ar ages overlap within 2 SDs. The ^3He_c age may be younger because of erosion of the Upper Prospect flow surface (Fenton et al. 2001). The surface of this flow is covered with a well-developed desert pavement with well-developed desert varnish; there are no primary flow surfaces. The Upper Prospect flow overlies the Lower Prospect flow, which is massive and has $^{39}Ar/^{40}Ar$ ages of 600 ± 60 and 630 ± 70 ka (McIntosh et al. 2002) and a K-Ar age of 1.8 ± 0.3 Ma (Dalrymple and Hamblin 1998). A thin layer of baked alluvium separates the Upper and Lower Prospect flows. This likely indicates that the Upper Prospect lava flow was not part of Hamblin's (1994) Prospect Dam, which has $^{39}Ar/^{40}Ar$ ages of 600 ± 60 and 630 ± 70 ka, on the basis of the hypothesis that stable lava dams lasted no more than 20 ka (Dalrymple and Hamblin 1998).

The Toroweap Valley Fill lava (*TVF*, fig. 1) is a subhorizontal basalt flow preserved at the mouth of the modern Toroweap Valley drainage east of Vulcans Throne. The flow yielded two ^3He_c ages of 127 ± 9 and 123 ± 9 ka and is stratigraphically older than Vulcans Throne, whose ^3He_c age is 75 ka (Fenton et al. 2001). The ^3He_c ages of the Toroweap Valley Fill lava may be minima, possibly affected by erosion of the flow surface. The flow appears to be stratigraphically lower than the Vulcans Footrest lava flow (210 ka). There are no primary flow surfaces on the Toroweap Valley Fill lava; it is covered in a well-developed desert varnish. The Younger Cascade (108 ± 11 ka) and Whitmore Cascade (180 ± 6 ka) both have abundant primary flow expressions such as pahoehoe features, pressure blisters, and tumuli (Fenton et al. 2002). Flows older than ~200 ka appear to lose their primary flow features and are covered by desert pavement. This suggests the Toroweap Valley Fill could be older than 200 ka.

The Upper Prospect and Toroweap Valley Fill lava flows have similar REE concentrations (fig. 12) but distinctly different exposure ages, and they are

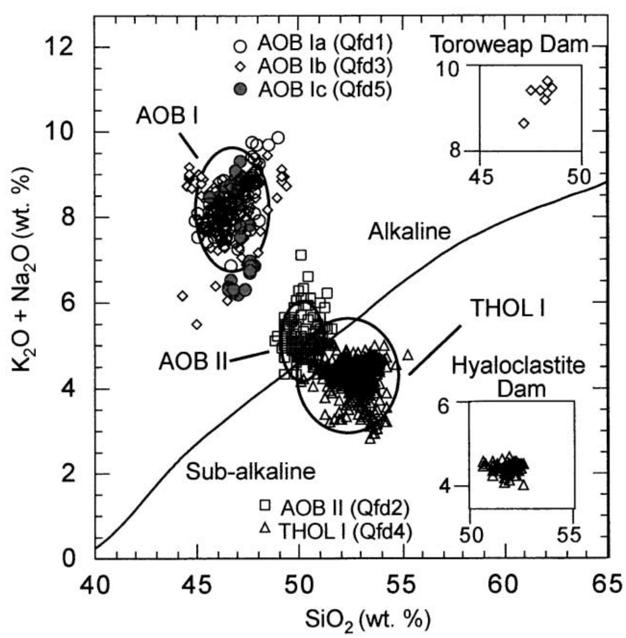


Figure 8. Total alkali and silica content of basalt glasses collected from lava-dam outburst-flood deposits and from the Hyaloclastite and Toroweap Dams (*insets*). Basalt glasses are either alkaline or subalkaline (after Irvine and Baragar 1971). Ovals represent average and 2σ values for each group.

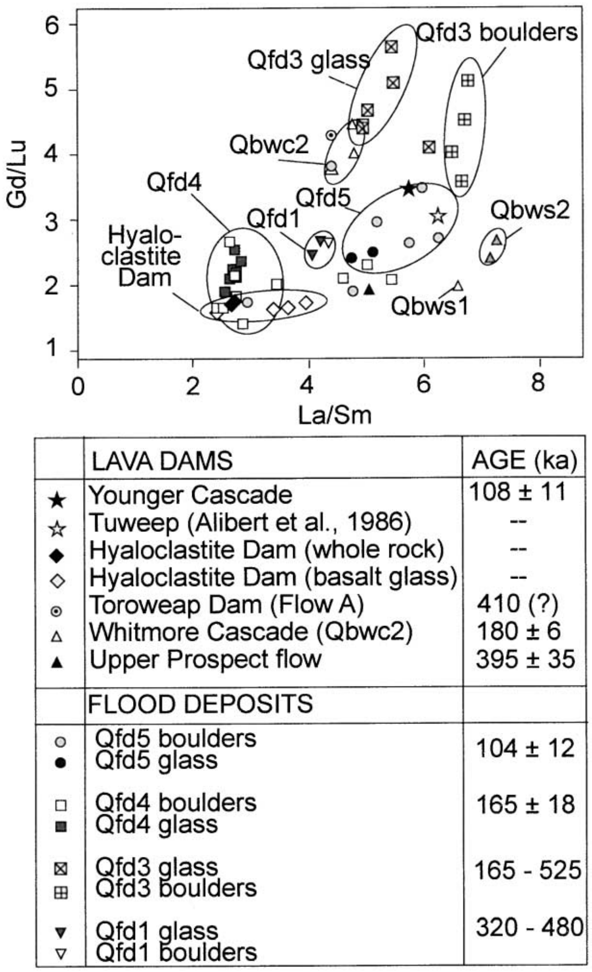


Figure 9. Chondrite-normalized La/Sm and Gd/Lu ratios of vitroclasts and whole rock basalts collected from lava flows, lava dams, and outburst-flood deposits.

on the south and north rims of the Colorado River. It is unlikely they are related. The tops of the Upper Prospect and Toroweap Valley Fill flows are at 1160- and 1280-m elevation, respectively, and both flows are on the upthrown block of the Toroweap fault. It has not been determined whether or not these lava flows created separate dams on the Colorado River. If the river was in its present-day position, the Prospect Dam could have been up to 650 m high. Likewise, a dam formed by the Toroweap Valley Fill lava flow could have been 770 m high.

Toroweap Dam and Toroweap Terrace. The base of the Toroweap Dam (flow A; K-Ar = 1.16 ± 18 Ma) is approximately 30 m above current river level, which is at 510-m elevation. The dam has 44.5 m of displacement on the Toroweap fault. Using a linear displacement rate of 110 m/Ma (Fenton et al. 2001), we find that the dam has an age estimate of 410 ka. The Upper Prospect flow and Toroweap Dam (flow A) have overlapping ages, using this estimate; both alkali olivine basalts are not related on the basis of field evidence and different REE patterns (figs. 10, 12), and REE patterns of whole rock basalt from these lavas are not parallel. If the Upper Prospect flow created a lava dam, then the dam was removed, and the river level had reached an elevation of ~540 m by the time the Toroweap Dam was emplaced.

Toroweap Terrace is a lava flow that caps a sequence of basaltic volcaniclasts and lava fill in a tributary drainage that incised through Toroweap Dam flows A, B, and C (Hamblin 1994, p. 50). ^3He_c ages for Toroweap Terrace range from 61 to 193 ka (app. C) and are affected by erosion; we use an average ^3He_c age of 144 ± 29 ka, but this is a minimum age. The average incorporates younger exposure ages of eroded surfaces. The surface of Toroweap Terrace is subhorizontal, has essentially no primary flow features, and is covered with a desert pavement. The Toroweap Terrace, Toroweap

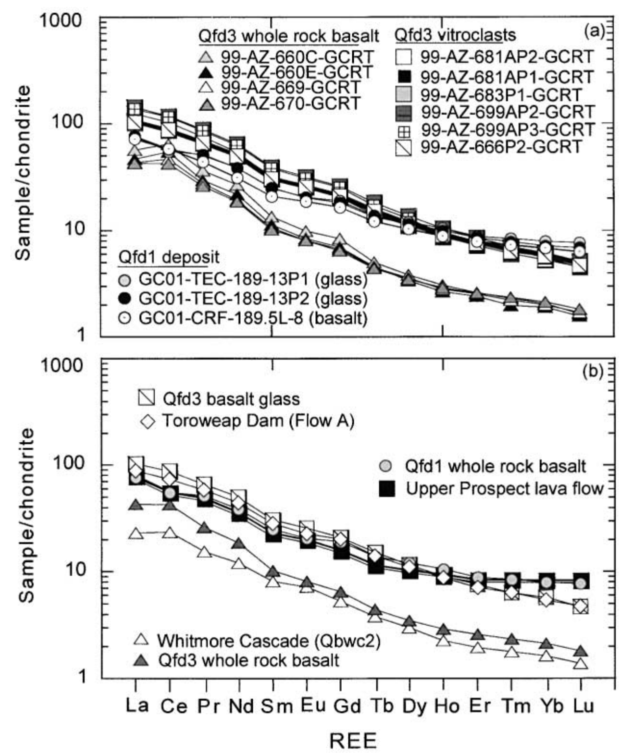
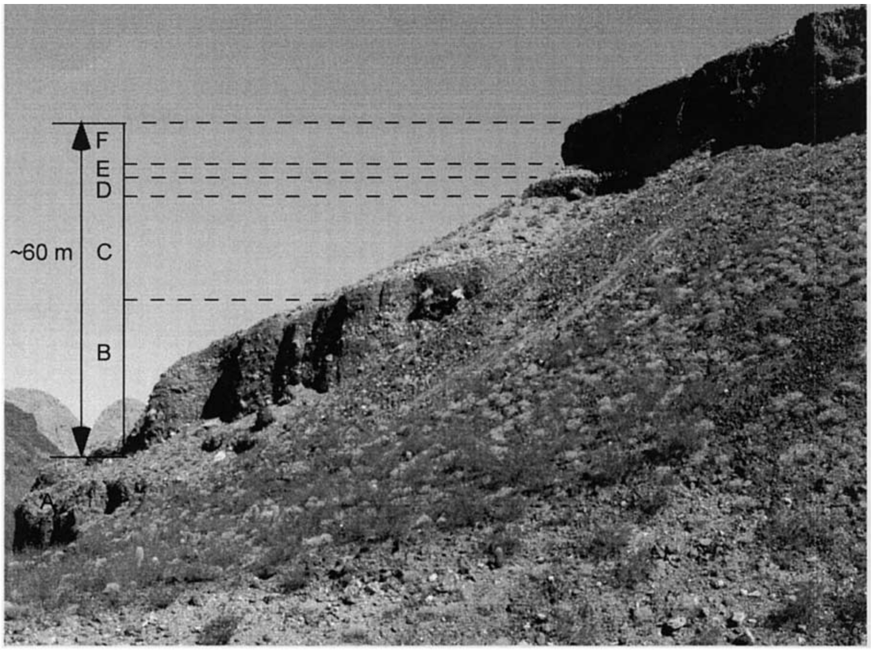


Figure 10. *a*, Chondrite-normalized REE patterns of Qfd1 and Qfd3 outburst-flood deposits. *b*, Representative chondrite-normalized REE patterns of whole rock basalt collected from Toroweap Dam (flow A), Upper Prospect lava flow, and the Whitmore Cascade and clasts from Qfd1 and Qfd3 outburst-flood deposits.



F - - 4 - 6 m of massive basalt flow (Qbws1(?)); 2 m of brecciated basalt at flow base.

E - - 2 m local talus; dominated by angular, clast-supported Muav limestone boulders.

D - - 2 m well-sorted conglomerate of imbricated basalt cobbles.

C 20 m bedded ash and lapilli volcaniclastic conglomerate containing gray angular pebbles and basalt boulders.

B - - 29 m very poorly-sorted, matrix-supported debris flow composed of abundant pillows of basalt with ~1 m b-axis diameters, shattered pillows, and shattered pillow groundmass. Cobble-sized angular vitroclasts, subangular to subrounded basalt boulders, and imbricated angular limestone boulders/blocks (up to 6 m b-axis) are also present. Base of unit contains numerous pillows, one of which formed around a limestone cobble (8 cm b-axis).

A - - Basalt flow mapped as Black Ledge flow. Elevation of top of flow is 110 m above current river level.

Figure 11. Qfd1 lava-dam outburst-flood deposit at RM 189.5L

Dam (flow A), and Younger Cascade have similar REE values (fig. 8) and may have had a common magma source, but the Younger Cascade lava flowed to the west of the Toroweap Terrace and is not related to the Toroweap Dam complex.

Younger Cascades Lava Flow. The Younger Cascade (^3He_c = 108 ± 11 ka; fig. 1) is separated from the Toroweap Dam by approximately 700 m of basalt flows comprising Hamblin's (1994) Toroweap Valley Fill. Our La/Sm and Gd/Lu values of whole rock basalt collected from the Younger Cascade are similar to those reported by Alibert et al. (1986) for the same lava flow (fig. 6). A lava-dam remnant near river level at RM 181R, previously mapped as an Esplanade dam remnant (Hamblin 1994), has a K-Ar age of 110 ± 53 ka (Dalrymple and Hamblin 1998). On the basis of field evidence and ^3He_c ages, we assign this remnant as part of the Younger Cascade. The Younger Cascade lavas flowed into the inner gorge and undoubtedly reached the river. The top of the Cascade terminates abruptly 180 m above current river level on a cliff created by remnants of the Toroweap Dam (Hamblin 1994). A dam created by the Cascade could have been up to 180 m high.

Correlation of Lava Dams with Outburst-Flood Deposits

Qfd1 Outburst-Flood Deposit and the Upper Prospect Lava Flow. On the basis of age and REE patterns, a dam formed by the Upper Prospect lava flow could have failed and produced the Qfd1 outburst-flood deposit at 400–500 ka (table 1; figs. 9, 10, 13). The Qfd1 age is between 315 and 480 ka. The Toroweap Dam (flow A) has an age of 410 ka, which

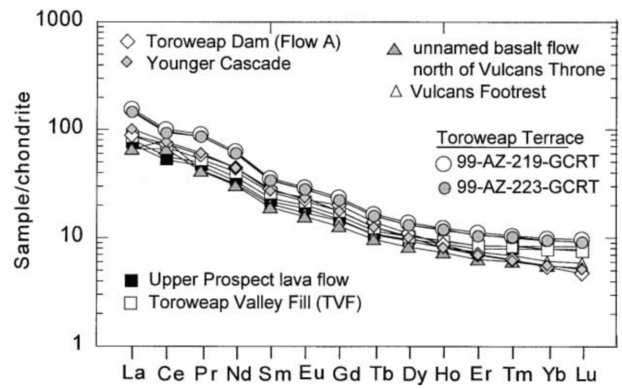


Figure 12. Chondrite-normalized REE patterns of whole rock basalt collected from basalt flows and lava dams in Toroweap and Prospect Valleys.

is within the stratigraphic age constraints of the Qfd1 deposit; however, the REE patterns of the Toroweap Dam and the Qfd1 boulders are not parallel, and the dam and deposit are not likely to be chemically related (fig. 10). On failure, the river may have been flowing on top of the Black Ledge flow (511 ± 63 ka; ~60 m above current river level), but the channel may have been within 36 m above current river level on the basis of the elevation of the base of the Black Ledge flow.

Qfd2 Outburst-Flood Deposit. We have not analyzed Qfd2 deposits for REE content, and the major-element concentrations of basalt glasses cannot be used alone to suggest a correlation with a lava dam. Thus, we have not yet identified the lava dam that failed and produced this flood deposit. On the basis of chemical signatures of basalt glasses and stratigraphy, we conclude that Qfd2 deposits between RM 185.7 and 195.2 were emplaced during a catastrophic lava-dam failure that occurred at 180–210 ka. At the time of the Qfd2 flood, the river channel was within 20 m of current river level, on the basis of the lowest Qfd2 exposure at RM 193.2L (app. D).

Qfd3 Outburst-Flood Deposits, the Toroweap Dam, and the Whitmore Cascade. Qfd3 deposits were emplaced at 155–525 ka and are preserved between RM 203 and 214. Stage III and V soil carbonates (100–250 ka and ~525 ka, respectively) are developed in locally derived limestone talus overlying parts of Qfd3 flood deposits between RM 207.3L and 208.7R (Lucchitta et al. 2000). All $^{3}He_{c}$ ages of these deposits are minima and <155 ka. REE data indicate that the vitroclasts and whole rock basalt in Qfd3 deposits are not chemically related. The presence of extralocal river gravels and quartz sands in the lower part of the deposits suggests that there may be two separate floods preserved and mapped as one depositional unit. The extralocal gravels indicate a time break and a free-flowing Colorado River at that elevation between 165 and 525 ka. Toroweap Dam (flow A; age estimate = 410 ka) has La/Sm and Gd/Lu ratios that are similar to those of Qfd3 basalt glasses (table 2; figs. 9, 10). In addition, average total alkali and SiO_2 concentrations measured in a pillow basalt at the base of the Toroweap Dam and in Qfd3 glasses overlap within 2 SDs.

The Whitmore Cascade ($^{3}He_{c}$ = 180 ka) also has La/Sm and Gd/Lu ratios that are similar to those of Qfd3 basalt glasses (table 2; fig. 8); however, a representative REE pattern of the Whitmore Cascade more closely parallels that of a representative Qfd3 boulder REE pattern than it does that of Qfd3 glasses (fig. 10*b*). Of the existing REE in this study, the Whitmore Cascade data most closely mimic that of the Qfd3 boulders and cobbles; however, we cannot state conclusively that the Whitmore Cascade is definitely related to the Qfd3 clasts. Other alkalic lavas in the age range of Qfd3 deposits ($^{3}He_{c}$ = 165 to $^{39}Ar/^{40}Ar$ = 525 ka) do not reproduce REE patterns or La/Sm and Gd/Lu values

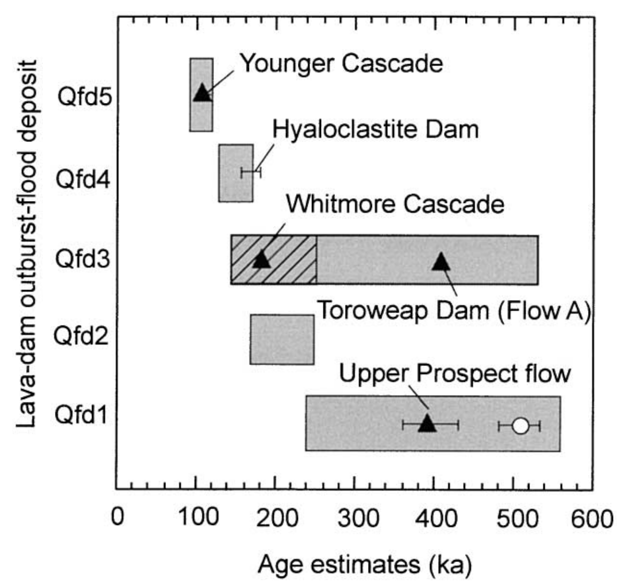


Figure 13. Age estimates of lava-dam outburst-flood deposits (*rectangles*) and related lava dams (*triangle with bar*). Estimates include standard deviations in $^{3}He_{c}$ and $^{39}Ar/^{40}Ar$ ages. The striped box in the Qfd3 age range represents the range in age of stage III soil carbonate. The age estimate of the Hyaloclastite Dam (150–180 ka) is represented by a bar; there is no absolute age for this dam. The white circle represents the $^{39}Ar/^{40}Ar$ age of the Upper Prospect lava flow.

yielded by either the Qfd3 boulders or basalt glasses (figs. 9, 10).

Failure of the Toroweap Dam may have emplaced an outburst-flood deposit that was mostly removed later by a free-flowing Colorado River. The only remaining evidence of such a failure exists in the preservation of Qfd3 basalt glasses and the presence of extralocal gravels. Failure of a lava dam created by the Whitmore Cascade may have reworked some of the previously deposited Qfd3 vitroclasts into the younger flood waters and deposited boulders and cobbles representative of the Whitmore Cascade on top of the Qfd3 glasses. This hypothesis is consistent with chemical signatures of the lavas and the deposits as well as the age estimates of stage III and V soil carbonate development within talus capping the deposits. Qfd3 deposits occur in an area where elevations of several outburst-flood deposits converge (fig. 4). It is also possible that one flood tapped separate basalt-clast sources along route. Detailed mapping and more extensive chemical characterization of Qfd3 deposits are needed to accurately establish whether two separate events are preserved.

The base of the Toroweap Dam is 30 m above current river level, and the base of the Massive Diabase, which could be as young as 140 ka, is 7 m above current river level and below the current water surface of the Colorado River. These elevations indicate the approximate position of the Colorado River bed about the time the Toroweap and Whitmore Cascade dams would have existed. Thus, the Toroweap and Whitmore Cascade Dams could have been 424 and 270 m high, respectively, on the basis of elevations of their outcrops near dam sites.

Qfd4 Outburst-Flood Deposit and the Hyaloclastite Dam. La/Sm and Gd/Lu ratios of whole rock basalt and major-element analyses of basalt glasses from the Hyaloclastite Dam and Qfd4 deposits are very similar and suggest that this tholeiitic lava dam failed and produced the Qfd4 deposits (figs. 1, 4, 6, 13; table 2). These basalts are the only tholeiitic basalts yet found in western Grand Canyon. The base of the Hyaloclastite Dam is composed of 20 m of brecciated basalt, hyaloclastite ash and lapilli, and shattered pillow basalts. Such structures would have provided fractures and conduits for piping of reservoir waters through the dam. These features and the preservation of the dam in a slump block are consistent with the hypothesis that this dam was unstable. The Colorado River was a maximum of 20 m above current river level at the time of the Qfd4 flood. This is based on the lowest exposure (17 m above current river level) of a 110-m-thick Qfd4 deposit that fills a paleochannel of the Colorado River at RM 194L.

Hamblin (1994) believes the Whitmore Dam complex was being constructed as the Colorado River was pushed toward the east wall of the canyon (fig. 1; RM 188–190), depositing river gravels (Qfd1, Qfd2, and Qfd4, this study) that were capped by or overlie Whitmore lava flows. He found no river gravels on the west side of the river within the Whitmore complex, but we have mapped Qfd2 and Qfd4 deposits at RM 189.8R (fig. 1). La/Sm and Gd/Lu ratios of tholeiitic Qfd4 basalt boulders are significantly different from those of the Whitmore Cascade (Qbwc2) and Whitmore Sink (Qbws1 and Qbws2) basalts (fig. 10). Qfd4 gravels are not related to lava dams constructed by the Whitmore Cascade or Whitmore Sink lavas, nor are they equivalent to Qfd1 or Qfd2 outburst-flood deposits found in the same area. Hamblin (1994) inferred that the Qfd4 gravels are remnants of the Colorado River bed preserved as construction of the Whitmore Dam pushed the river to the east. If such were the case, we would expect chemical signatures of the boulders in the deposit to match the composition of lavas coming from Whitmore Canyon.

Qfd5 Outburst-Flood Deposits and the Younger Cascade. The strong similarities between the geochemical signatures (fig. 10) and ^3He_c ages of the Qfd5 flood deposit (104 ± 12 ka) and the Younger Cascade lava flow (108 ± 11 ka) strongly suggest they are related (fig. 13). Although there are no preserved remnants of a dam constructed by the Younger Cascade (Hamblin 1994), the cascade reached the river, on the basis of an outcrop of Hamblin's (1994, p. 71) Esplanade lava cascade at RM 181R that we have correlated with the Younger Cascade. The lack of dam remnants may represent postflood erosion, or it could support the hypothesis of lava-dam instability. The age of the Qfd5 flood deposit also overlaps the ^3He_c age of the Esplanade lava cascade (Qbe1) at RM 182, although this is a minimum age. More accurate age constraints and REE analyses of the Qbe1 cascade are necessary to rule out the possibility of a correlation between the Qbe1 and Qfd5 landforms. The bases of the deposits are approximately 45 m above current river level; however, Qfd3 glasses were collected 33 m above current river level in an exposure in Whitmore Canyon, indicating that the Colorado River bed was at least within 33 m of its current elevation. Also, the Gray Ledge dam remnants indicate incision depths of 7 m above current river level at approximately 100 ka (table 1); Qfd5 deposits overlie the Gray Ledge remnants.

Conclusions

The Uinkaret Volcanic Field had great influence on the Colorado River during the Pleistocene epoch. Eruption of lava flows resulted in the damming of the Colorado River at least 13 times, and the failure of at least five of those dams resulted in cataclysmic floods whose records are preserved in deposits perched high (up to 200 m) above the Colorado River. The elevation of the Colorado River bed fluctuated during construction and destruction of lava dams but likely remained within 40 m of current river level at 100–600 ka.

Geochemical analyses of lava flows, lava dams, and outburst-flood deposits, combined with ^3He_c dates, have greatly improved our ability to map the extent of Quaternary basalt flows, lava-dam remnants, and lava-dam outburst-flood deposits in western Grand Canyon. With these geochemical data, we are able to distinguish individual volcanic events that were otherwise mapped collectively, and we gain insight to the fluctuations of the Colorado River bed during that period of time. The ability to distinguish such events increases our understanding of the timing of construction and destruction of Pleistocene lava dams in western Grand Canyon. This information can be used in future studies to hydraulically model the catastrophic failure of each lava dam and to determine the magnitude of these large-scale outburst floods.

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