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A new model for Quaternary lava dams in Grand Canyon based on ^{40}Ar/^{39}Ar dating, basalt geochemistry, and field mapping

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ABSTRACT

The geomorphic response to volcanic incursions is spectacularly documented in western Grand Canyon, where numerous Quaternary lava flows dammed the Colorado River. This paper uses new ^{40}Ar/^{39}Ar ages, geochemistry, paleomagnetism, and field relationships to suggest 17 damming events, requiring major revision to previously published intracanyon flow sequences. From ca. 850 to 400 ka and at ca. 320 ka, numerous lava dams formed near the modern-day Lava Falls area. Starting around 250 ka, major volcanism shifted to the Whitmore Wash area, where additional dams formed. From ca. 200 to 100 ka, cascades flowed over the north rim in areas between Lava Falls and Whitmore Wash to form the youngest set of lava dams.

Field observations and new dam reconstructions require a new model for how the Colorado River interacted with ephemeral lava dams in Grand Canyon. Specifically, the structure of lava dams, the position, character, and provenance of basaltic gravels within and above dams, and cooling structures in intracanyon flows suggest that unstable upstream dam portions failed quickly, while stable downstream dam segments were dismantled by the Colorado River more slowly. Time scales of dam removal are hard to assess, but we infer that lava dams that are overlain by monomictic basalt gravels were removed by the river in tens of years to centuries. In contrast, dams overlain by far-traveled gravel may have persisted for millennia.

INTRODUCTION

The geomorphic response to volcanic incursions into major fluvial systems remains incompletely understood. Landslide dams, glacier-ice dams, and moraine dams have been the focus of a large number of studies due to the hazards associated with these relatively common "extrafluvial" events (e.g., Costa and Schuster, 1988). Fewer studies have focused on the geomorphic effects of lava dams, especially in large river systems (Howard et al., 1982; Malde, 1982; Hamblin, 1994; Fenton et al., 2002; Huscroft et al., 2004; Fenton et al., 2006; Ely et al., 2012 and references therein). The controls on the response to these unique channel blockages are poorly understood due to: (1) relatively few modern analogs and (2) poor preservation in the geologic record, as they often form in erosional environments. Characterization of the original state of dams is important because dam structure, erodibility, and size are expected to affect the processes and time scales of lava dam removal along with landscape morphology, the hydrology of the affected river system, and the local geology (e.g., van Gorp et al., 2014). These factors in turn control the river's ability to reestablish its previous profile and potentially have long-lasting effects on bedrock incision rates, sediment transport, and hillslope morphology.

To better understand these interactions between volcanic and fluvial processes, we focus on western Grand Canyon, which was partially filled by numerous basalt flows. Ever since John Wesley Powell's famous trip down the Colorado River in 1869, western Grand Canyon has been regarded as one of the best exposed and most iconic lava dam localities. However, despite almost 150 years of study, there is still no consensus as to the longevity of Grand Canyon's lava dams, the processes by which they failed, or the effect on the Colorado River system. The dominant models suggest slow removal over tens of thousands of years (Hamblin, 1994) or catastrophic failure within a few years of formation (Fenton et al., 2002; Fenton et al., 2004; Fenton et al., 2006). Much of the uncertainty in the dam removal mechanism comes from the fact that very little is known about the source, age, structure, and extent of individual dams. Very little remains of each dam and multiple dams have left multiple generations of erosional remnants that cannot be easily correlated. Although Hamblin (1994) described 13 named dams based on field appearance, subsequent ^{40}Ar/^{39}Ar dating (Karlstrom et al., 2007) and dam reconstruction using light detection and ranging (LiDAR) (Crow et al., 2008) have shown that many remnants were miscorrelated between key outcrops where inset relationships were noted, resulting in an incorrect sequence of dams and erroneous dam reconstructions. Miscorrelations are, perhaps, to be expected as Hamblin did not have the benefit of reliable geochronology (Dalrymple and Hamblin, 1998) or flow geochemistry.

This study provides the most comprehensive correlation, to date, of these remnants using ^{40}Ar/^{39}Ar geochronology, inset and stratigraphic relationships, LiDAR-derived flow heights, paleomagnetism, and whole-rock geochemistry, with the goal of reconstructing the source, timing, extent, and structure of the intracanyon flows. We examine the extent to which intracanyon lava

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flows formed lava dams, which we define as volcanic river blockages that impounded river water in a lake above the normal pool-riffle, pre–dam-river profile. We also describe internal cooling structures, the apparent dearth of lake deposits, and the presence and nature of gravels within and above flows to evaluate the extent to which dams formed. We compare and contrast lava dams around the world to Grand Canyon's dams to better understand the spectrum of lava dam types, their longevities, the processes of their removal, and their effects on local geomorphology. Thus, beyond reconstructing the Grand Canyon's lava dam history from the fragmentary evidence, our goal is to discern lava-river interaction processes that are of general applicability to other regions.

BACKGROUND, PREVIOUS WORK, AND CONTINUING DEBATES

All of the intracanyon basalt flows in Grand Canyon were sourced from the Uinkaret volcanic field, which is centered between the Toroweap and Hurricane faults mostly north of western Grand Canyon, in northwestern Arizona (Fig. 1). Lava cascades, "plastered" to the canyon walls, record where basalt flows poured into Grand Canyon, mostly from the north rim. Intrusive features including dikes, sills, and plugs are also found deep in Grand Canyon recording the plumbing of volcanoes once centered within Grand Canyon and in some cases directly within the channel of the Colorado River (Hamblin, 1994; Crow et al., 2008). Also found in the canyon are reworked and partially

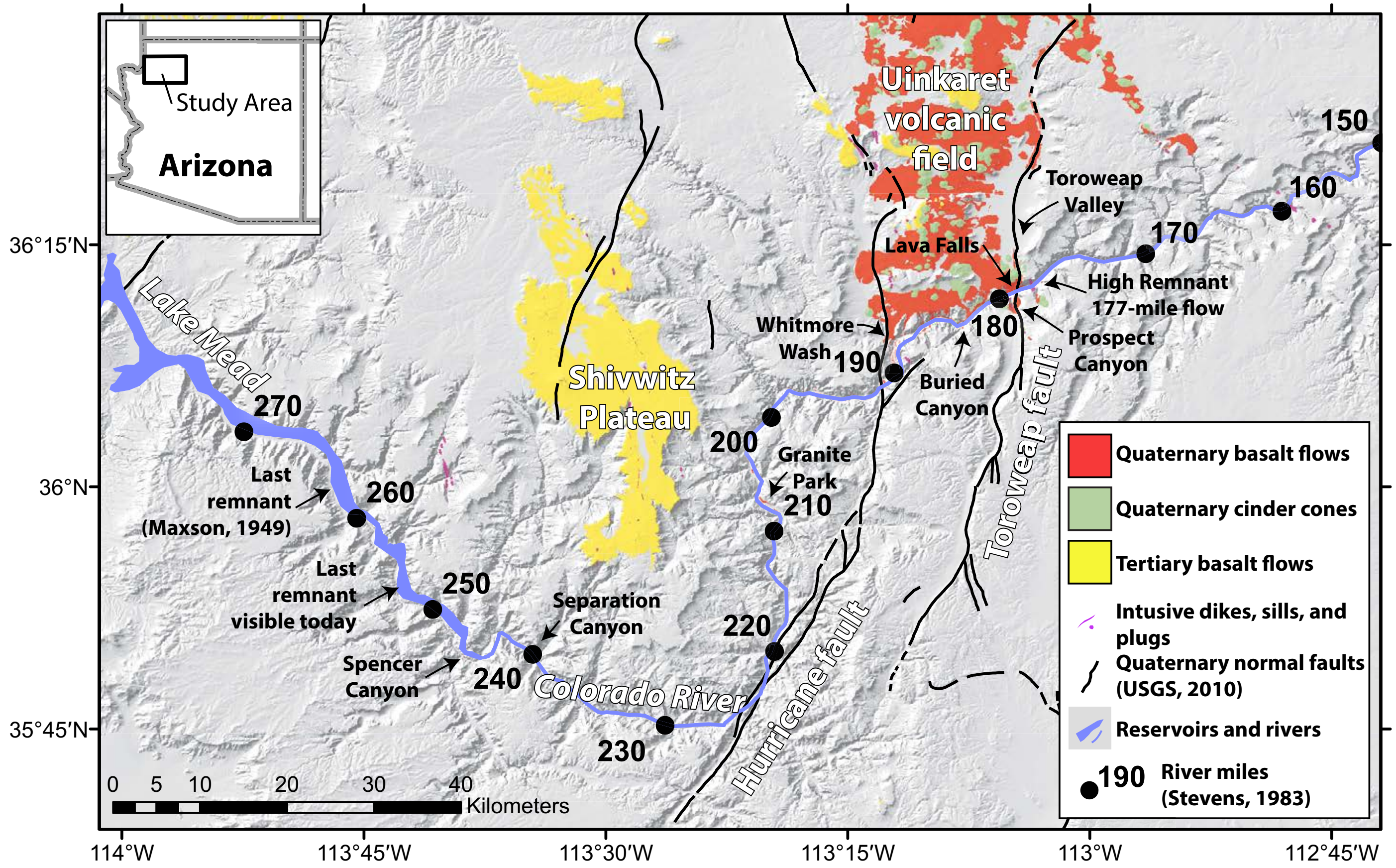


Figure 1. Simplified geologic map of the study area (after Billingsley, 2000; Billingsley and Wellmeyer, 2003; Billingsley et al., 2006) showing the distribution of Tertiary and Quaternary basaltic volcanism. Quaternary normal faults from U.S. Geological Survey and Arizona Geological Survey (2010).

dissected pyroclastic and hydroclastic deposits (Hamblin, 1994). Regardless of whether an eruption was located on the rim and cascaded into Grand Canyon or was erupted directly into the canyon, lava flows pooled at the canyon bottom during each flow event, and flowed upstream a few kilometers and downstream over 135 km, in the case of the longest intracanyon flow. These flows were partially removed prior to the next intracanyon flow, leaving a patchwork of isolated remnants, with infrequent inset relationships.

Despite extensive work using dated basalts for river incision and fault slip studies (Pederson et al., 2002; Karlstrom et al., 2007; Karlstrom et al., 2008), and early efforts to correlate remnants based on LiDAR-derived flow heights (Crow et al., 2008) and flow appearance (Hamblin, 1994), the extent and structure of most dams are not well understood. The variable height of flow bottoms above the modern river reflects differential bedrock incision due to fault dampening and fault-related folding (Pederson et al., 2002; Karlstrom et al., 2007; Crow et al., 2008; Karlstrom et al., 2008). The heights of flow tops also vary as flows pinched out. Although LiDAR analysis, along with geochronology, was useful in grouping similar-aged intracanyon flows, individual flows and dams could not be identified, especially during relatively short episodes with multiple eruptions, such that new correlations based on additional data were still needed to determine individual flow geometries (Crow et al., 2008).

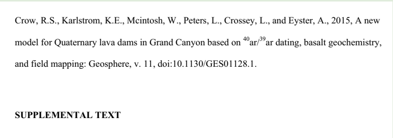
Perhaps because of a difficulty in accurately correlating remnants and reconstructing dams, the longevity and failure mechanisms for Grand Canyon's lava dams have been much debated. Fenton et al. (2002, 2004) identified deposits in western Grand Canyon that they interpreted to be outburst-flood deposits. These are dominantly composed of subangular to rounded basalt boulders and cobbles (82%–98% of the clasts are basaltic) in a matrix of hyaloclastite fragments (Fenton et al., 2002; Fenton et al., 2004) (Figs. 2A and 2B). Downstream from hypothesized dam sites, these deposits decrease in elevation, thickness, and clast size, indicative of catastrophic floods with waning energy (Fenton et al., 2002; Fenton et al., 2004; Fenton et al., 2006). Although these deposits have similar rounding and sorting to Holocene gravels at downstream locations, outcrops close to hypothesized dam failure sites exhibit >45-m-thick cross beds of imbricated 8- to 35-m-diameter limestone blocks and basalt boulders clearly requiring discharges much greater than normally produced by the Colorado River during runoff (Fenton et al., 2004). Although Crow et al. (2008) were skeptical that these deposits were in all cases formed by outburst-flood events, especially at downstream locations, the >45-m-thick cross bedding seen in one location (above the Gray Ledge flow across from Whitmore Canyon; Fig. 2B) provides strong evidence that at least parts of some dams did indeed fail catastrophically. Conversely, channels cut into the top of remnants with exotic Colorado River clasts (Crow et al., 2008) strongly suggest that some dams existed long enough for a "normal" river, carrying far-traveled clasts, to establish itself on top of some dams. This dichotomy suggests that some dams may have been long lived while others were short lived. For example, Hamblin (1994) suggested they lasted ~20,000 years based on a comparison to Niagara Falls, while others may have failed catastrophically before overtopping (<10 years; Fenton et al., 2002; Fenton et al., 2004; Fenton et al., 2006). Or, alternatively, individual dams may have had progressive multi-staged failures, a hypothesis that will be investigated further below.

A lack of verifiable lake deposits in Grand Canyon is puzzling because dams have been universally interpreted by all previous studies. Hamblin (1994) proposed a number of possible lacustrine deposits related to proposed lakes associated with lava dams, but subsequent work has refuted most of the deposits (Kaufman et al., 2002). This dearth of lacustrine deposits has been interpreted to support the short-lived dam model (Kaufman et al., 2002; Fenton et al., 2004) and may indicate that dams were leaky (Crow et al., 2008) or that such deposits have been completely removed by erosion or may yet be found.

A major motivation for this study is to compare Grand Canyon lava dams to those around the world to improve understanding of lava-water interactions. Prehistoric basaltic lava dams on major rivers both larger (e.g., Yukon [Huscroft et al., 2004] and Fraser [Andrews et al., 2012] in Canada) and smaller (e.g., Snake [Malde, 1982], Owyhee [Ely et al., 2012], Boise [Howard et al., 1982], McKenzie [Taylor, 1965], Deschutes [Stearns, 1931; Licciardi et al., 1999], Gediz [van Gorp et al., 2013], and Atenguillo [Righter and Carmichael, 1992]) than the Colorado River in Grand Canyon, offer important corollaries in terms of structure, longevity, geomorphic effect, and failure processes. Modern examples of basalt-dammed rivers include: Lake Mývatn, in Iceland (Ólafsson, 1979), the Laki Fissure eruption in Iceland (Thordarson and Self, 1993), and the Aiyansh dam, in British Columbia (Brown, 1969) among others. Thus better characterization of the source, age, structure, and extent of Grand Canyon's lava dams is an important contribution to the literature on the geomorphic effect of lava dams, particularly in regard to their longevity and modes of removal.

METHODS

Field work included mapping and surveying volcanic features along the river corridor (Supplemental Fig. SF1 in Supplemental File[1]) and sampling of basalt remnants for ^{40}Ar/^{39}Ar dating and geochemical and paleomagnetic analyses. The height of remnants above the modern river level (MRL) was determined using LiDAR data (and paired air photos) and cross-checked with hand-held laser-range finders (Tru Pulse 200). The original thickness of flows was estimated using the following equation: $T_o = H_m + D_m - IR_b{*}t$, where T_o is the reconstructed flow thickness (or the height of the flow top above the paleostrath), H_m is the modern height of the remnant above the river, IR_b is the bedrock incision rate, t is the age of the flow, and D_m is the modern depth to bedrock below the river. Bedrock incision rates (IR_b), calculated using ^{40}Ar/^{39}Ar dating of basalts overlying strath terraces and the height of the paleostrath above the modern strath, vary from 165 to 60 m/Ma throughout the study area (Supplemental Fig. SF2 [see footnote 1]) as a result of primarily fault slip and fault-related flexures (Karlstrom et al., 2007). Because D_m is also used in calculating the bedrock incision rates, the equation can be simplified to: $T_o = H_m - IR_{rl}{*}t$, where IR_{rl} is the incision rate calculated from the paleostrath to the modern river level. The paired graphs in Figure 3 plot the modern elevation of all



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SUPPLEMENTAL TEXT

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[1] Supplemental File. Supplemental text, 8 supplemental figures, and 11 supplemental tables. Supplemental Figures: (1) Preliminary geologic map of volcanic features in western Grand Canyon. (2) Graph showing incision rates variations due to fault offset and fault-related flexures from Karlstrom et al. (2007). These incision rates were used to estimate the original thickness of dam. (3) Step-heated spectra for the newly reported ^{40}Ar/^{39}Ar ages. (4) Reverse isochrons for the newly reported ^{40}Ar/^{39}Ar ages. (5) Rare-earth element (REE) signatures from duplicate analyses from this study (A) and Fenton et al. (2004) and Fenton (2002). (C). B, D, E, and F compare results from this study and Fenton et al. (2004). (6) Equal area plots of paleomagnetic data. (A) Data for remnants of the Lower Black Ledge flow between river mile (RM) 194 and 253. Consistent paleomagnetic directions support the theory that all of these remnants were part of the same flow. (B) Data for Vulcans Anvil and a nearby sill. The consistent paleomagnetic directions of these two samples suggest that Vulcan's Anvil has not rotated significantly. (C) Data from the 183.4-mile remnant. The consistent paleomagnetic directions that are very close to the present-day axial dipole direction (shown in all plots by the black circle) indicate that the 183.4-mile remnant has not rotated significantly. However, it may have slumped down without rotating—see text. (7) (A) Graph showing the reservoir capacity of dams of various heights sited at Lava Falls based on modern topography. (B) Graph showing the time needed to completely fill those reservoirs with sediment assuming the historic sediment accumulation rate measured in Lake Mead from 1935 to 1963 (Ferrari, 2008). (C) Graph showing the time needed to completely fill those reservoirs with water assuming the historic Grand Canyon discharge from 1923 to 1962. (8) Representative demagnetization behavior. On the left, vector component diagrams are plotted, and on the right, the corresponding magnetic intensity (J/J0) is plotted. In the vector component diagrams, the least squares linear fit with decay to the origin is indicated by pale arrows. (A) Graph shows the behavior for core sample A1314-1A; (B) shows the behavior for core sample A1314-7C; and (C) shows the behavior for core sample A1314-8D. Supplemental Tables: (1) ^{40}Ar/^{39}Ar data tables. (2) X-ray fluorescence (XRF) data. (3) Duplicate XRF analyses from the same sample. (4) Duplicate XRF analyses on the same remnant. (5) Inductively coupled plasma mass spectrometer (ICPMS) data. (6) Duplicate ICPMS analyses from the same sample. (7) Duplicate ICPMS analyses from the same remnant. (8) Duplicate ICPMS analyses from Fenton et al. (2004) and Fenton (2002). (9) Individual paleomagnetism core data. (10) Mean paleomagnetism core data. (11) Summary of analytical setup for ^{40}Ar/^{39}Ar dating including blank values and sensitivities for different analyses. Please visit http://dx.doi.org/10.1130/GES01128.S1 or the full-text article on www.gsapubs.org to view the Supplemental File.

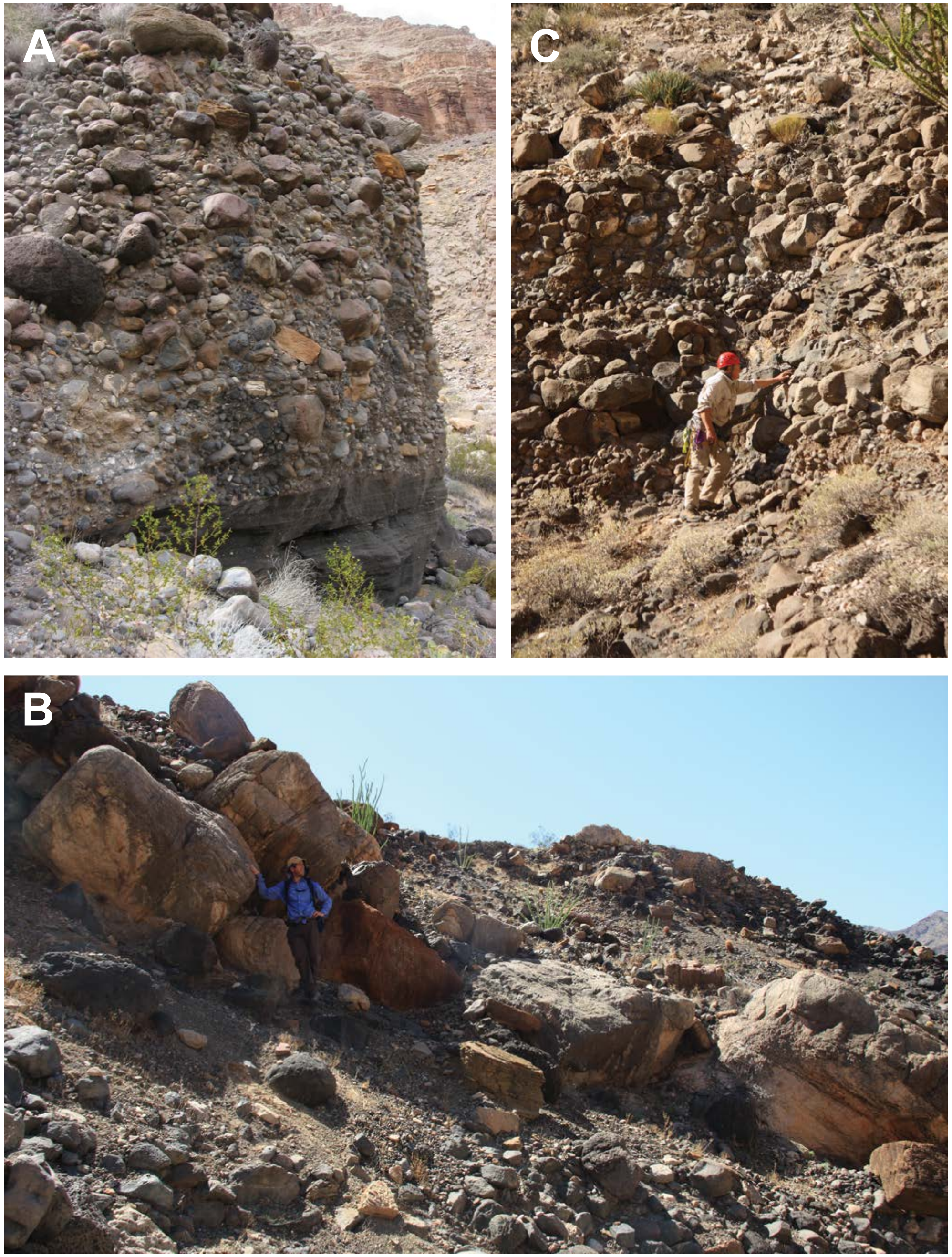

Figure 2. Representative photographs showing the gravels that overlie basalt remnants in Grand Canyon. (A) Well-rounded to subrounded dominantly basaltic gravels interpreted to be outburst-flood deposits by Fenton et al. (2004). This particular outcrop is near river mile 192 and was mapped as Qfd4 by Fenton et al. (2004); it overlies Upper Whitmore flows. (B) Close-up of limestone boulders that make up a 45-m-high cross bed (see Fig. 12B for an overview of the deposit) in a dominantly basaltic outburst-flood deposit (Qfd5 of Fenton et al., 2004), which overlies Upper Gray Ledge deposits near river mile 188. (C) Monomictic basaltic gravels that overlie the Buried Canyon remnant near river mile 183.

known remnants associated with a given flow (the vast majority of which are not underlain by strath terraces) and the reconstructed thickness of the flows.

^{40}Ar/^{39}Ar analyses using the step-heating age-spectrum method were conducted at the New Mexico Geochronology Research Laboratory with a Mass Analyzer 215-50 and/or a Thermo-Fisher Scientific multi-collector ARGUS VI mass spectrometer. Whole-rock geochemical analyses were conducted at the GeoAnalytical Lab at Washington State University with a ThermoARL Advant'XP+ sequential X-ray fluorescence (XRF) spectrometer and an Agilent 4500 inductively coupled plasma mass spectrometer (ICPMS). Paleomagnetic samples were measured using a 2G-755 SQUID superconducting rock magnetometer and underwent step-wise alternating field demagnetization at the Massachusetts Institute of Technology Paleomagnetism Laboratory. See the Supplemental File (see footnote 1) for a detailed description of all analytical methods used.

Remnant correlations were made based on comparison of the position, age, paleomagnetism, and geochemistry of remnants. Although similarities between remnants were helpful to support hypothesized correlations, differences were more informative, especially since multiple flows could have had similar compositions, ages, and/or geometries. Unless otherwise noted, all positive correlations between remnants were made only when all the available data sets suggested such a correlation. ^{40}Ar/^{39}Ar ages were compared at the 95% confidence level, and geochemical data (relying primarily on the less mobile rare-earth elements) were compared qualitatively due to variable quality between different studies and due to geologic uncertainties not reflected in the precision of the analyses.

RESULTS

In this section, we report new geochemical and geochronologic results and use them along with field relationships to define at least 17 individual lava flows (see the Supplemental File [see footnote 1] for paleomagnetism results and methods). Table 1 lists these flows from oldest to youngest and details their thickness, length, age, and the location of all known remnants. The name of the flow is used for descriptive purposes (e.g., Black Ledge flow), and the same name is also used for interpretive discussions of the inferred dam (e.g., Black Ledge Dam). Terminology used here is retained from Hamblin (1994) where possible and refined when necessary (see column 2 of Table 1).

^{40}Ar/^{39}Ar Geochronology

This paper builds on four studies (Lucchitta et al., 2000; Fenton et al., 2004; Raucci, 2004; Karlstrom et al., 2007) that have reported ^{40}Ar/^{39}Ar dates on western Grand Canyon intracanyon basalt flows. Table 2, Supplemental Table SF1 [see footnote 1], and Figure 4 present the aggregate 142 dates, which range from ca. 830 to 80 ka. Of these, 70% are newly reported here, including new ages on 44 previously undated flow remnants. The new plateau ages reported here are weighted-mean ages of the greatest number of heating steps whose apparent ages overlap at 2 sigma and include at least 50% of the released ^{39}Ar (see Table 2 and asterisks in Supplemental Fig. SF3 [see footnote 1] for exceptions). Isochrons generally have atmospheric ^{40}Ar/^{36}Ar intercepts, and isochron ages are almost always statistically indistinguishable from plateau ages (Supplemental Table SF1 and Supplemental Fig. SF4 [see footnote 1]). In the few cases where high ^{40}Ar/^{36}Ar intercept values indicate excess argon and isochrons are well defined, isochron ages are favored over plateau ages (see comments in Table 2).

To investigate the analytical precision and accuracy of the new ages, we performed duplicate analyses on the same sample, dated separate samples from the same remnant, and interpreted all ages in their stratigraphic context. Duplicate analyses reported here and by Karlstrom et al. (2007) have been obtained on 27 different samples. Seventy-two of 87 (83%) duplicate analyses overlap at 2 sigma (see Table 2 for outliers), slightly less than expected for the 95% confidence interval. In addition to duplicate analyses on the same sample, we have also dated multiple samples from four different remnants. All agree, except the 728 ± 31 ka (Karlstrom et al., 2007) age on a Black Ledge remnant near river mile (RM)[2] 246 R[3] that appears to be erroneously old. Redating of a new sample from the same remnant yielded a considerably younger weighted mean age of 574 ± 14 ka. The new younger age is consistent with six separate dates on remnants that have been correlated on the basis of geochemistry and paleomagnetism. It is unclear whether the older 728 ka result is a statistical outlier, the result of an unknown analytical issue, or due to an unknown geologic contaminant. Redating of the original Karlstrom et al. (2007) sample yielded poor results with no reliable age information.

Dating of samples taken in stratigraphic order at seven localities allows for further assessment of the reliability of new ^{40}Ar/^{39}Ar ages. Although most of these ages are consistent with their stratigraphy, at Toroweap (RM 179R) and Upper Prospect (RM 179.6L), ages in the middle of flow stacks are inconsistent with the ages on the bracketing flows. Because of this, we suggest that those ages are outliers that do not accurately reflect the eruption age of the flows.

In summary, new ^{40}Ar/^{39}Ar results are significantly more precise and accurate than previously reported ^{40}K/^{40}Ar ages (e.g., Dalrymple and Hamblin, 1998), which were not reproducible and significantly older, likely due to excess ^{40}Ar. However, a few inconsistent ages that are not reproducible or do not agree with the stratigraphic sequence of samples indicate that, in at least some cases, the reported analytical precision of the new ages does not reflect the accuracy of the ages. Although these anomalous ages may reflect unknown analytical issues or be due to an unknown geologic contaminant (possibly due to interactions with clay-rich river water [Karlstrom et al., 2007]), we suggest that most are more likely statistical outliers that are to be expected in such a large data set. The new ^{40}Ar/^{39}Ar results are the best age constraints available, and we rely on them heavily along with flow geochemistry, paleomagnetism, and field relationships to correlate remnants and establish the timing of flows.

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[2] River miles are measured downstream from Lees Ferry (Stevens, 1983).

[3] R refers to the right side of the river as viewed looking downstream. L refers to the left side.

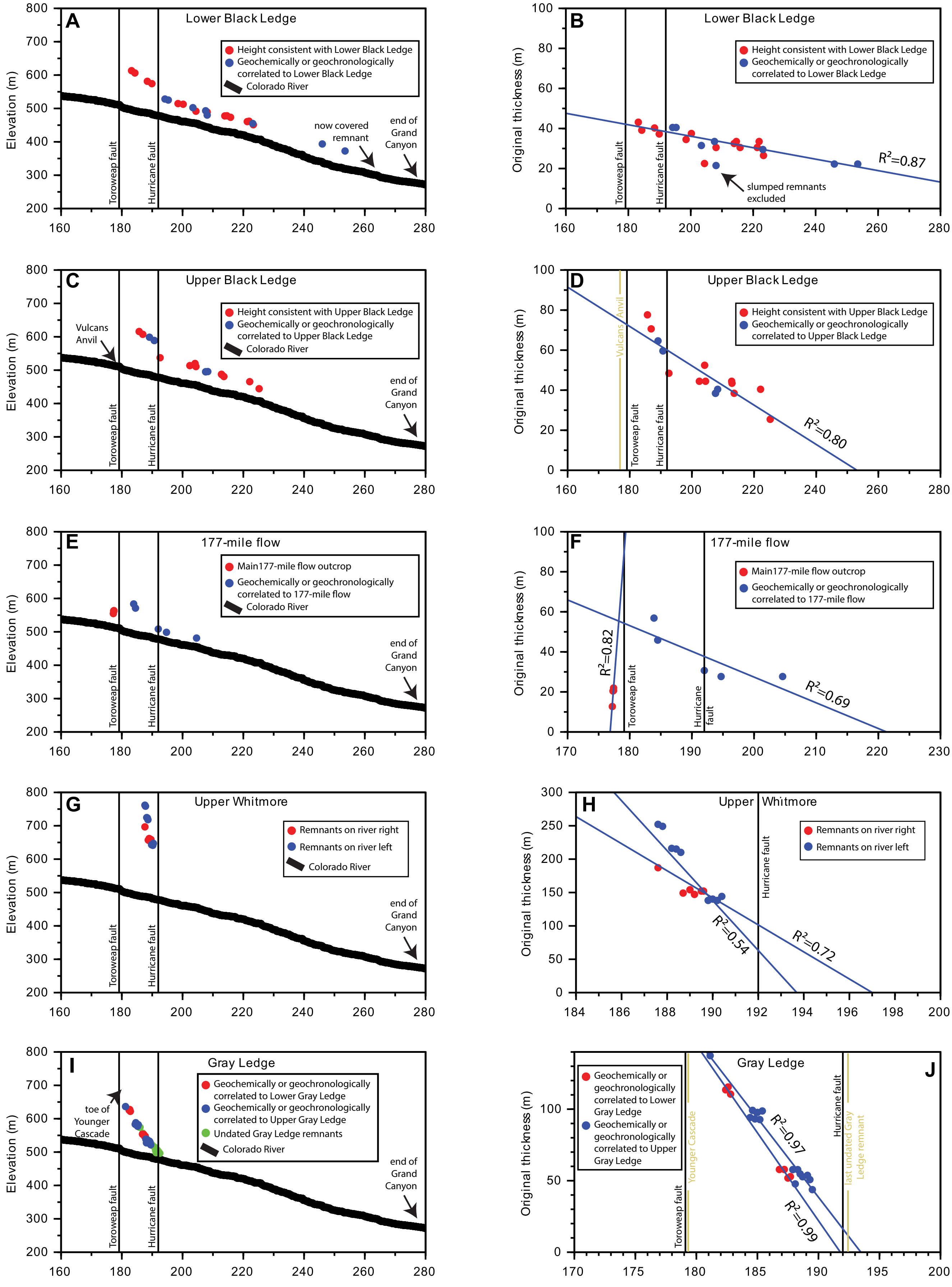

Figure 3. Plots of the elevation of flow tops along their longitudinal length (left-hand side) and plots of the reconstructed dam thickness based on incision rates of Karlstrom et al. (2007) and Pederson et al. (2002) (right-hand side). Note that the scale of the graphs on the right change, and multiple measurements of long remnants are included.

TABLE 1. SUMMARY OF GRAND CANYON'S INTRACANYON LAVA DAMS

	Nomenclature in this study	Hamblin (1994) nomeclature and river mile of geochemically (†) and geochronologically (*) correlated remnants	Age (ka)	Structure	Maximum thickness (m)£	Original length (km)£	Notes
Episode 1	188.7-mile flow	Unnamed remnant below Black Ledge 188.7L	829 ± 9 n = 2	Single flow	??	??	Only one known remnant; remnant height needs to be surveyed
Episode 2	Whitmore Rapids flow	Massive Diabase 188.1R	630 ± 30	Single flow	>30	??	Only one known remnant; inset into Black Ledge
	High Remnant flows	Toroweap remnant 176.9L	617 ± 38 n = 2	Multiple flows	> 330	??	Only one known remnant
	Lower Black Ledge flows	Lower and older of the basanitic Black Ledge remnants (195.4L, 246R,203.4R, 194.2R, 223.1R, 253.5R, 207.6L)*†, 208R†	575 ± 19 n = 8	Single flow	~45	>135	Geospatial analysis suggests remnants may be present upstream to RM 183, and Maxson (1950) reports remnant now covered by Lake Mead sediments at RM 263.
	Lower Prospect flows	Lower Prospect flows (179.6L)*, D-Dam (179.1L)*	572 ± 52 n = 3	Multiple flows	??	??	Could include multiple dams, similar to Ponderosa flow chemically but different age; remnant height needs to be surveyed
	Buried Canyon flows	182.9-183R*	524 ± 34 n = 4	Multiple flows	~200	??	May be related to Lower Black Ledge
	Upper Prospect flows	Upper Prospect flows 179.6L*, 179.3L*, Prospect dikes 179.4L*	535 ± 14 n = 5	Multiple flows	<<640	??	Ponderosa remnant similar chemically but is too young to be related
	Upper Black Ledge flow	Black Ledge (207.6L,189.L,208.3R)*†, Whitmore 190.7L*†, Vulcans Anvil 178*†	526 ± 21 n = 5	Single flow	~70	>76	Two lobes present at 190.7
	183.4-mile flow	183.4R	492 ± 32 n = 2	Single flow	>192	??	Only one known remnant; may be slumped
	Toroweap flows	Toroweap 179.1 - 179*†, Black Ledge 179.5R*†	448 ± 37 n = 5	Multiple flows	~395	??	Could include multiple dams; Ponderosa flow somewhat similar chemically but is younger
	Ponderosa	181.6R	424 ± 17	Single flow	>120	??	Only one known remnant, could be related to Toroweap A
Episode 3	177-mile flow	Unnamed remnants 177.3L*†, Massive Diabase (204.6L, 194.8)*†, Layered Diabase (192L, 183.9R)*	322 ± 13 n = 5	Multiple flows	~60	>44	
Episode 4	Lower Whitmore flows	Basal Whitmore flows (189.6L,188.3R,189.1L,187.5L, 188L)*†, Ponderosa 187.7R*†	243 ± 14 n = 6	Multiple flows	>190	>5	Thickness estimate includes the aggraded cinders, gravel, and colluvium under the flow; older ca. 300 ka remnants may be an older "Whitmore" eruptive stage but are better explained as part of the Lower Whitmore age population
	Lower Gray Ledge flow	Gray Ledge (187.5L)*†, Black Ledge (186.7R)* Lava Falls remnant 182.8R*†	209 ± 16 n = 3	Single flow	>110	>16	Older Esplanade remnant may be related; "Lava Falls" remnant rests on a higher strath than Lower Gray Ledge at RM 187.7
	180.8-mile flow	Cascade and unnamed remnants 180.8R	200 ± 30 ka	Multiple flows	>70	??	Only one known remnant
	Upper Whitmore flows	Top/upper Whitmore flows (190R, 188.1L, 187.5L, 187.7R, 187.6R)*†	186 ± 13 n = 6	Multiple flows	190–260	>5	Includes younger cascade on Plate 1 of Hamblin, 1994, "Whitmore Cascade" flows (Qdwc1 and 2) and upper flows in the "Hyaloclastite Dam" of Fenton et al., 2004
Episode 5	Upper Gray Ledge flow	Gray Ledge (190.9L, 188.1R, 187.9L, 189.1L)*†, Esplanade (181.2R)* Black Ledge (184.6L)*†, Younger Cascade of Fenton et al., 2004 179.2 *†	102 ± 8 ka n = 6	Single flow	>140	>21	Esplanade remnant included

*Correlated based on geochronology.
†Correlated based on geochemistry.

TABLE 2. Ar/Ar GEOCHRONOLGY ON GRAND CANYON INTRACANYON BASALT FLOWS AND INTRUSIONS

	Basalt flow	Sample number	River mile	Ar/Ar age (ka)	Latitude*	Longitude*	References	Comments
Episode 1	**188.7-mile flow**	**Mean of four analyses from two samples**	188.7L	**829 ± 9 n = 4**	**36.13503**	**#NAME?**	**This study**	**Considerably older than any other known flow**
		RC06-188.85-4a		840 ± 40			This study	Laser analysis; plateau age; glassy
		RC06-188.85-4b		830 ± 40			This study	Furnace analysis; plateau age; glassy
		RC06-188.85-4c[†]		832 ± 12			This study	Plateau age; glassy
		RC12-188.7-1[†]		822 ± 17			This study	Plateau age; glassy
Episode 2	**Whitmore Rapids flow**	**RC05-188.1R-1**	**188.1R**	**630 ± 30**	**36.14493**	**–113.20374**	**This study**	**Plateau age; disturbed spectrum**
	High Remnant flows	**Mean of two samples from multiple flows**	**176.9L**	**617 ± 38 n = 2**	**36.21249**	**–113.04519**	**Karlstrom et al., 2007**	
		K01-177-05		605 ± 35			Karlstrom et al., 2007	Lower flow; plateau age
		K01-177-01		647 ± 54			Karlstrom et al., 2007	Upper flow; plateau age
	Lower Black Ledge flow	**Mean of eight samples**		**575 ± 19 n = 8**				**581 ± 28 ka n = 9 including K01-246-1**
		RC06-194.6-1	194.2R	570 ± 30	36.08924	–113.25621	This study	Plateau age
		RC06-195.3-2	195.4L	542 ± 13	36.09510	–113.27480	This study	Plateau age
		RC06-203.8-1 Mean of six analyses	203.4R	574 ± 14 n = 6	36.03138	–113.35224	This study	569 ± 11 n = 5 excluding c
		RC06-203.8-1a		551 ± 16			This study	Plateau age (<50% ^{39}Ar released)
		RC06-203.8-1b		581 ± 15			This study	HCl treatment; plateau age
		RC06-203.8-1c		606 ± 19[§]			This study	WSU treatment; plateau age
		RC06-203.8-1d		560 ± 20			This study	DI treatment; plateau age
		RC06-203.8-1e		574 ± 11			This study	Plateau age
		RC06-203.8-1f		580 ± 70			This study	1/2 WSU treatment; plateau age
		RC07-246-1C Mean of six analyses	246R	575 ± 14 n = 6	35.82407	–113.64638	This study	569 ± 8 ka n = 5 excluding f
		RC07-246-1Ca		553 ± 14			This study	HCl treatment; plateau age
		RC07-246-1Cb		580 ± 20			This study	WSU treatment; plateau age
		RC07-246-1Cc		568 ± 16			This study	1/2 WSU treatment; plateau age
		RC07-246-1Cd		567 ± 20			This study	DI treatment; plateau age
		RC07-246-1Ce		574 ± 8			This study	406.32 mg; plateau age
		RC07-246-1Cf		605 ± 13[§]			This study	205.45 mg; plateau age
		RC07-246-2E		520 ± 80			This study	Plateau age; glassy
		K01-246-1	246R	728 ± 31	35.82407	–113.64638	Karlstrom et al., 2007	Same remnant as RC07-246-1C; duplicate analyses on separate samples suggest this age is too old
		RC07-253.5-1(DI)a	253.6R	590 ± 50	35.90580	–113.71505	This study	Plateau age; disturbed spectrum; glassy
		RC07-253.5-1(DI)b	253.6R	250 ± 60			This study	Plateau age; age inconsistent with other analyses on Lower Black Ledge; glassy
		RC06-207.6-3	207.6L	610 ± 40	35.98180	–113.33010	This study	Same remnant as GC-26-93?; plateau age
		RC06-223.1-2	223.1R	615 ± 15	35.79106	–113.34117	This study	Plateau age
	Undivided Black Ledge of Granite Park	GC-26-93	207.6L	608 ± 16	35.98178	–113.33006	Lucchitta et al., 2000	Same remnant as RC06-207.6-3?; Lower Black Ledge?

(*continued*)

TABLE 2. Ar/Ar GEOCHRONOLGY ON GRAND CANYON INTRACANYON BASALT FLOWS AND INTRUSIONS (*continued*)

	Basalt flow	Sample number	River mile	Ar/Ar age (ka)	Latitude*	Longitude*	References	Comments
Episode 2 (*continued*)	**Lower Prospect flow(s)**	**Mean of three samples from multiple flows**		**572 ± 52 n = 3**			**Karlstrom et al., 2007**	**Multiple dams possible**
		LP01-179-06	179.6L	636 ± 45	36.18182	–113.07880	Karlstrom et al., 2007	In hanging wall of Toroweap fault
		LP01-179-08	179.1L	606 ± 37	36.19675	–113.07781	Karlstrom et al., 2007	D-dam of Hamblin, 1994; no chemistry available
		LP01-179-07 Mean of five analyses	179.6L	544 ± 22 n = 5	36.18040	–113.07736	Karlstrom et al., 2007	In footwall of Toroweap fault
		LP01-179-07a		584 ± 79			Karlstrom et al., 2007	
		LP01-179-07b		530 ± 39			Karlstrom et al., 2007	
		LP01-179-07c		544 ± 28			Karlstrom et al., 2007	
		LP01-179-07d		531 ± 31			Karlstrom et al., 2007	
		LP01-179-07e		612 ± 66			Karlstrom et al., 2007	
	Buried Canyon flows	**Mean of four ages from multiple flows**		**524 ± 34 n = 4**				
		RC08-182.9Aa Mean of three analyses	182.9R	575 ± 46 n = 3	36.16980	–113.13252	This study	Buried Canyon A; samples in stratigraphic order; bottom
		RC08-182.9Aa		581 ± 15			This study	Plateau age
		RC08-182.9Ab[†]		541 ± 6[§]			This study	Plateau age
		RC08-182.9Ac[†#]		609 ± 6[§]			This study	Plateau age
		RC08-183.0-D Mean of four analyses	183R	509 ± 43 n = 4	36.16914	–113.13384	This study	Buried Canyon D; 527 ± 34 ka n = 3 excluding b
		RC08-183.0-Da		530 ± 40			This study	Plateau age
		RC08-183.0-Db[†]		456 ± 19[§]			This study	Plateau age
		RC08-183.0-Dc[†]		507 ± 15			This study	Plateau age
		RC08-183.0-Dd[†#]		559 ± 19			This study	Plateau age
		ND02-183-9 Mean of four analyses	182.9R	551 ± 13 n = 4	36.17123	–113.13271	This study	Buried Canyon G
		ND02-183-9a		520 ± 30			This study	Plateau age
		ND02-183-9b[†]		566 ± 17			This study	Plateau age
		ND02-183-9c[†]		547 ± 15			This study	Plateau age
		ND02-183-9d[†#]		551 ± 12			This study	Plateau age
		RC12-183-6a Mean of three analyses	182.9R	494 ± 13 n = 3	36.17133	–113.13331	This study	Top-most Buried Canyon flow (I); 491 ± 5 ka n = 2 excluding b
		RC12-183-6a[†]		490 ± 12			This study	Plateau age
		RC12-183-6b[†]		516 ± 13[§]			This study	Plateau age
		RC12-183-6c[†#]		491 ± 6			This study	Plateau age
	Clast on top of Buried Canyon	RC12-183-1[†]	182.9R	477 ± 10	36.17161	–113.13424	This study	Plateau age
	Older Whitmore flow	WC0424-01	187.2R	543 ± 30	36.17476	–113.21624	Raucci, 2004	Same as Older Whitmore Sink of Fenton et al., 2004; dated flow on rim of Grand Canyon

(*continued*)

TABLE 2. Ar/Ar GEOCHRONOLGY ON GRAND CANYON INTRACANYON BASALT FLOWS AND INTRUSIONS (*continued*)

	Basalt flow	Sample number	River mile	Ar/Ar age (ka)	Latitude*	Longitude*	References	Comments
Episode 2 (*continued*)	**Upper Prospect flows and Prospect Dike**	**Mean of five samples from multiple flows**		**535 ± 14 n = 5**			**Pederson et al., 2002**	**515 ± 20 ka n = 6 with K00-179-PR5; 515 ± 23 ka n = 5 excluding prospect dike**
		K00-179-PR3	179.6L	533 ± 23	36.17827	–113.07663	Pederson et al., 2002	Samples in stratigraphic order; bottom (#1 in Fig. 5)
		K00-179-PR4	179.6L	544 ± 53	36.17816	–113.07655	Pederson et al., 2002	(#2 in Fig. 5)
		K00-179-PR5	179.6L	489 ± 16	36.17805	–113.07645	Pederson et al., 2002	Despite its precision, age may be unreliable as it is not consistent with the stratigraphy (#3 in Fig. 5)
		K00-179-PR10	179.3L	536 ± 20	36.17651	–113.07527	Pederson et al., 2002	(#5 in Fig. 5; #4 not dated)
		K00-179-PR6	179.6L	536 ± 82	36.18348	–113.07559	Pederson et al., 2002	Samples in stratigraphic order; top (#6 in Fig. 5)
		LP01-179-12 Mean of two analyses	179.4L	524 ± 60 n = 2	36.19452	–113.08164	Karlstrom et al. 2007	Prospect dike
		LP01-179-12a		501 ± 28			Karlstrom et al. 2007	Float
		LP01-179-12b		563 ± 36			Karlstrom et al. 2007	Float
	178-mile cascade	RC06-178.1-5	178.1L	490 ± 20	36.18937	–113.05102	This study	Plateau age; <50% of the ^{39}Ar released; disturbed spectrum
	Upper Black Ledge flow and Vulcans Anvil	**Mean of five samples**		**526 ± 21 n = 5**			**This study**	**525 ± 26 ka n = 4 without Vulcans Anvil**
		RC06-178.0-1	178	530 ± 30	36.20760	–113.05960	This study	Vulcans Anvil; isochron age
		RC08-189.1-3	189L	543 ± 14	36.13103	–113.20254	This study	Isochron age; stratigraphically higher than the 188.8-mile flow
		99-AZ-116	189L	486 ± 80	36.13103	–113.20254	Fenton et al., 2004	“Black Ledge” of Hamblin (1994) (no chemistry available); same remnant as RC08-189.1-3?—originally listed as RM 189.5L (Fenton et al., 2004, p. 98)
		RC08-190.7-2	190.7L	496 ± 18	36.10941	–113.20993	This study	“Whitmore” of Hamblin, 1994; isochron age
		LP01-208-01 Mean of two analyses	208.3R	531 ± 39 n = 2	35.97341	–113.32079	Karlstrom et al., 2007	Same remnant as GC-22-93?
		LP01-208-01a		528 ± 49			Pederson et al., 2002	
		LP01-208-01b		537 ± 64			Karlstrom et al., 2007	
	Undivided Black Ledge of Granite Park	GC-22-93	208.6R	589 ± 28	35.97034	–113.31933	Lucchitta et al., 2000	Same remnant as LP01-208-01?; Upper Black Ledge?
		GC-24-93	208.1R	613 ± 12	35.97479	–113.32255	Lucchitta et al., 2000	Sample above intra-Black-Ledge basaltic gravel; Upper Black Ledge?
		GC-29-93	207.6L	528 ± 26	35.98186	–113.33007	Lucchitta et al., 2000	Younger flow of Lucchitta et al., 2000; stratigraphically above GC-26b-93; Upper Black Ledge?
		GC-26b-93	207.6L	611 ± 18	35.98178	–113.33006	Lucchitta et al., 2000	Same remnant as RC06-207.6-1 and 2 (geochemical samples)?; Upper Black Ledge?; stratigraphically above GC-26-93
		GC-35-93	207.7L	503 ± 14	35.98157	–113.32904	Lucchitta et al., 2000	Younger flow of Lucchitta et al., 2000; Upper Black Ledge?
		GC-34-93	207.7L	563 ± 18	35.98157	–113.32904	Lucchitta et al., 2000	Younger flow of Lucchitta et al., 2000; Upper Black Ledge?
	183.4-mile flow	**RC09-183.4-1 Mean of two analyses**	**183.4R**	**492 ± 32 n = 2**	**36.16776**	**–113.13959**	**This study**	**Base of remnant below river level, plateau age**
		RC09-183.4-1a		460 ± 60			This study	Plateau age; glassy
		RC09-183.4-1b[†#]		500 ± 30			This study	Plateau age; glassy

(*continued*)

TABLE 2. Ar/Ar GEOCHRONOLGY ON GRAND CANYON INTRACANYON BASALT FLOWS AND INTRUSIONS (*continued*)

	Basalt flow	Sample number	River mile	Ar/Ar age (ka)	Latitude*	Longitude*	References	Comments
Episode 2 (*continued*)	**Toroweap flows**	**Mean of five samples from multiple flows**		**448 ± 37 n = 5**			**This study**	**443 ± 35 ka n = 3 excluding Toroweap B**
		Mean of next two samples (Toroweap A)		478 ± 24 n = 2				
		LP01-179-02 Mean of four analyses	179.1R	485 ± 7 n = 4	36.19964	–113.07971	This study	Toroweap A; 483 ± 4 ka n = 3 excluding b; samples in stratigraphic order; bottom
		LP01-179-02a		488 ± 18			This study	Plateau age; disturbed spectrum
		LP01-179-02b[†]		505 ± 10[§]			This study	Plateau age; disturbed spectrum
		LP01-179-02c[†]		484 ± 3			This study	Plateau age; disturbed spectrum
		LP01-179-02d[†]		477 ± 7			This study	Plateau age; disturbed spectrum
		RC08-179.5-1	179.5R	458 ± 12	36.19745	–113.08553	This study	“Black Ledge” of Hamblin (1994); interpreted as part of Toroweap A; plateau age
		Mean of next two samples (Toroweap B)		588 ± 17 n = 2	36.20102	–113.07895	This study	Toroweap B; age considered unreliable (see text)
		ND02-179.1-01 Mean of six analyses	179R	590 ± 17 n = 5			This study	595 ± 6 ka n = 4 excluding d
		ND02-179.1-01a		594 ± 17			This study	Plateau age; disturbed spectrum
		ND02-179.1-01b[†]		581 ± 12			This study	Plateau age; disturbed spectrum
		ND02-179.1-01d[†]		537 ± 14[§]			This study	Plateau age
		ND02-179.1-01e[†#]		592 ± 12			This study	Plateau age
		ND02-179.1-01f[†#]		598 ± 5			This study	Plateau age
		RC12-179-5 Mean of two analyses		560 ± 74 n = 3			This study	
		RC12-179-5a[†]		533 ± 15			This study	Plateau age
		RC12-179-5b[†]		513 ± 20			This study	Plateau age; disturbed spectrum
		RC12-179-5c[†#]		638 ± 18[§]			This study	Plateau age; disturbed spectrum
		LP01-179-04 Mean of four analyses	179.1R	427 ± 4 n = 5	36.20042	–113.07972	This study	Toroweap C; 427 ± 3 ka n = 3 excluding a
		LP01-179-04a		490 ± 48[§]			Karlstrom et al., 2007	
		LP01-179-04b[†]		423 ± 8			This study	Plateau age
		LP01-179-04c[†]		425 ± 5			This study	Plateau age
		LP01-179-04d[†]		430 ± 4			This study	Plateau age
		LP01-179-04e[†#]		426 ± 7			This study	Plateau age
	Ponderosa flow	**RC06-181.6-2**	**181.6R**	**424 ± 17**	**36.18250**	**–113.11680**	**This study**	**May be related to Toroweap A flow; chemically very similar to Upper Prospect but much younger; isochron age**
Episode 3	**177-mile flow**	**Mean of five samples**		**322 ± 13 n = 5**			**This study**	
		W00-177-02 Mean of three analyses	177.3L	353 ± 25 n = 3	36.21028	–113.05059	Karlstrom et al., 2007	Unnamed by Hamblin, 1994
		W00-177-02a		351 ± 29			Pederson et al., 2002	
		W00-177-02b		387 ± 47			Karlstrom et al., 2007	
		W00-177-02c		336 ± 36			Karlstrom et al., 2007	
		LP01-192-01 Mean of two analyses	192L	334 ± 39 n = 2	36.09591	–113.21959	Karlstrom et al. 2007	“Layered Diabase” of Hamblin (1994); tentatively correlated to 177-mile flow on the basis of age (no chemistry)
		LP01-192-01a		311 ± 20			Karlstrom et al. 2007	
		LP01-192-01b		350 ± 17[§]			Karlstrom et al. 2007	

(*continued*)

TABLE 2. Ar/Ar GEOCHRONOLOGY ON GRAND CANYON INTRACANYON BASALT FLOWS AND INTRUSIONS (*continued*)

	Basalt flow	Sample number	River mile	Ar/Ar age (ka)	Latitude*	Longitude*	References	Comments
Episode 3 (*continued*)	**177-mile flow** (*continued*)							
		W00-195-01 Mean of two analyses	194.8L	341 ± 25 n = 2	36.09231	–113.26491	This study	"Massive Diabase" of Hamblin (1994); correlated to 177-mile flow on the basis of age and chemistry
		W00-195-01a		300 ± 57			Pederson et al., 2002	
		W00-195-01b		345 ± 17			This study	Plateau age
		RC08-183.9-1	183.9R	320 ± 13	36.17357	–113.14475	This study	"Layered Diabase" of Hamblin (1994); tentatively correlated to 177-mile flow on the basis of age (no chemistry); plateau age
		RC08-204.6-1	204.6L	312 ± 11	36.01450	–113.34800	This study	"Massive Diabase" of Hamblin (1994); correlated to 177-mile flow on the basis of age and chemistry; plateau age
Episode 4	**Lower Whitmore flows**	**Mean of six samples from multiple flows**		**243 ± 14 n = 6**				
		RC08-187.5-2	187.5L	254 ± 19	36.14991	–113.19619	This study	Lower flow in Hamblin's (1994) "Whitmore" remnant; plateau age
		RC05-187.7R-W Mean of two analyses	187.7R	195 ± 70 n = 2	36.15144	–113.20355	This study	"Ponderosa" remnant of Hamblin (1994)
		RC05-187.7R-Wa		160 ± 40			This study	Plateau age
		RC05-187.7R-Wb		230 ± 40			This study	Plateau age
		W00-190-02 Mean of three analyses	189.6L	234 ± 34 n = 3	36.12388	–113.19664	This study	Basal flow in Hamblin's (1994) "Whitmore" remnant; 230 ± 27 ka n = 2 excluding a
		W00-190-02a		318 ± 69[§]			Pederson et al., 2002	
		W00-190-02b		220 ± 20			This study	Plateau age
		W00-190-02c[†]		250 ± 30			This study	Plateau age
		K08-188-1	188L	230 ± 30	36.14480	–113.19970	This study	Lower flow in Hamblin's (1994) "Whitmore" remnant; near bottom of Fenton et al.'s (2004) "Hyaloclastite Dam"; plateau age; only 2 steps in plateau
		LP01-188-01 Mean of two analyses	188.3R	265 ± 71 n = 3	36.14274	–113.20606	This study	Basal flow in Hamblin's (1994) "Whitmore" remnant
		LP01-188-01a		325 ± 141			Karlstrom et al., 2007	
		LP01-188-01b		320 ± 60			This study	Plateau age
		LP01-188-01c[†]		220 ± 50			This study	Plateau age; 45% of ^{39}Ar released; disturbed spectrum
		RC08-189.1-1	189.1L	230 ± 70	36.13023	–113.20062	This study	Lower flow in Hamblin's (1994) "Whitmore" remnant; plateau age
	Lower Gray Ledge flow	**Mean of three samples**		**209 ± 16 n = 3**			**This study**	**206 ± 11 ka without the "Lava Falls" remnant**
		RC06-182.8-1	182.8R	250 ± 40	36.16997	–113.12927	This study	"Lava Falls" of Hamblin (1994); plateau age
		RC08-186.7-1	186.7R	207 ± 11	36.15796	–113.18670	This study	Float; plateau age
		W00-188-02	187.5L	195 ± 39	36.15087	–113.19884	Pederson et al., 2002	Date on basalt block below the main flow in basaltic gravel deposit
	180.8-mile flows	**RC05-180.75-1**	**180.8R**	**200 ± 30**	**36.18890**	**–113.10539**	**This study**	**Sample from peperite at base of flow; isochron age; glassy**
	Upper Whitmore flows	**Mean of six samples from multiple flows**		**186 ± 13 n = 6**				
		RC08-187.5-1	187.5L	200 ± 40	36.14980	–113.19560	This study	Top flow in Hamblin's (1994) "Whitmore" remnant; plateau age
		Mean of next two samples	187.7R	187 ± 26 n = 2	36.15229	–113.20750	Raucci, 2004	Mean of next 3 samples 201 ± 18 ka n = 3
		Colonnade 1		172 ± 50			Raucci, 2004	Upper flow in Hamblin's (1994) "Whitmore" remnant; float; sampled in modern Whitmore Wash
		Colonnade 2		192 ± 30			Raucci, 2004	Upper flows in Hamblin's (1994) "Whitmore" remnant; float; sampled in modern Whitmore Wash

(*continued*)

TABLE 2. Ar/Ar GEOCHRONOLGY ON GRAND CANYON INTRACANYON BASALT FLOWS AND INTRUSIONS (*continued*)

	Basalt flow	Sample number	River mile	Ar/Ar age (ka)	Latitude[*]	Longitude[*]	References	Comments
Episode 4 (*continued*)	**Upper Whitmore flows** (*continued*)							
		RC06-187.7-1	187.7R	210 ± 20	36.15276	–113.20903	This study	Upper flows in Hamblin's (1994) "Whitmore" remnant; sampled in modern Whitmore Wash; plateau age
		RC08-188.1-1 Mean of two analyses	188.1L	213 ± 26 n = 2	36.14438	–113.19908	This study	Upper flow in Hamblin's (1994) "Whitmore" remnant; near top of Fenton et al.'s (2004) "Hyaloclastite Dam"
		RC08-188.1-1a		210 ± 30			This study	Furnace; plateau age
		RC08-188.1-1b		220 ± 50			This study	Laser; plateau age
		RC06-189.9-1	190R	140 ± 80	36.11887	–113.20453	This study	Top flow in Hamblin's (1994) "Whitmore" remnant; plateau age
		K08-187.7-1[†]	187.6R	178 ± 9	36.15301	–113.20188	This study	Plateau age; lowest flow thin flow in "Whitmore" fill
	Basalt clast in Qfd4	K06-192-1	191.6L	180 ± 20	36.09877	–113.21556	This study	Clast in the Qfd4 flood deposit of Fenton et al. (2004) which is offset by a Quaternary fault; plateau age
Episode 5	**Upper Gray Ledge flow**	**Mean of six samples**		**102 ± 8 n = 6**			**This study**	**101 ± 7 n = 5 excluding the "Esplanade" remnant**
		ND02-181.2-01	181.2R	117 ± 20	36.18627	–113.11174	This study	Basal "Esplanade" flow of Hamblin, 1994; plateau age
		LP01-184-01 Mean of three analyses	184.6L	113 ± 20 n = 3	36.17253	–113.15702	This study	"Lower Gray Ledge" of Karlstrom et al., 2007; "Black Ledge" of Hamblin, 1994
		LP01-184-01a		201 ± 72[§]			Pederson et al., 2002	
		LP01-184-01b		85 ± 16[§]			This study	Plateau age
		LP01-184-01c[†]		117 ± 7			This study	Plateau age
		W00-188-03	188.1R	98 ± 26	36.14360	–113.20272	Pederson et al., 2002	
		LP01-189-01 Mean of two analyses	189.1L	128 ± 27 n = 2	36.12951	–113.20362	Karlstrom et al., 2007	
		LP01-189-01a		114 ± 29			Karlstrom et al., 2007	
		LP01-189-01b		141 ± 29			Karlstrom et al., 2007	
		RC08-190.9-1 Mean of two analyses	190.9L	84 ± 14 n = 2	36.10818	–113.21461	This study	
		RC08-190.9-1a		87 ± 19			This study	Isochron age
		RC08-190.9-1b[†]		80 ± 20			This study	Isochron age
		RC05-187.9L-1 Mean of four analyses	187.9L	102 ± 6 n = 4	36.14714	–113.20084	This study	
		RC05-187.9L-1a		110 ± 40			This study	Isochron age
		RC05-187.9L-1b[†]		105 ± 12			This study	Plateau age
		RC05-187.9L-1c[†]		98 ± 5			This study	Plateau age
		RC05-187.9L-1d[†][#]		110 ± 7			This study	Plateau age
	Toroweap Cascades	Mean of three samples		82 ± 13 n = 3			This study	
		RC08-TV-3	180R	79 ± 13	36.20601	–113.10057	This study	Isochron age
		RC08-TV-2	179.4R	70 ± 20	36.20890	–113.09111	This study	Lower flow of two; isochron age
		RC08-TV-4	179.3R	94 ± 16	36.21077	–113.09013	This study	Isochron age

Note: Major intracanyon flows resulting in lava dams in bold; all previously published ages were updated to reflect the Fish Canyon Tuff sanidine age of 28.201 Ma (Kuiper et al., 2008).

[*] Locations updated using field notes, handheld GPS locations, and geologic mapping; no GPS locations available for W00, LP01, and ND02 samples; NAD83.

[†] Analyzed on multicollector.

[§] Does not overlap with other analyses on same sample.

[#] No "degas" and improved gettering.

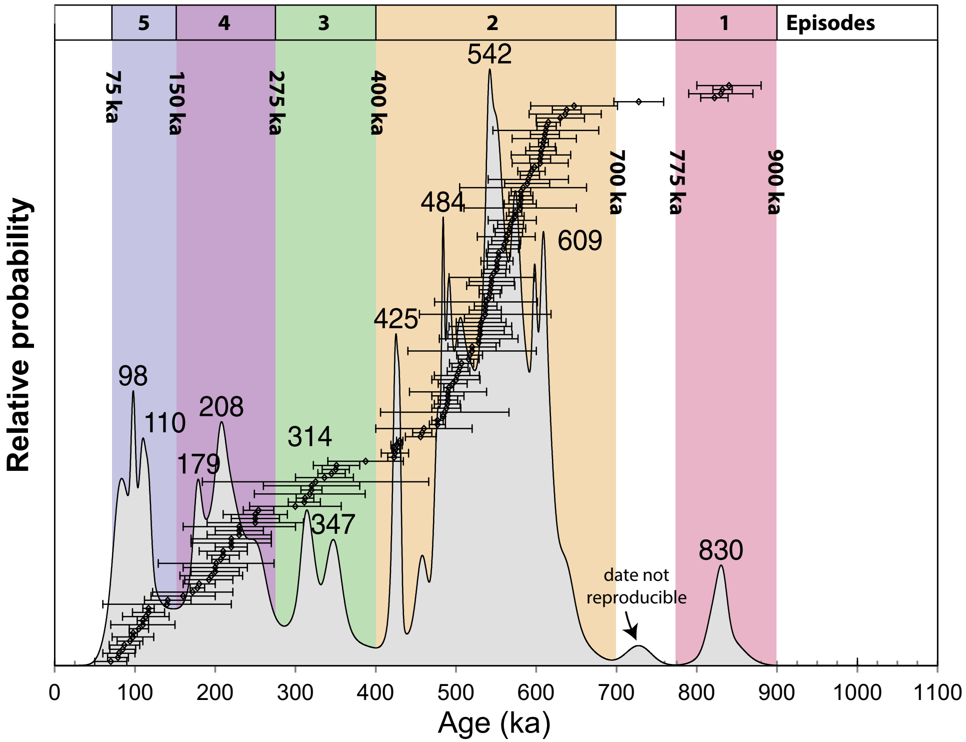

Figure 4. Age-distribution curve for all $^{40}Ar/^{39}Ar$ ages on intracanyon flows. The colored fields show the main episodes of volcanism resulting in intracanyon flows.

Geochemistry

Figure 5A shows the total alkali–silica (TAS) classification for 65 samples from 59 flow remnants (Supplemental Table SF2 [see footnote 1]). These basalts range in composition from tholeiites to alkali basalts and basanites. Distinct compositions are interpreted to reflect separate eruptions from distinct magma chambers, while small variations within the same flow may reflect alteration, unidentified contaminants, mixing, or fractional crystallization. Lower Black Ledge flow remnants, which are separated by ~40 RM and can be independently correlated by paleomagnetism and $^{40}Ar/^{39}Ar$ age, show consistent major- and rare-earth element compositions, indicating that along flow geochemical variations are generally small. Although duplicate analyses and samples generally produce similar results with standard deviations <0.33 wt% for major elements (Supplemental Tables SF3 and SF4 [see footnote 1]), duplicate samples from one remnant (Toroweap A) produced standard deviations as high as 2.7 wt%, due to visible amygdules of an unidentified white mineral. Although care was taken to sample the freshest part of a flow remnant, similar contaminants, including carbonates, zeolites, mantle xenoliths, and weathered basalt, were noted in some samples. However, in the remaining samples, visible contaminants could be completely removed during the sample preparation such that this is considered a minor source of error for the remaining samples.

Figures 5B and 6 show the REE composition of 47 samples from 46 remnants (Supplemental Table SF5 [see footnote 1]). Duplicate analyses and samples yielded consistent results with a maximum standard deviation of 0.5 ppm for REE (Supplemental Tables SF6 and SF7 [see footnote 1]). However, the same remnant (Toroweap A) analyzed in this study and by Fenton et al. (2004) shows large differences (maximum standard deviation of 20 ppm; see Supplemental Table SF7 and Supplemental Fig. SF5B [see footnote 1]). We suggest that this may be due to the lower precision of the Fenton et al. (2004) analyses, as duplicate analyses on the same samples from that study have standard deviations as high as 5 ppm (% difference of ~50%) (Supplemental Table SF8 and Supplemental Fig. SF5 [see footnote 1]) (Fenton, 2002). Although these issues make comparisons to the earlier Fenton et al. (2002, 2004) analyses difficult, we are confident that the new analytical results presented here are reproducible.

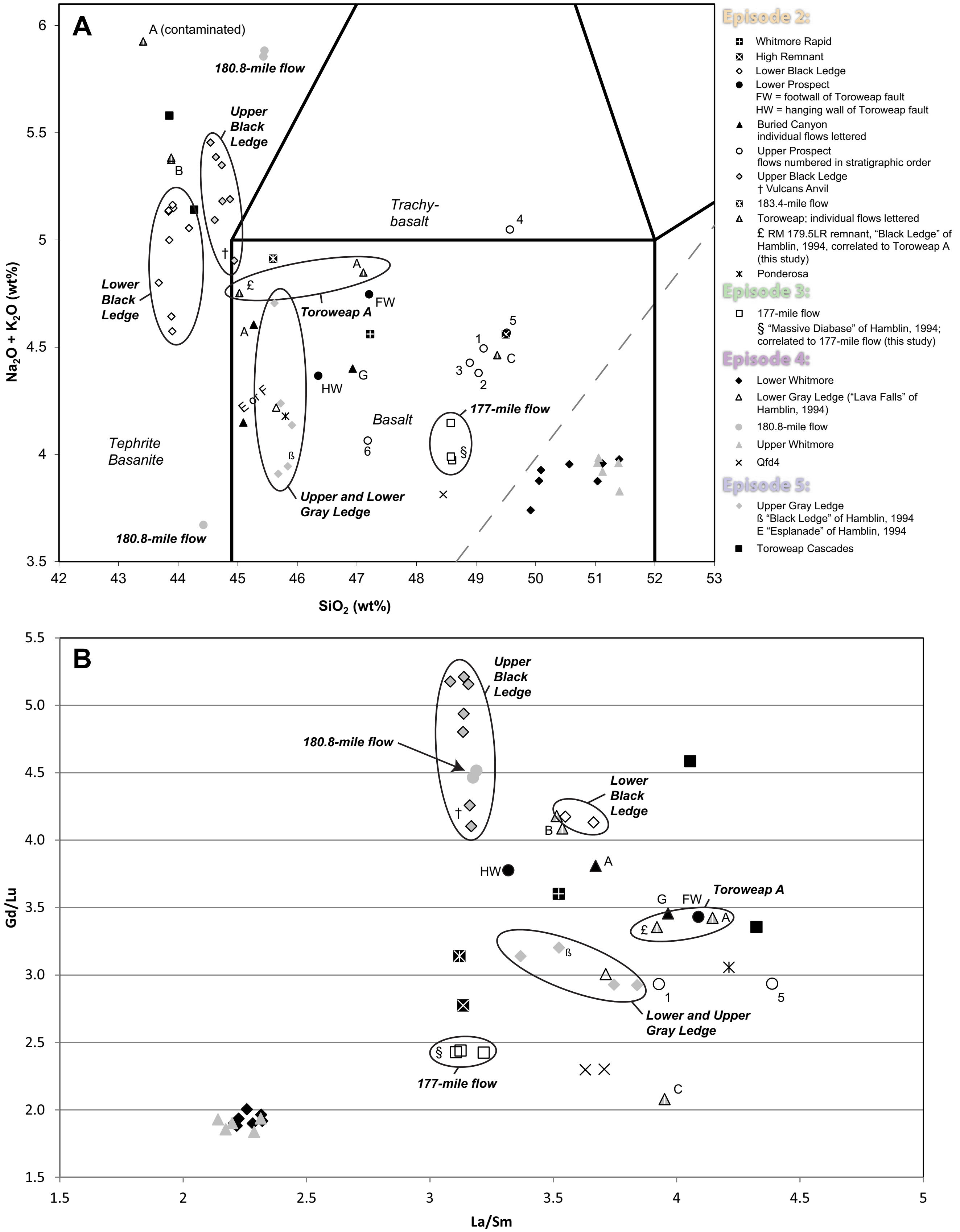

Figure 5. Geochemical plots of all analyzed remnants. Analyses from the same flow are circled and labeled. (A) Total alkali–silica plot showing a wide range in major-element compositions for Grand Canyon intracanyon flows. (B) Gd/Lu versus La/Sm plot showing the range in rare-earth element (REE) composition for Grand Canyon's intracanyon flows.

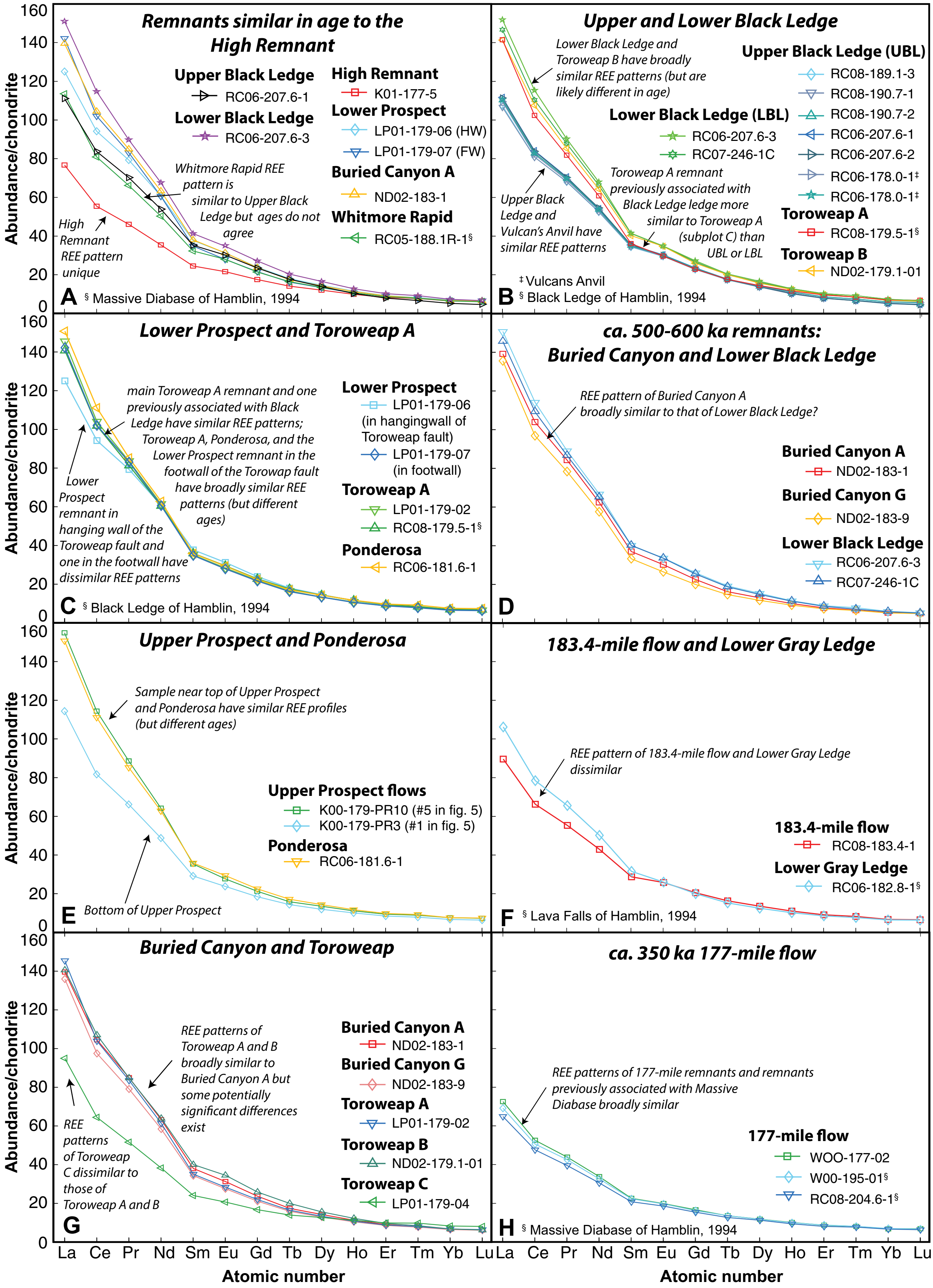

Figure 6 (*on this and following page*). Rare-earth element (REE) plots of analyses on key remnants illustrating similarities or differences useful in correlating remnants. See the text for a discussion of each subplot.

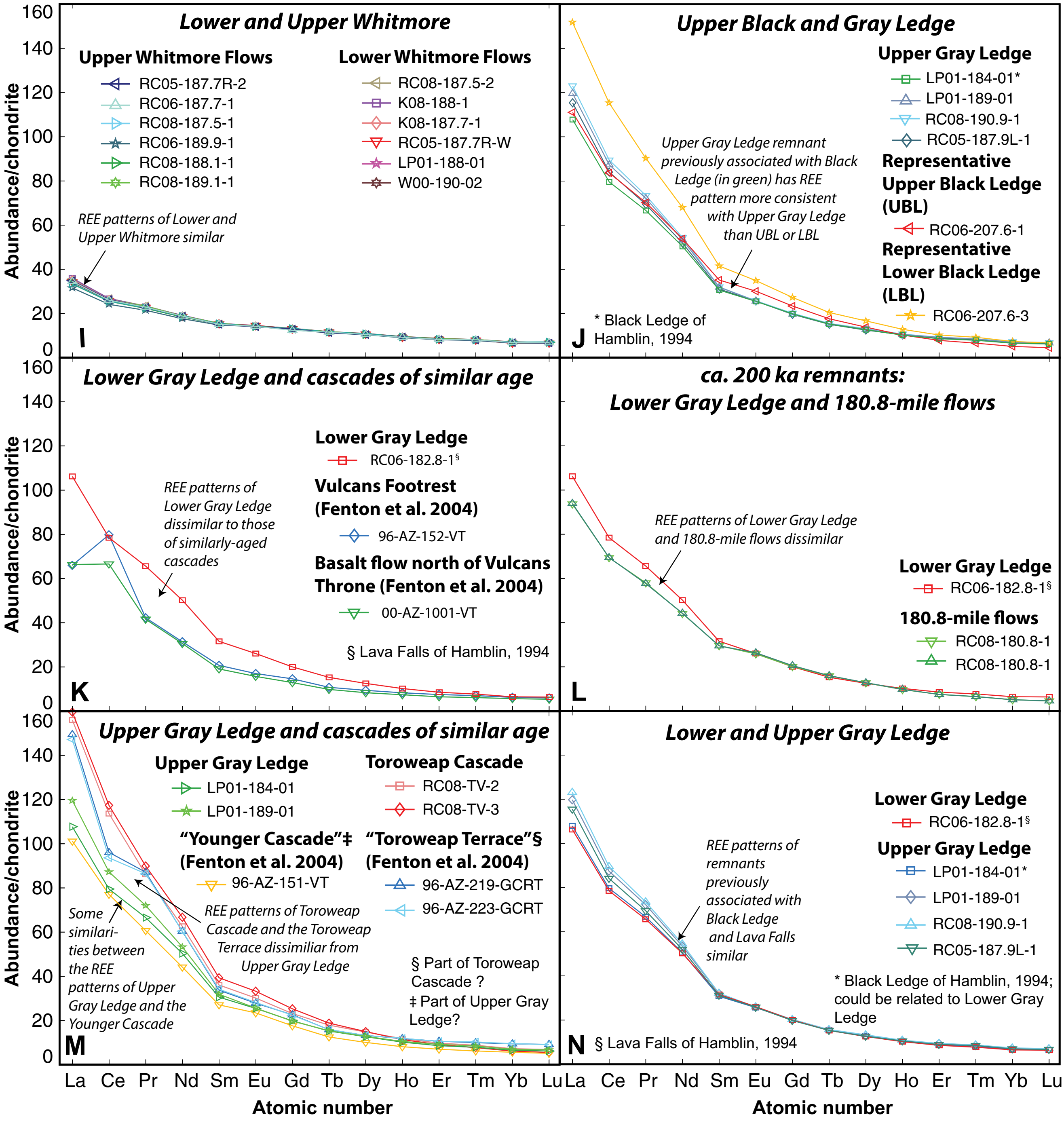

Figure 6 (*continued*).

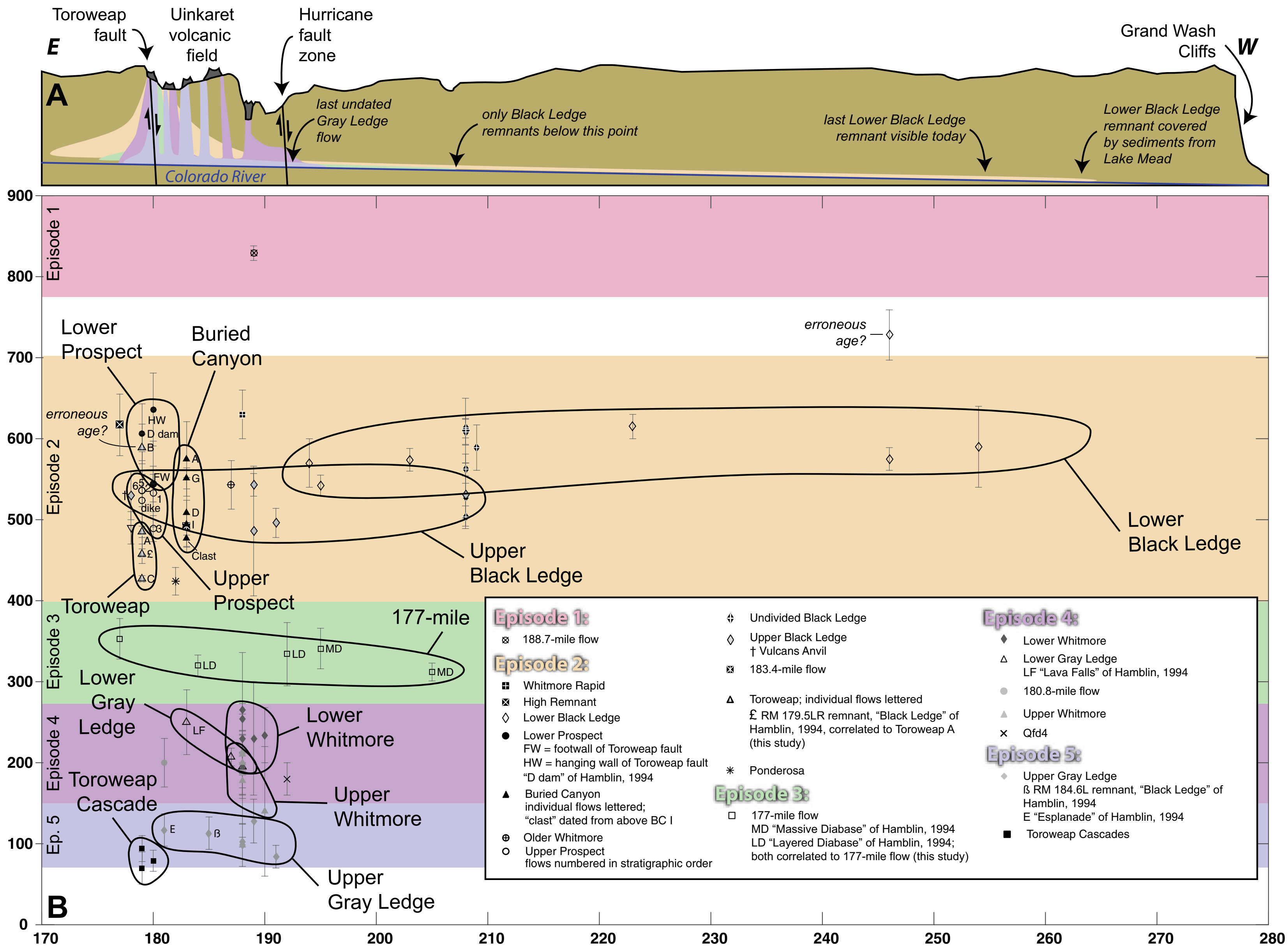

Figure 7. (A) Simplified longitudinal river profile showing the source and extent of intracanyon flows from the five episodes (color coded to Figs. 7B and 4). (B) Graph showing the ages of all dated remnants and how they correlate throughout the canyon.

NEW INTRACANYON FLOW STRATIGRAPHY

New $^{40}Ar/^{39}Ar$ ages and whole-rock geochemistry presented here suggest the need for major refinements to the flow-remnant correlations and flow stratigraphy of Hamblin (1994). In this section, we describe our best understanding about the timing, structure, and geometry of 17 individual intracanyon flows or flow stacks based on the new data. We will later argue that most if not all of these flows resulted in dams. We group the flows into five major episodes of intracanyon volcanism (Fig. 4; Crow et al., 2008) and describe the flows in each sequentially. However, it should be noted that the ages on some flows overlap and inset relationships are rare such that the true sequence of flows is not always known. Table 1 and Figure 7 summarize the individual named flows, the remnant correlations, and the new sequence of intracanyon flows we are proposing. See Supplemental Figure SF1 (see footnote 1) for a preliminary geologic map of the area showing the position of remnants mentioned in the text as well as the locations of key photographs.

Episode 1: 900–775 ka: 188.7-Mile Flow

Only one remnant from the earliest episode of volcanism is known. It is located a little over 1 km downstream from Whitmore Wash (Fig. 1), at RM 188.7L. Peperite overlying river sand has been dated there at 829 ± 9 ka. The new age is the oldest reliable age on intracanyon basalts in Grand Canyon.

Episode 2: 700–400 ka: Voluminous Flows Emanating from the Lava Falls Area

During episode two, at least ten flows entered Grand Canyon in the Lava Falls area (Fig. 1) as cascades and intracanyon eruptions, producing the most voluminous, highest, and longest dams.

Whitmore Rapid Flow

The 630 ± 30 ka Whitmore Rapid remnant, at RM 188.1R, named after the rapid near its base, was originally mapped as Massive Diabase by Hamblin (1994). Since other Massive Diabase remnants have been dated at ca. 320 ka and correlated to the 177-mile flow (see below), the Whitmore Rapid remnant, which is geochemically distinct from all similarly aged remnants (Figs. 5 and 6A), is interpreted as a remnant of a separate intracanyon flow. Black Ledge is inset into the Whitmore Rapid remnant, requiring that it is older than Black Ledge.

High Remnant Flows

The High Remnant is the remains of a ca. 620 ka set of flows that are ~400 m above MRL at their top. The remnant is located at RM 176.9L (Fig. 8), 2 km upstream from large flow remnants in the Lava Falls area and 1 km upstream

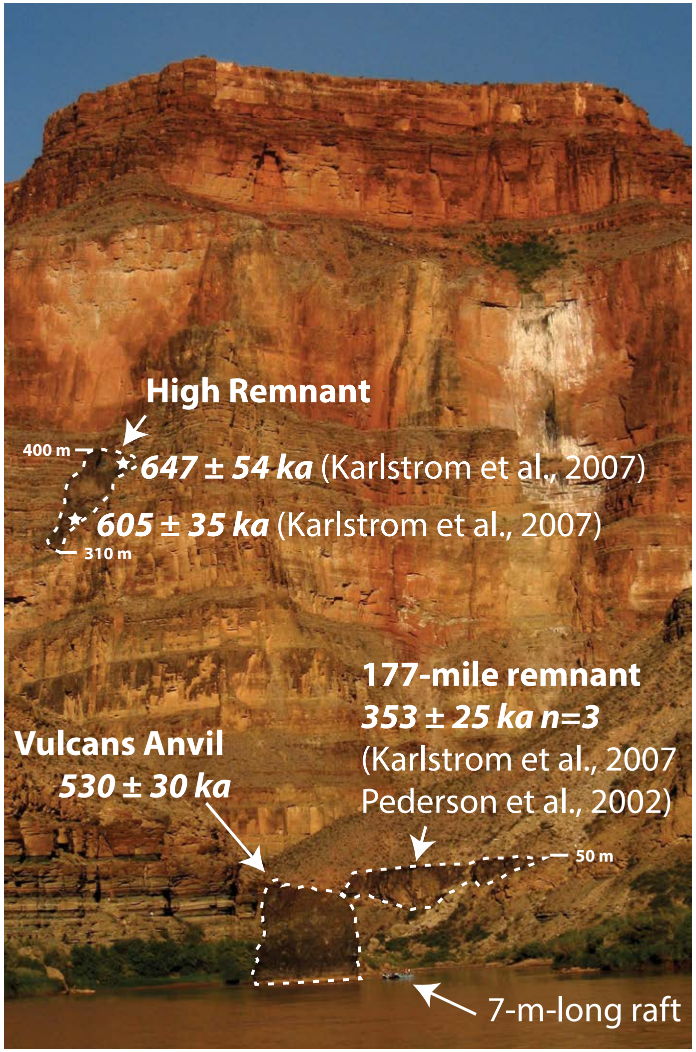

Figure 8. Annotated photograph taken pointing upstream showing Vulcans Anvil, the 177-mile remnant, and the High Remnant. Heights are in meters above modern river level.

from the most upstream basalt cascade or cinder cone. The remnant is composed of three massive flows that rest on tephra and colluvium (Fig. 9). Two of those have been dated at 605 ± 35 ka and 647 ± 54 ka. Although the dated flows are distinct, the statistically indistinguishable ages suggest that the whole sequence was emplaced quickly at ca. 620 ka, making it one of Grand Canyon's oldest intracanyon flows. Although a number of different flows are similar in age to the High Remnant (Fig. 7), it has a markedly different REE signature (Figs. 5B and 6A), indicating that it is part of a separate series of lava flows that created a volcanic edifice that was at least 330 m thick, if incision rates in the footwall of the Toroweap fault can be extrapolated past ca. 490 ka (Karlstrom et al., 2007; Crow et al., 2008; cf. Abbott et al., 2015).

Lower Black Ledge Flow

We use the name Black Ledge, after Hamblin (1994), to refer to two ca. 575 and 525 ka basanitic flows that were originally thought to be the remains of a single flow. To date, 19 separate remnants identified as Black Ledge by Hamblin have been dated between ca. 600 and 100 ka. The large range in ages strongly suggests that multiple flows have been erroneously grouped together (Lucchitta et al., 2000; Karlstrom et al., 2007). New geochemical data support this conclusion, as groups of remnants cluster on a TAS plot (Fig. 5A) and two distinct groups of REE patterns are seen (Figs. 5B and 6B). We split those Black Ledge remnants with basanitic compositions into Lower and Upper Black Ledge. Weighted mean ages of the chemically distinct Lower and Upper Black Ledge remnants are 575 ± 19 ka and 526 ± 21 ka, respectively. Hamblin proposed that the Black Ledge flow was one of youngest flows in the canyon based on misinterpreted inset relationships, but ^{40}Ar/^{39}Ar dating shows that the Black Ledge flows are actually one of the oldest (Lucchitta et al., 2000; Karlstrom et al., 2007; Crow et al., 2008). At Granite Park (RM 207–209), Lucchitta et al. (2000) found stratigraphically separated Black Ledge flows that are geochronologically distinct; new geochemical data on these stacked flows indicate that both Upper and Lower Black Ledge are present there.

Remnants of the Lower Black Ledge flow are currently known in the canyon between RM 194 and 253 based on geochemistry and geochronology (Fig. 7) but are likely present from RM 183–264 based on comparison of flow top heights and pre–Lake Mead observations (Figs. 1 and 3A) (Maxson, 1949). Paleomagnetic analyses of four samples from separate Lower Black Ledge remnants between RM 194 and 253 have similar paleomagnetic directions (Supplemental Fig. SF6A [see footnote 1]), which are most simply explained by simultaneous magnetization as opposed to random secular variation, supporting the correlation of these Lower Black Ledge remnants. Although the exact source of the Lower Black Ledge flow is unknown, we suspect it was in the Lava Falls area, where the vast majority of the remnants of this age have been found. Lower Black Ledge has similar REE composition to Toroweap B (see below; Fig. 6B). Although new ^{40}Ar/^{39}Ar dating on Toroweap B indicates that it

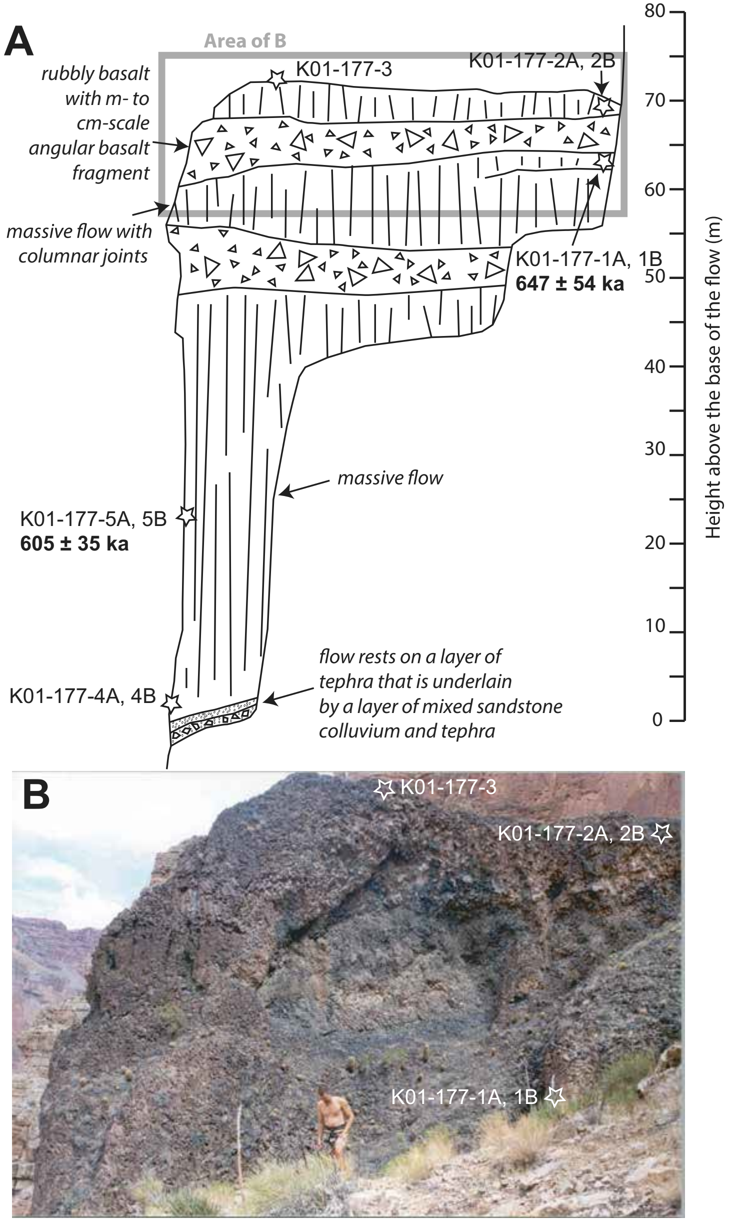

Figure 9. Sketch (A) and photograph (B) of the High Remnant showing sample locations and internal structure.

is 589 ± 16 ka, which overlaps at 2 sigma with that of Lower Black Ledge, we believe the age is inaccurate because it does not agree with ages that are stratigraphically above and below it (see below). Although the exact eruptive source is unknown, the Lower Black Ledge flow traveled at least 120 km (distance from the last remnant to the closest vent) and likely over 135 km, if the flow was sourced in the Lava Falls area, where the vast majority of similar-aged remnants are found (Fig. 3A; see the Supplemental File [see footnote 1] for a justification of these extreme lengths). The Lower Black Ledge flow decreased in thickness from ~45 m around RM 183 to ~20 m by RM 260 (Fig. 3B).

Lower Prospect Flow(s)

The Prospect flows are found only in Prospect Canyon, near RM 179L (Fig. 10). The flows can be divided into two groups, Lower and Upper Prospect, which are separated by a red fine-grained sediment layer. Two remnants of the Lower Prospect flow(s) sampled across the Toroweap fault yielded ages of 544 ± 22 ka and 636 ± 45 ka. The disparity in the ages and differences in their major-element (Fig. 5A) and REE signatures (Figs. 5B and 6C) suggest that they are not part of the same flow. Although the flow in the footwall of the Toroweap fault is geochemically similar to Toroweap A, the ages do not support that correlation. Karlstrom et al. (2007) suggested that a remnant originally mapped as D-dam may be related to Lower Prospect based on similarities in age (no chemistry is available).

Buried Canyon Flows

The only complete cross section of a lava dam in Grand Canyon is the stacked ca. 575–500 ka Buried Canyon flows at river mile 183, which filled a Colorado River paleochannel (Fig. 11). Our mapping suggests that there are seven eruptive units (Fig. 11), whereas, Hamblin (1994) identified nine

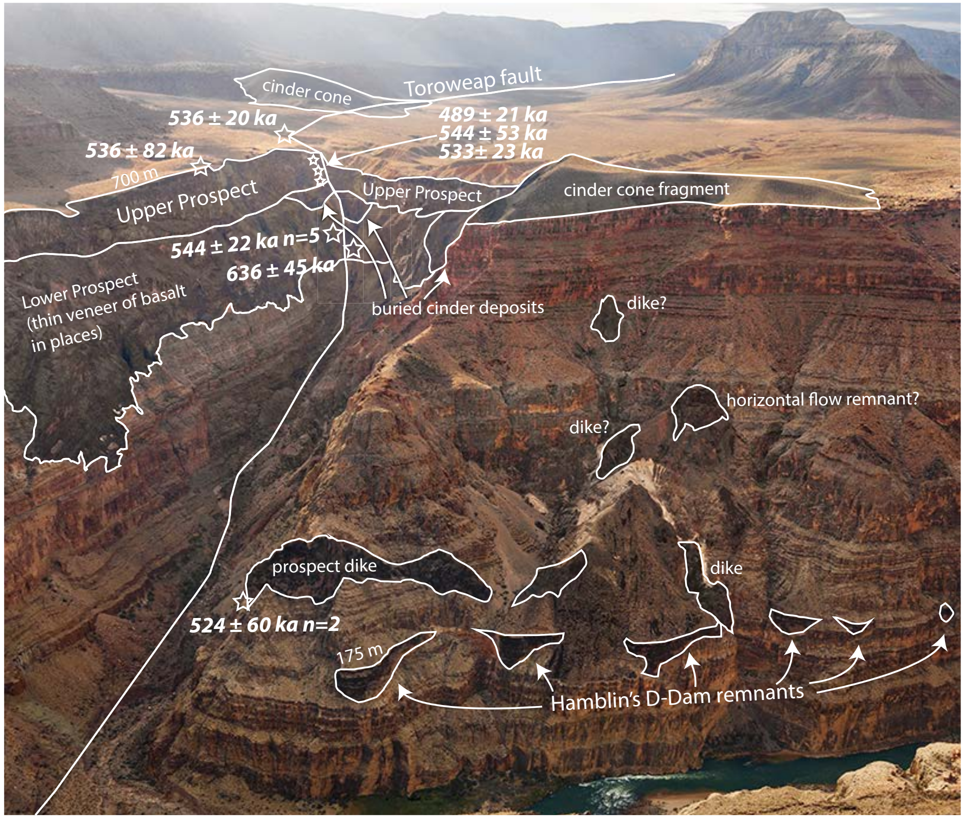

Figure 10. Annotated photograph of Prospect Canyon showing the extent of the Prospect flows and associated dikes. Cinder cone fragments under the Upper Prospect flows indicate it was likely sourced from the south rim when a large edifice was built on the southern flank of Grand Canyon. Heights are above modern river level. ^{40}Ar/^{39}Ar ages from Karlstrom et al. (2007) and Pederson et al. (2002) (photograph taken using a helicopter by Aerial Filmworks; view to the south).

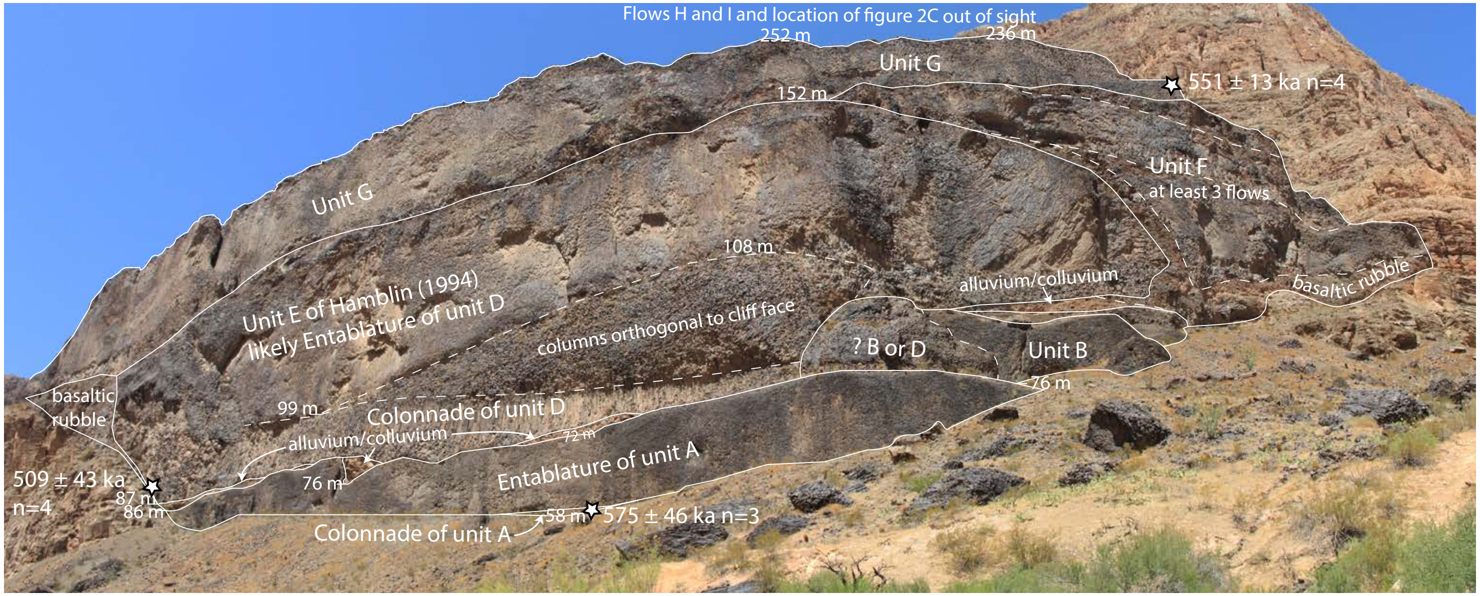

Figure 11. Annotated photograph taken from river level toward the northwest showing the Buried Canyon flow sequence and the locations of new geochronologic constraints. Heights above modern river level (MRL), determined by laser range finder, are also shown for key contacts.

flow units (his units A–I). We could not find evidence for flow C and suggest that units D and E may be different cooling zones within the same flow. Hamblin's units A, D, G, and I have new weighted mean ages of 575 ± 46 ka, 509 ± 43 ka, 551 ± 13 ka, and 494 ± 13 ka, respectively. Although the individual dates on flows A and G are potentially separated by ca. 100 ka, the low precision of the mean ages is also consistent with rapid emplacement potentially during a single eruption. The individual dates on flow I and A suggest at least 5 ka difference between those flows; however, the fact that none of the three duplicate dates on the same flow A sample overlap at 2 sigma suggests major uncertainty in its age beyond the analytical error on any one date. Buried Canyon A is similar in age to Lower Black Ledge; however, slight differences in the REE profiles (Fig. 6D) and larger differences in major-element chemistry (Fig. 5A) make this possible correlation uncertain; additional testing is needed.

Interbedded gravels sit on top of Buried Canyon A, B, and F. The gravel atop A has far-traveled Colorado River clasts, indicating that the Colorado River aggraded such that sediment was being transported over the dam. The gravels atop flow B are entirely composed of rounded basalt pebbles (up to decimeter scale) with a matrix of cm-scale clasts of hyaloclastite that appears to be reworked. The gravels are overlain by a thin flow that has pillows and then locally sourced colluvium. The entirely basaltic composition of the pebbles indicates that the river was impounded upstream, preventing passage of far-traveled detritus. The presence of colluvium suggests a significant amount of time between flow events. The gravels above F were mentioned by Hamblin (1994) but were not examined as part of this study. The presence of these gravels, along with the discontinuous nature of units B and F, suggests that individual flows were overtopped and partially eroded in some cases prior to the next flow event and that the Buried Canyon dam may have been relatively long lived (centuries to millennia). By at least 492 ± 32 ka, the river had established its new channel south of the basalt-filled Buried Canyon channel and incised back to near its previous level based on new dating of the 183.4-mile remnant (see below).

The top of the highest Buried Canyon flow (I) is ~200 m above the base of the paleochannel. Hamblin (1994) reports that the upper flows are overlain by a 60-m-thick deposit of well-rounded gravel with clasts up to 1 m in diameter. We climbed up the upstream end of the Buried Canyon remnant and verified the presence of the gravels, which are entirely basaltic and likely represent the overtopping of the Buried Canyon dam (Fig. 2C). A clast from this deposit gave an age of 477 ± 10 ka, similar to the age on the topmost Buried Canyon flow (I). We did not measure the thickness of the gravel but estimate the thickness to be at least 6 m at the outcrop we visited (Fig. 2C). The top of the gravel was obscured by colluvium.

Older Whitmore Flow

Although the vast majority of eruptions producing the episode 2 intracanyon flows seem to have occurred in the Lava Falls area, basalts of this age have also been found in the Whitmore Wash area (Fig. 1). Raucci (2004) obtained a single ^{40}Ar/^{39}Ar date of 540 ± 30 ka on a basalt flow 4 km up Whitmore Canyon (Older Whitmore Sink of Fenton et al., 2004). ^{40}Ar/^{39}Ar dating of the base of the Whitmore flow stack at the confluence with the Grand Canyon (Fig. 12A) indicates that correlative flows never reached Grand Canyon or that they were subsequently removed before emplacement of the younger flows. Since it is unclear if these flows reached the Grand Canyon, we do not include them as a separate intracanyon flow or dam.

Upper Prospect Flows

The Upper Prospect flows, which overlie Lower Prospect, give a weighted mean ^{40}Ar/^{39}Ar age of 515 ± 23 ka (Pederson et al., 2002). The Prospect Dikes, which outcrop west of the mouth of Prospect Canyon (Fig. 10), have been dated at 524 ± 60 ka (Karlstrom et al., 2007). Although chemical data for the dated dike samples are not available, we suggest, based on their proximity and similarity in ages, that the Prospect Dikes are the source of the Upper Prospect flows (Crow et al., 2008). Cinder cone fragments below the Upper Prospect flows (Fig. 10) are likely the remains of the volcano that erupted to produce the Upper Prospect flows. About 2.5 km upstream from Prospect Canyon, on the south rim (RM 178.1L), a flow remnant at the base of a cinder cone has been dated at

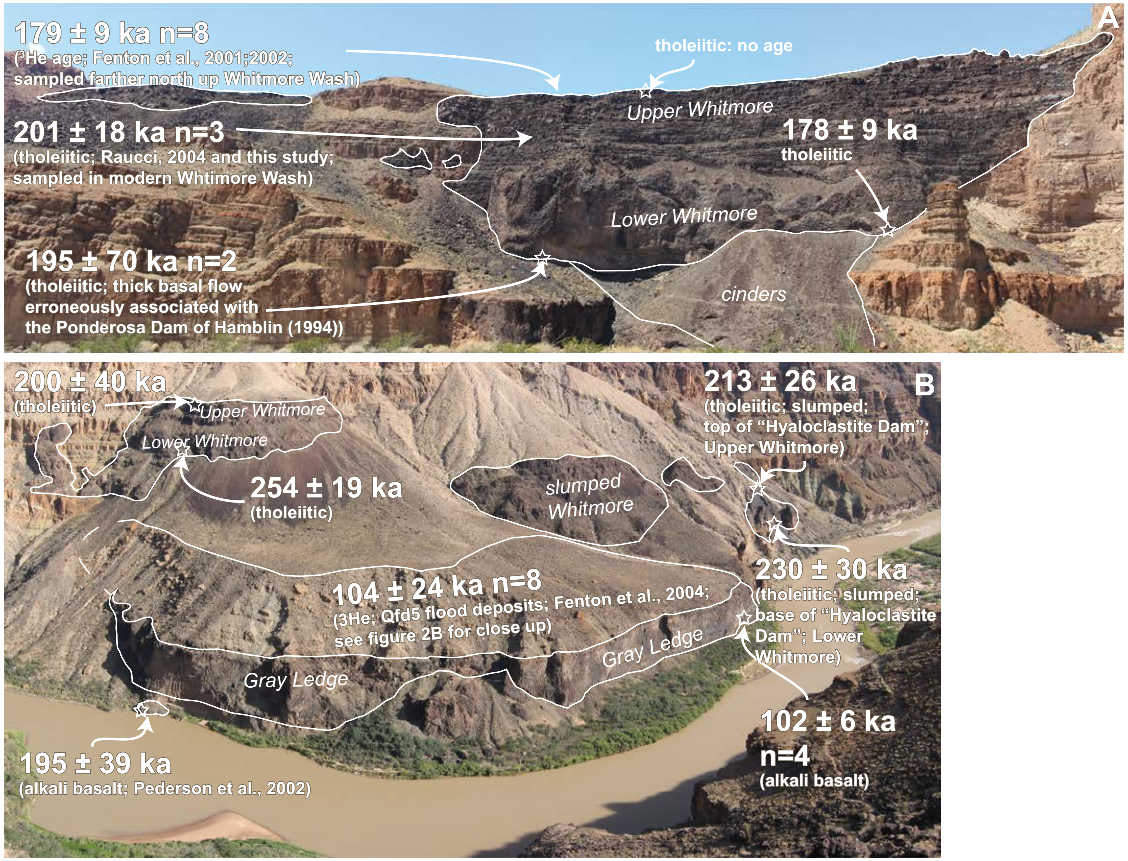

Figure 12. Photographs of Whitmore remnants at RM 187.6, annotated with the best available geochronology. The photographs were taken from the river toward the northwest (A) and the north rim toward the southeast (B).

490 ± 20 ka; we name it the 178-mile cascade (Fig. 13). Discontinuous remnants in a small unnamed tributary down slope from the dated remnant suggest that this flow likely reached the canyon bottom. The newly dated 178-mile cascade remnant is similar in age to the Upper Prospect flows and the Prospect dikes suggesting that multiple vents on the south side of the canyon may have been active at Upper Prospect time. No other remnants of the Upper Prospect flows are known. Differences in the geochemistry of the Upper Prospect flows (Figs. 5A, 5B, and 6E) suggest multiple eruptions of distinct or evolving magmas.

Hamblin (1994) suggested that Prospect flows resulted in the highest lava dam in Grand Canyon, almost completely filling the canyon to a height of 700 m above MRL. This interpretation is based on the projection of the Upper Prospect flows, which are only known on the south side of the canyon, across the canyon to the north. Although such a large volume of lava erupted on the flank of the canyon would likely have resulted in far-traveled intracanyon flows, none have been identified, and a lack of correlative remnants on the north side of the canyon suggest that the Upper Prospect flows need not have been part of a single high dam that blocked the Colorado River.

Upper Black Ledge Flow

The geochemically defined Upper Black Ledge remnants are only found between RM 189 and 208, but analysis of remnant heights suggests they are present to RM 226 (Fig. 3C). The REE patterns for the Upper Black Ledge flow

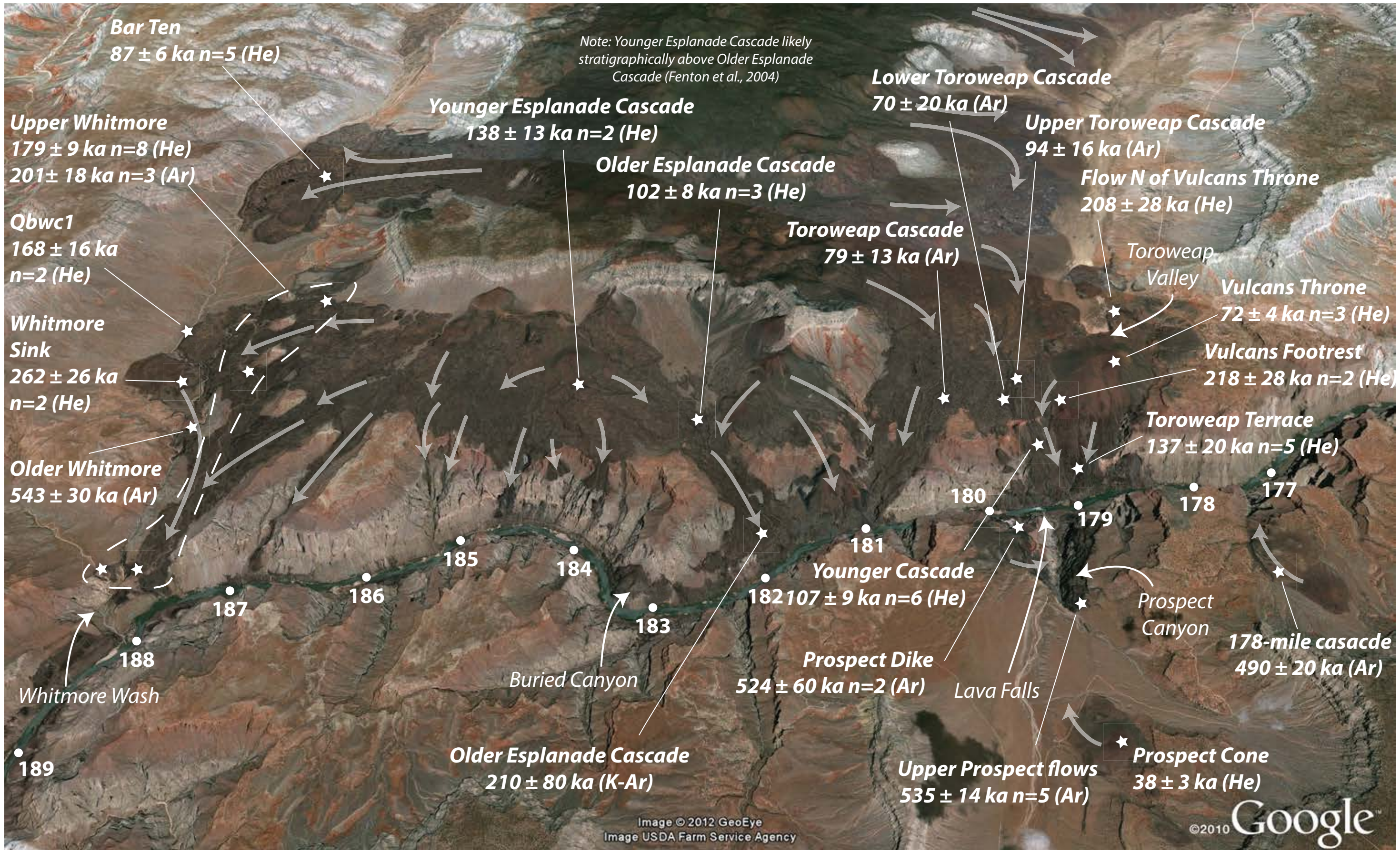

Figure 13. Three-dimensional perspective view of the southern Uinkaret volcanic field showing the locations of lava cascades and their ages. ^{3}He ages from Fenton et al. (2004). ^{40}Ar/^{39}Ar ages from Pederson et al. (2002), Raucci (2004), Karlstrom et al. (2007), and this study. ^{40}K/^{40}Ar ages from Hamblin (1994).

are very similar to that of Vulcans Anvil (Figs. 5B and 6B), a cylindrical basaltic mass that protrudes ~15 m from the river, at RM 178 (Fig. 8). Maxson (1949) suggested it was the remnant of a lava dam, but the fact that the top of the feature is below the paleostrath level determined from dating nearby perched river gravels (Karlstrom et al., 2007) indicates that an alternate hypothesis is needed. New paleomagnetic analyses on Vulcans Anvil and a nearby presumably coeval sill show similar mean paleomagnetic directions that overlap at the 95% confidence level with each other and the axial dipole direction (Supplemental Fig. SF6B [see footnote 1]), indicating that it has not rotated significantly and is unlikely to have fallen into its current position. Thus based on this information, its shape, and its alignment with dikes in the adjacent canyon walls, we agree with Hamblin (1994) that Vulcans Anvil is a volcanic plug.

A new $^{40}Ar/^{39}Ar$ age of 530 ± 30 ka on Vulcans Anvil supports its correlation to the 525 ± 26 ka Upper Black Ledge flow. This could explain the long length of the Upper Black Ledge flow because the lava would spread out less in a canyon setting (Hamblin, 1994). If the Vulcans Anvil vent is also the source of the older Lower Black Ledge flow, this would also explain its even longer length. Based on reconstructions of the original thickness, we suggest that the Upper Black flow was ~70 m thick at Vulcans Anvil, tapered to ~20 m thick by about RM 230 (Fig. 3D), and was at least 76 km long (distance between Vulcans Anvil and the last remnant correlated to Upper Black Ledge).

183.4-Mile Flow

Inset into tephra on the other side of a bedrock divide from Buried Canyon, at RM 183.4R, is a remnant originally mapped as Lava Falls. Although we suspect that the outcrop may have been slumped to its current position partially below MRL, new paleomagnetic analyses indicating that the mean paleomagnetic direction of the direction remnant is only ~11° from the axial dipole direction, suggest that a major rotation has not occurred (Supplemental Fig. SF6E [see footnote 1]). It is, however, possible that the remnant slumped down along the contact with the tephra without rotating significantly. It has a weighted mean age at 492 ± 32 ka. Since this remnant is significantly older and geochemically distinct from the main Lava Falls remnant (Fig. 6F; note that we relate the main Lava Falls remnant to Lower Gray Ledge; see below), we refer to it as the 183.4-mile remnant.

Toroweap Flows

The stacked Toroweap flows in the cliff face on the north side of Lava Falls rapid form a complex set of five flow units with interbedded gravel, colluvium, and hyaloclastite (Fig. 14). They rest on mainstem river gravel and are cut by the Toroweap fault. Flow units A, B, and C have new weighted mean ages of 485 ± 7 ka, 588 ± 17 ka, and 427 ± 4 ka, respectively. These ages are inconsistent with the flow stratigraphy as the Toroweap flows were deposited one atop the next. Assuming the ages are basically correct, either the Toroweap A date is erroneously young, or the Toroweap B date is erroneously old. The Toroweap flows are displaced ~50 m by the Toroweap fault, which is thought to have had a steady slip rate of ~100 m/Ma over the past 500 ka (Fenton et al., 2001; Karlstrom et al., 2007). This would suggest that the Toroweap A flow should be ca. 500 ka. Because of this, we suggest that the Toroweap B date is inaccurate.

Based on 3–5 m of well-rounded gravel between Toroweap B and C flows, Hamblin (1994) suggested the dam was overtopped at least once while the multi-flow dam was being emplaced. The E and F flows in the Toroweap flow stack, shown in Figure 14, have not been dated or sampled for geochemistry and thus cannot be definitively correlated to other intracanyon flow remnants. Toroweap C[4], E, and F are a series of basalt flows that transition from a massive flow in the downstream direction to interbedded basalts and hyaloclastites, which dip ~10° in the upstream direction. These dipping layers of hyaloclastite likely represent the upstream flow of basalts into standing water impounded behind the Toroweap dam. The highest remnant in the Toroweap F flow suggests an original thickness of at least 395 m.

We suggest that Hamblin's "Black Ledge" remnant at RM 179.5R, which he suggested was inset into the Toroweap flow stack (Fig. 14), is actually part of the Toroweap A flow. This is supported by geochemical similarities (Figs. 5B and 6C) and its 458 ± 12 ka age, which is much younger than either Lower or Upper Black Ledge. The RM 179.5R remnant is slightly younger than Toroweap A but overlaps with the age of Toroweap C. Our examination of the supposed contact indicates that it is a cooling feature. Columns radiate away from it in both units indicating that it was a primary fracture in the basalt that became a cooling front (see below for more on these types of cooling structures). Hamblin used the supposed inset relationship of this remnant to infer a young relative age for the Black Ledge flows, which $^{40}Ar/^{39}Ar$ shows are actually among the oldest in Grand Canyon. This shows how miscorrelations between key outcrops can result in an incorrect flow sequence.

Although the Toroweap and Buried Canyon flows have similarities, including gravels on top of the second flow, evidence for significant incision after the second flow and prior to the third, similar heights to their base and top, and similar geochemistry (Figs. 5B and 6G), the geochronology indicates that the basal flows are not related. Buried Canyon A has a weighted mean age of 575 ± 46 ka, which is significantly older than the mean age of 478 ± 24 ka for the Toroweap A flow; also none of the individual ages overlap at 2 sigma. The age of Buried Canyon I, 494 ± 13 ka, is similar to Toroweap A; but the fact that Buried Canyon I is >100 m higher than Toroweap A suggests the two are not related.

Ponderosa Flow

The Ponderosa remnant at RM 181.6 R, named by Hamblin (1994), has been dated at 424 ± 17 ka. Although it has some geochemical similarities to Lower and Upper Prospect and Toroweap A (Figs. 5B, 6C, and 6E), differences in age lead us to believe that it is an unrelated dam remnant.

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[4] Note that there is no Toroweap D in the nomenclature of Hamblin (1994).

Figure 14. Annotated photograph taken from the south rim, toward the north, showing the opposite side of Grand Canyon above Lava Falls rapid, showing ^{40}Ar/^{39}Ar (bold) and ^{3}He (italic) ages on basalt remnants. The lettered flows near the canyon bottom are part of the Toroweap flow sequence.

Episode 3: 400–275 ka: 177-Mile Flow

Following an apparent volcanic lull from 425 to 350 ka (Fig. 4), isolated eruptions in the Lava Falls area resumed. In the following 100 ka, only one intracanyon flow, the 177-mile flow, has been identified in contrast to the ten flows that occurred during episode 2.

177-Mile Flow

Upstream from the Toroweap fault is a small remnant dated at 353 ± 25 ka, named the 177-mile flow (Fig. 7) because it is located at RM 177.3L. The top of the remnant slopes upstream, indicating that it flowed upstream at least a short distance (Crow et al., 2008). The base of the flow, which has pillow structures, overlies mainstem Colorado River gravel (Pederson et al., 2002). Remnants 27 and 17 km downstream, below Whitmore Wash, at RM 194.8R and 204.6L, mapped as Massive Diabase by Hamblin (1994), are believed to be correlative based on a new ^{40}Ar/^{39}Ar ages of 341 ± 25 ka and 312 ± 11 ka, respectively, and similarities in major-element and REE concentrations (Figs. 5A, 5B, and 6H). Similarly, remnants mapped as Layered Diabase at RM 192L and 183.9R have similar ages of 334 ± 39 ka and 320 ± 13 ka, respectively. Although no geochemistry is available for the Layered Diabase remnants, we tentatively group them in with the 177-mile flow. We suggest that the terms Layered and Massive Diabase should be dropped because the remnants are not shallow intrusions as the term diabase implies; instead, we suggest that these specific remnants now be referred to as part of the 177-mile flow. Extrapolation of the upstream-dipping surface indicates the 177-mile flow probably did not extend far past its most upstream remnants (Figs. 3E and 3F). The downstream part of the flow was at least 44 km long and had a thickness of ~60 m (Fig. 3F). Based on the reconstructed top of this flow, its vent area and/or cascade site is inferred to be in the Lava Falls area (Fig. 3F).

Episode 4: 275–150 ka: Major Volcanism Begins in the Whitmore Wash Area

Starting ca. 250 ka, the locus of volcanism shifted to the Whitmore Wash area (Fig. 1). A number of thin flows poured down that tributary almost completely filling it and partially filling at least a 5.5 km reach of Grand Canyon. At ca. 200 ka, multiple cascades entered Grand Canyon downstream from Lava Falls, forming the Lower Gray Ledge and 180.8-mile flows.

Upper and Lower Whitmore Flows

Whitmore Wash, a tributary to Grand Canyon, was completely filled with more than 50 individual basalt flows that originated from cinder cones up that tributary, diverting Whitmore Wash downstream ~1 km. A cross section of the filled paleo–Whitmore Wash is present at RM 187.6R (Fig. 12A), where the now-diverted paleotributary once entered Grand Canyon. The flows that filled Whitmore Wash are distinctive amongst Grand Canyon lava flows in that they are almost all relatively thin (3–6 m thick). Hamblin (1994) referred to them as remnants of the "Whitmore Dam." Fenton et al. (2004) subdivided these remnants into five separate units: the Whitmore Sink flows (Qbws1 and Qbws2: present only in Whitmore Wash), Whitmore Cascade, the top flow of the Whitmore Wash fill (Qbwc2), Qbwc1 (a flow underling Qbwc2 in Whitmore Wash), and their "Hyaloclastite Dam." The "Hyaloclastite Dam" (RM 188.1L) is a slumped region of interbedded hyaloclastites, pillow basalts, and lava flows, which was interpreted to be a dam site (Fenton et al., 2004).

New XRF analyses on 12 Whitmore remnants indicate they are all tholeiites; they plot in the subalkaline field in total alkali–silica space (Fig. 5A) and have normative hypersthene. These same samples also have flat, nearly identical REE profiles indicative of tholeiitic compositions (Fig. 6I). This agrees with Fenton et al. (2002), who suggested, based on REE profiles, that the Whitmore Cascade was a tholeiite but does not support Fenton et al. (2004, 2006), who stated that the Whitmore Cascade is an alkali basalt.

The Whitmore flows cannot be discriminated on the basis of major-element and REE chemistry because of geochemical similarities. Instead we use the available geochronology and stratigraphic position to define two flow units within the Whitmore flows. These units were emplaced stratigraphically above each other, with no known inset relations. At three locations, the top and base of these "Whitmore" flow stacks have been dated (Fig. 12B) at ca. 200 ka and ca. 250 ka respectively. However, the individual ages also overlap at 2 sigma. The ca. 200 ka age for the upper flows agrees well with the weighted mean cosmogenic ^{3}He age (179 ± 9 ka; Fenton et al., 2004) on the topmost flow in Whitmore Wash ("Whitmore Cascade" of Fenton et al., 2004). Although earlier, less precise ages suggested that some ca. 330 ka flows existed within the Whitmore flows, more precise ages suggest the basal flows are ca. 250 ka.

We rely on the distinct weighted mean ages of the stratigraphically separated upper and lower flow units to define the Upper and Lower Whitmore flow units. We include the Qbwc2 and Qbwc1 (Whitmore Cascade) flows of Fenton et al. (2004) in the Upper Whitmore flows but not their Whitmore Sink flows (Qbws1 and Qbws2) because they are alkali basalts not related to Upper or Lower Whitmore (Fenton et al., 2004). We interpret their "Hyaloclastite Dam" to be a slumped "Whitmore" remnant that contains flows from both Upper and Lower Whitmore. The ^{40}Ar/^{39}Ar dating is not precise enough to determine whether a hiatus exists between the Upper and Lower Whitmore flows or they were erupted in quick succession. However, at RM 189L (Fig. 15) and from RM 189.2L to 189.4L (Figs. 16 and 17), Lower Whitmore flows are separated from undated Upper Whitmore flows by a ~2-m-thick colluvial lens, which may represent a hiatus between Lower and Upper Whitmore. We have not been able to verify the reported presence of interbedded fluvial gravels within the Lower or Upper Whitmore flows that Hamblin (1994; p. 58) used to suggest that the Colorado River was overtopping the Whitmore dams as they were constructed.

Lower Whitmore remnants have been identified by ^{40}Ar/^{39}Ar dating between RM 187.5 and 189.6 and are likely present to RM 190.5, where remnants of similarly stacked flows are present at consistent heights of 120–160 m above MRL. Remnants with similar ages at RM 192, 194.8, and 204.6 are not related because they are not tholeiitic. Crow et al. (2008) used these alkali basalt remnants, which are within tens of meters of MRL, to suggest that the Whitmore Dams had a step-like morphology, but the new geochemistry indicates that these alkali basalt remnants are not related to either the Lower or Upper Whitmore flows and are part of the 177-mile flow. The Lower Whitmore flows flowed down Grand Canyon at least 5.5 km and likely much farther. The 85-m-thick basal flow in paleo–Whitmore Wash (Fig. 12A), which Hamblin erroneously related to the Ponderosa flow, is the best estimate of the thickness of the Lower Whitmore flows. However, this is a minimum estimate that does not include the aggraded cinders and gravels under it, which were >100 m thick (see below).

Upper Whitmore flows stratigraphically overlie the Lower Whitmore flows within the same 5.5 km reach. The top of the Upper Whitmore flows, in a 2 km reach below the paleo–Whitmore Wash (RM 187.6), is ~60 m higher on the north side of the canyon as compared to the south side (Fig. 3G). Although this may indicate partial removal, we suggest that it instead indicates ponding of flows on the north rim near where Whitmore Wash enters Grand Canyon. After excluding the high north-rim remnants, analysis of the thickness of the Upper Whitmore (Figs. 3G and 3H) Dam suggests it had a thickness of ~190 m and a minimum length of 5 km.

To help determine the longevity and duration of the Upper and Lower Whitmore flows, we have also examined the deposits immediately above and below them. Cinder deposits tens of meters thick are found below the Lower Whitmore flows at five locations: RM 187.6R (Fig. 12A), 189L (Figs. 15 and 18), 189.4L (Fig. 17), 188.6R and 190.2R. These deposits, partially mapped as outburst flood deposits by Fenton et al. (2004), typically show evidence for reworking by fluvial processes and at RM 189L grade into rounded and moderately sorted basaltic river gravels with up to 1-m-diameter boulders (Figs. 15 and 18). The basaltic gravels are present at 130 m above the ca. 250 ka strath

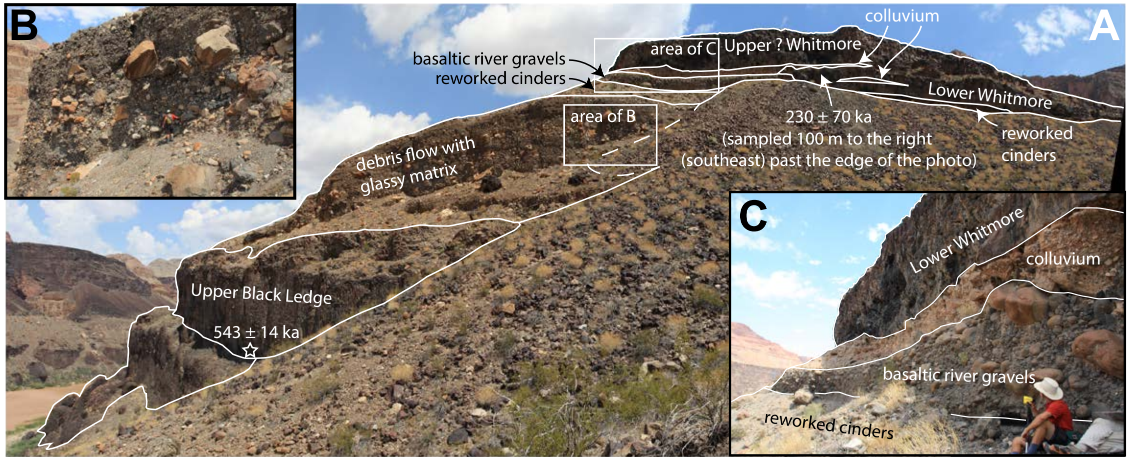

Figure 15. Annotated photographs from near RM 189L showing deposits below the Lower Whitmore flows and above Upper Black Ledge. The view is toward the north.

level. These observations strongly suggest that the Colorado River aggraded over 100 m prior to the emplacement of the ca. 250 ka Lower Whitmore flows. Upper Whitmore is overlain by a ca. 200 ka outburst flood deposit dominated by tholeiitic basalt (Fig. 2A) (see below; Fenton et al., 2004).

Lower Gray Ledge Flow

Hamblin (1994) defined Gray Ledge remnants between RM 185.7 and 192. Karlstrom et al. (2007) suggested that in addition to those remnants, a misidentified Black Ledge remnant at RM 184.6L was also related based on ^{40}Ar/^{39}Ar dating (ca. 115 ka) and now geochemistry (Figs. 5 and 6J). They also suggested that separate Upper and Lower Gray Ledge flows are present based on ^{40}Ar/^{39}Ar ages of ca. 100 ka and 200 ka. We follow the discrimination of Upper and Lower Gray Ledge on the basis of age but also caution that multiple ca. 200 ka Gray Ledge flows have been subsequently redated at ca. 100 ka, suggesting that the original 200 ka dates were incorrect and indicating that only one flow may exist as originally thought.

The ca. 200 ka Lower Gray Ledge is similar in age to a 250 ± 40 ka Lava Falls remnant at RM 182.8R; we suggest that the two are likely related. Reconstruction of the original thickness of the Lower Gray Ledge dam indicates it was at least 110 m thick (Figs. 3I and 3J). Lower Gray Ledge remnants are only known

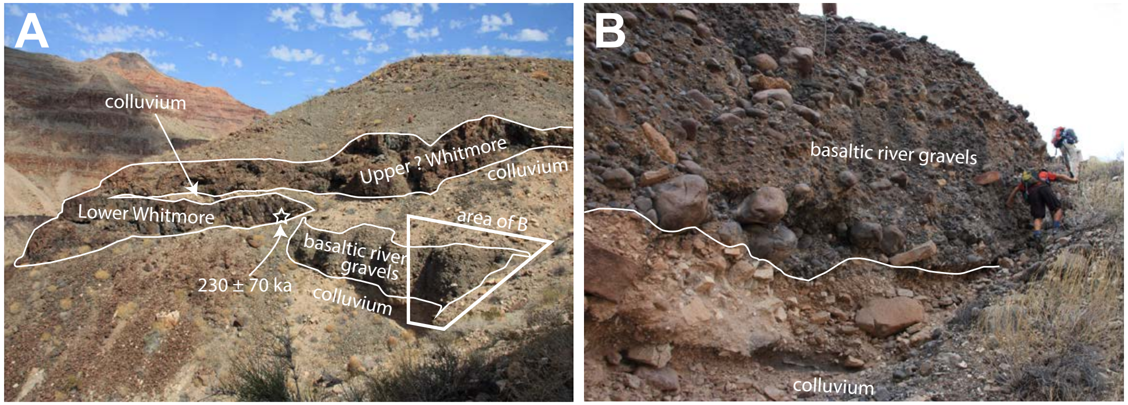

Figure 16. Annotated photographs from near RM 189.2 (river left) of gravels interpreted to pre-date the Lower and Upper Whitmore flows. Colluvial aprons obscure key contacts.

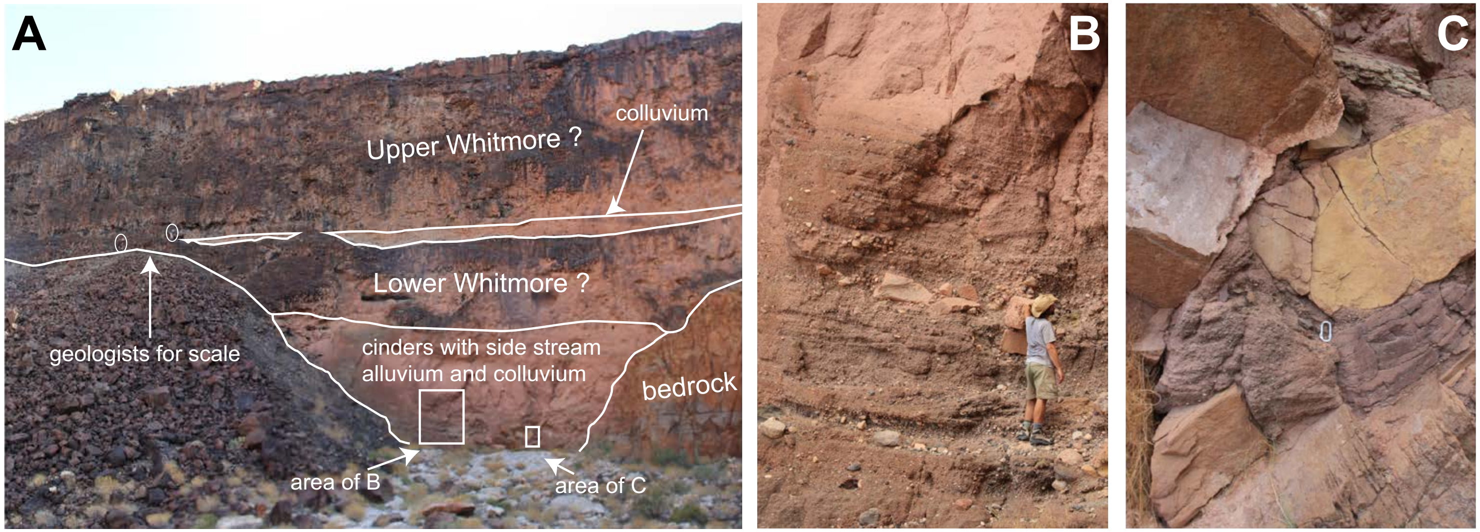

Figure 17. Annotated photographs taken near RM 189.4 (river left) showing the reworked cinders and lenses of sediment at the base of the Whitmore flows.

between RM 182.2 and 187.9, but the flow was likely longer than 16 km based on the location of the last undated Gray Ledge remnant.

The likely source of the Gray Ledge flows is basalt cascades on the north rim between the Lava Falls area and Whitmore Wash (Fig. 13). Apart from the tholeiities in Whitmore Wash, cascades in this area with ca. 200 ka ages include the Older Esplanade Cascade at RM 182R (Hamblin, 1994), a flow north of Vulcans Throne, and Vulcans Footrest (Fenton et al., 2004); see Figure 13 for exact ages. Rare-earth element data indicate that the latter two are not related (Fig. 6K). No geochemistry is available for the Older Esplanade Cascade.

180.8-Mile Flows

About 2.5 km downstream from Lava Falls rapid, at RM 180.8R, is a series of flat-lying basalt flows at the base of a cascade that we call the 180.8-mile flows. Peperite at the base of the flows is underlain by mainstem river gravels and overlain by a 20–30-m-thick irregular shaped hyaloclastite zone in the basalt flow (Fig. 19), suggesting rapid quenching by Colorado River water.

A pillow-like basalt lens in the peperite yielded a ^{40}Ar/^{39}Ar age of 200 ± 30 ka. Although the similarity in age suggests a possible correlation to Lower Gray Ledge, the REE signatures suggest they are distinct (Figs. 5 and 6L). The top of the flow is ~70 m above MRL and is directly overlain by other flat-lying flows. No other remnants of this flow have been found; so an estimate of its length is not possible.

Episode 5: 150–75 ka: 100 ka Cascades and the Upper Gray Ledge Flow

At ca. 100 ka, multiple cascades were active between the Lava Falls area and Whitmore Wash. At least one major intracanyon flow, Upper Gray Ledge, resulted from these cascades. Most of the 100 ka cascades are from eruptions in the Toroweap Valley area and are located between RM 179 and 181; see Figure 13. Three new ^{40}Ar/^{39}Ar ages of ca. 80 ka have been obtained for flows west of Vulcans Throne at the very edge of Grand Canyon (Figs. 13 and 14). We are referring to these as the Toroweap Cascade flows. The three ages that came from two stacked flows give statistically indistinguishable ages with a weighted mean of 82 ± 13 ka. These ages are somewhat similar to cosmogenic ^{3}He dates on the 107 ± 9 ka "Younger Cascade" (Figs. 13 and 14; Fenton et al., 2004). Rare-earth element signatures, however, indicate that Toroweap Cascade and the Younger Cascade may be unrelated (Fig. 6M), suggesting numerous separate low-volume cascades.

Upper Gray Ledge Flow

Upper Gray Ledge is indistinguishable from Lower Gray Ledge in the field; the heights to the tops of the two flows are extremely similar (Fig. 3I), and the geochemistry of the two flows is also similar (Figs. 5 and 6N). The two flows can only be distinguished based on ^{40}Ar/^{39}Ar ages. Dated Upper Gray Ledge remnants give a mean age of 102 ± 8 ka. The basal Esplanade flow at RM 181.2R,

Figure 18. Photograph near RM 189L showing reworked cinders that grade into Basaltic River Gravels below the Lower Whitmore flow.

dated at 117 ± 20 ka, is likely related. This remnant is distinct from the Esplanade Cascades, which entered the canyon in the same area but are not necessarily related. Rare-earth element similarities to Fenton et al.'s (2002) Younger Cascade (Fig. 6M) offer the most likely source of the Upper Gray Ledge flow. The Upper Gray Ledge flow was at least 140 m thick and at least 21 km long based on the location of the last undated Gray Ledge remnant (Fig. 3J).

DISCUSSION AND IMPLICATIONS

The following sections will examine the structure of flows as it pertains to their stability. In particular the discussion will center on the degree to which intracanyon flows backed up Colorado River water and the nature of associated sediment, lava-water interactions, and the failure mechanism of the Grand Canyon's dams.

Effectiveness of Lava Dams at Restricting Flow of Water and Sediment

A natural question is: to what extent did Grand Canyon's intracanyon flows form dams and how rapidly did they fill with water and fluviolacustrine sediments? The presence of rounded river gravels 200–260 m above MRL on top of the Upper Whitmore and the Buried Canyon flows requires that the Colorado River was raised to that level by lava dams. A lack of far-traveled clasts in those monomictic basalt gravels and a lack of coeval aggradation events (Pederson et al., 2006) precluded the possibility that these deposits were due to climate-driven aggradation and suggests that the resulting reservoir had yet to completely fill with sediment. The lake formed behind the 260-m-high Buried Canyon lava dam would have backed water up to the 760 m modern elevation contour (ignoring slip on the Toroweap fault), past Phantom Ranch to about RM 80 (to near Sockdologer rapid in the Upper Granite Gorge) and would have a reservoir capacity of ~5 km^3. Although gravels are not known to overlie the High Remnant and Toroweap flows, the original thicknesses of these dams, 330 m and 395 m, respectively, strongly suggest significant blockages that are likely to have impounded Colorado River water and sediment even if the flows were leaky. This is especially true of dams with long upstream (>1 km in the case of the High Remnant) and downstream run-outs (>135 km in the case of Lower Black Ledge). Although parts of these dams that were underlain by unconsolidated sediments or volcanic debris and contained lava tubes may have been leaky, it is hard to imagine the Colorado River with mean annual floods of 2440 m^3/s (86,000 cfs) (Howard and Dolan, 1981) and a mean annual sediment load of 140 million tons (Smith et al., 1960) passing through the entire length of a dam without constricting flow and backing up an associated lake. Monomictic basaltic gravels within the Buried Canyon and Toroweap flows and above Gray Ledge similarly require 50–75-m-high dams and related lakes, based on the heights of the gravels above the flow bases. We suggest that most if not all of the 17 separate intracanyon flows produced significant impoundments of the Colorado River (lava dams).

Although many of Grand Canyon's lava dam remnants are topped by monomictic basalt gravels, at least a few remnants are overlain by mainstem Colorado River gravels. Near Spencer Canyon (RM 246R), a 27-m-thick Lower Black Ledge remnant has benches, channels, and ~5-m-diameter potholes cut into it; these features are covered in places by a lag of mainstem Colorado gravels, including exotic clasts foreign to Grand Canyon (Crow et al., 2008). In the Granite Park area, between RM 204 and 207, the Qfd3 flood deposits,

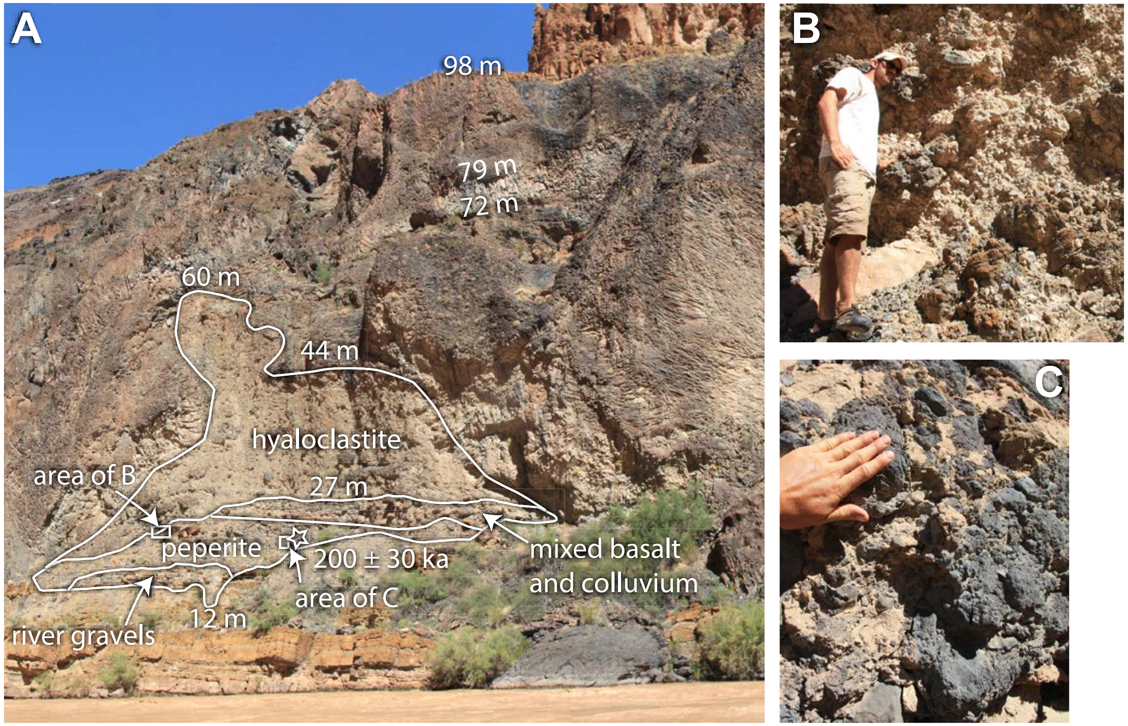

Figure 19. Photographs of (A) the 180.8-mile flow showing a zone of hyaloclastite (B) and peperite (C) indicating lava-water interactions.

which are preserved on top of Upper and Lower Black Ledge remnants, contain exotic clasts deposited by a free-flowing Colorado River at heights of up to 87 m above MRL (Fenton et al., 2004). Exotic clasts have also been found on top of the Buried Canyon A flow. This indicates that the Colorado River aggraded after the Black Ledge and Buried Canyon A flow events and established itself on top of the stable distal portions of those dams.

Studies focused on determining the useful life of modern human-constructed dams give the best estimates of the rates and processes by which sediment would have filled behind Grand Canyon's lava dams. Lake Mead and Lake Powell, located immediately below and above Grand Canyon, have been filling with sediment since their completion in 1935 and 1963, respectively. In both reservoirs, predominantly sand and silt are deposited in downstream prograding deltas that form where flow velocity decreases as sediment laden water enters the reservoir (Ferrari, 1988; Ferrari, 2008). In 1963, prior to the construction of Lake Powell, the annual sediment accumulation rate in Lake Mead was estimated to be ~109,000,000 m^3/a (Ferrari, 2008). Based on its capacity and the sediment accumulation rate, Lake Mead would have completely filled with 40 km^3 of sediment in ~400 years, and Lake Powell should fill with 33 km^3 of sediment in ~300 years. Using modern topography, 400-, 200-, and 100-m-high lava dams at Lava Falls would have maximum capacities of ~27, 3.6, and 0.6 km^3 and would completely fill with sediment (ignoring compaction) in 248, 33, and 6 years, assuming historic pre-dam sediment accumulation rates (Supplemental Fig. SF7 [see footnote 1]). Since we know that during glacial periods the sediment load in Grand Canyon was much higher, causing the river to aggrade (Pederson et al., 2006), the time needed to completely fill the resulting reservoirs of a lava dam with sediment should be considered maxima. Mean annual water discharge from 1923 to 1962, measured in Grand Canyon near Phantom Ranch (RM 87), suggests that ~15 km^3 of water passed through Grand Canyon annually prior to dam construction. This would completely fill dams that were 400, 200, and 100 m high to overtopping in 1.8 years, 13 weeks, and 15 days, respectively (Supplemental Fig. SF7 [see footnote 1]).

Hamblin (1994) identified proposed lake sediments throughout Grand Canyon all the way up to Lees Ferry. These deposits vary from fine-grained siltstones to diamictons and gravels and were interpreted to have formed in deltaic environments, as would be expected in the upstream portions of a reservoir. Kaufman et al. (2002) suggested, as earlier and subsequent works have (Machette and Rosholt, 1991; Anders et al., 2005; Pederson et al., 2006), that the supposed deltaic deposits are mainstem river gravels in fill, strath, and side-stream terraces, and debris-flow deposits. The ages of the mainstem terraces, determined by U-series dating of calcite cement around gravel clasts and optical stimulated luminesce dating of sands (Pederson et al., 2006; Crow et al., 2014), do not agree well in most cases with the timing of intracanyon flows. During the past 400 ka, the period over which the ages of fill terraces have been determined, four aggradation events have been identified at 15 ka, 50 ka, 110 ka, and 320 ka. Only the earlier two episodes correspond to times of intracanyon volcanism, specifically the Upper Gray Ledge and 177-mile flows. The fact that the other younger episodes do not correspond to times of intracanyon volcanism and because other known times of intracanyon flows are not associated with fill terraces suggests that most of the fill terraces are a response to climatic fluctuations that affect sediment supply and stream power (Pederson et al., 2006) and are not due to lava dams.

Kaufman et al. (2002) revisited many of the siltstones reported to be lake deposits and determined they were too young to be associated with lava dams and likely formed in spring-fed pools. Supposed lake deposits at Elves Chasm and in Havasu Creek are interpreted to have formed in shallow travertine-dammed pools. Deposits in the Surprise Valley area are landslide deposits (Huntoon, 1975) but may have been triggered by lava dam lakes. Red Slide is a coarse colluvial wedge containing debris flows with bedding and cross-bedding parallel to the modern canyon walls, not an upstream-fed delta.

Erosional remnants of lake deposits associated with potentially analogous lava dams exist throughout the world (Howard et al., 1982; Malde, 1982; Righter and Carmichael, 1992; Kataoka et al., 2008; Ely et al., 2012; van Gorp et al., 2013) and remain for up to 1.8 Ma. Lakes are also inferred to have formed behind lava dams on the Yukon and Fraser rivers in Canada, which have larger discharges than the Colorado River in Grand Canyon. Modern basaltic lava dams have also impounded large lakes (e.g., Brown, 1969; Ólafsson, 1979). Although these environments may have greater preservation potential for lacustrine deposits, one would expect vestiges of lacustrine deposits in Grand Canyon if long-lived lakes existed there during the past 0.85 Ma. Although a lack of lake deposits in Grand Canyon may indicate that Grand Canyon's intracanyon flows were leaky (Crow et al., 2008) and short lived (Fenton et al., 2002; Kaufman et al., 2002; Fenton et al., 2004; Fenton et al., 2006), unequivocal evidence for damming requires that lake deposits once existed in Grand Canyon. They were either completely removed or have yet to be found.

Lava-Water Interactions

The structure of Grand Canyon's lava dams varied greatly over their length. Textures indicative of water-lava interactions, including pillows, peperite, and hyaloclastite, are only known near the upstream-most extent of the 177-mile, Toroweap, 180.8-mile, and Lower and Upper Whitmore flows, indicating that the upstream part of intracanyon flows was quenched quickly by river water. A lack of these features in the far-traveled parts of flows (i.e., Black Ledge, 177-mile, Whitmore, and Gray Ledge flows) indicates that the Colorado River was temporarily blocked during early stages of dam formation and that much of the erupted volume flowed down a mostly dry river bed (Hamblin, 1994).

The Toroweap flow stack is one of the best examples of the structure contained within the upstream-most end of a flow. The Toroweap A flow transitions from a massive flow to almost entirely peperite in the upstream direction (Hamblin, 1994). Toroweap C, E, and F also transition in the upstream direction from solid basalt flows to deltaic foresets of hyaloclastite and basalt that dip ~10° in the upstream direction. Deltaic foresets composed of hyaloclastite and pillow basalts in other regions have also been interpreted to represent the upstream flow of lavas into standing water (Jones and Nelson, 1970; Howard et al., 1982; Huscroft et al., 2004; Andrews et al., 2012; Ely et al., 2012), suggesting that a lake was forming behind the dam created by Toroweap A and B when C, E, and F were emplaced.

The 200 ka 180.8-mile flows, below Lava Falls, also comprise an excellent example of the upstream structure of an intracanyon flow. At RM 180.8R, ~30 m of hyaloclastite overlie peperite and mainstem Colorado River gravels, strongly suggesting that the 180.8-mile flows poured directly into the Colorado River, which rapidly quenched and brecciated the lava. More examples of these types of lava-water interactions are plausibly lacking because pervasively fractured basalt formed during quenching is much less resistant to erosion and was likely removed during dam failure.

Additional evidence for lava-water interaction comes from cooling textures observed in many intracanyon lava flows. Most of Grand Canyon's intracanyon basalt flows exhibit two-tiered cooling structures with a relatively thin zone at the base of flows composed of large-diameter (up to 1 m) well-formed vertical columns, referred to as the colonnade, which is overlain by a much thicker zone of irregularly oriented columns (typically 10–20 cm diameter), referred to as the entablature (Fig. 20A). These textures were first described by Tomkeieff (1940) and are widely thought to form when water penetrates the flow top and cools the upper part of the flow convectively (downwards), forming the entablature, while the lower colonnade cools slowly (upwards) by conduction (Swanson, 1967; Saemundsson, 1970; Bjornsson et al., 1982; Long and Wood, 1986; Degraff et al., 1989; Walker, 1993; Lyle, 2000). Direct observation of the Kilauea Lake indicates that rainfall of <250 cm/a is insufficient to generate entablatures (Hardee, 1980), indicating that precipitation an order of magnitude greater than present-day amounts of 20–50 cm/a (Daly and Taylor, 1991) is needed, if rainwater alone is the source of the water influx that cooled the entablature zone. Although the Grand Canyon region was likely wetter during glacial times, recent studies in south-central Utah suggest precipitation was only nominally greater (150% of modern) there during the latest glacial maximum (Marchetti et al., 2011). The close association of entablature occurrences to basalt-filled rivers suggests that these cooling structures probably form most often due to stream flow on top of cooling lava (Saemundsson, 1970; Long and Wood, 1986; Degraff et al., 1989). In many flows, the smaller columns that make up the entablature radiate away from primary fractures (Fig. 20B) suggesting that water-steam convection in those fractures created

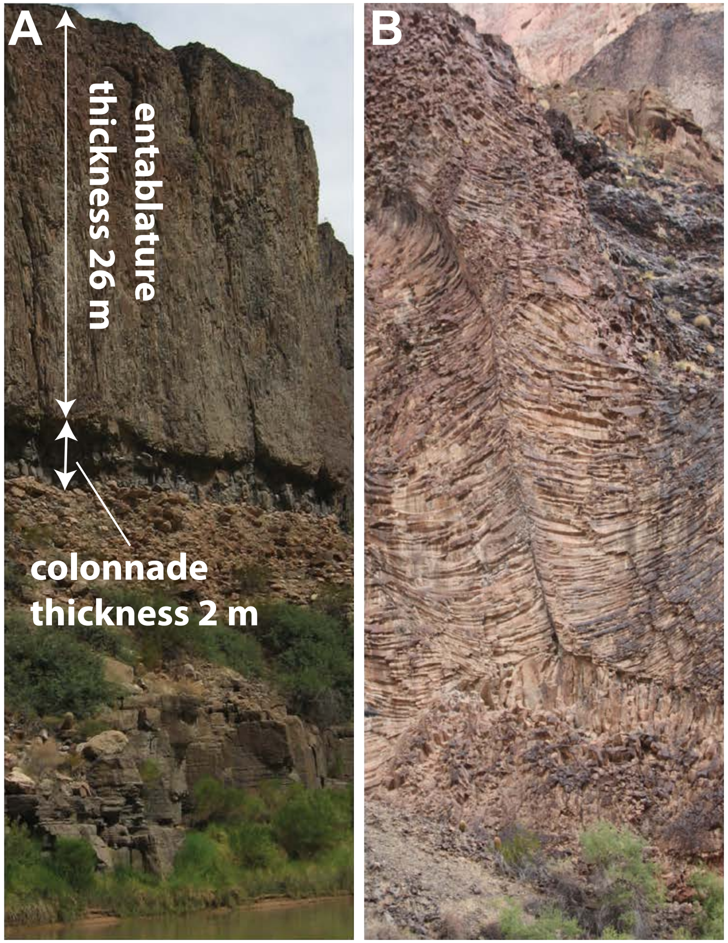

Figure 20. Photographs of intracanyon dam remnants showing cooling structures. (A) Columns in the entablature of a remnant at river mile (RM) 184R are orthogonal to a master fracture due to convective flow of water in the fracture. (B) Most remnants (like this one from RM 194R) have a much thicker entablature than colonnade that were likely formed as the Colorado River flowed over them.

cooling fronts within the flow. Simple numerical cooling models based on the time needed to form the colonnade by conduction alone (Degraff et al., 1989) and the assumption that flows fully solidify when the downward- and upward-migrating fracture systems meet, can be used to estimate the time needed for solidification. In Grand Canyon, these models suggest solidification times of a few months to as many as three years, during which the Colorado River was likely flowing over the flows. Thus the two-tiered cooling structures, in most of Grand Canyon's lava flows, strongly suggest that many flows were overtopped by Colorado River water while the flows were still solidifying. This is reasonable as average-height lava dams (200 m) are expected to be overtopped by Colorado River water in about a year given historical discharges.

Outburst Flood Deposits

In order to more fully understand how structural and geometric differences in Grand Canyon's lava dams might affect the mechanisms by which they failed, reconstructed lava dams need to be related when possible to the often monomictic basalt gravels produced during their removal. Fenton et al. (2004) identified five such deposits, named Qfd1–5, in order of decreasing age, which they interpreted to be outburst-flood deposits. Although some of these are clearly related to outburst-flood events, others are plausibly related to more gradual failure mechanisms, and we use the non-genetic term monomictic basalt gravels when describing similar deposits without structures clearly indicative of outburst flooding. Although Fenton et al. (2004) proposed possible correlations between four of their flood deposits and specific dams on the basis of geochemical similarities, only ten of Grand Canyon's intracanyon flow remnants were characterized geochemically at the time of their study. The addition of 43 new REE analyses on separate dam remnants warrants the revisiting of the potential links between dams and flood deposits.

Fenton et al. (2004) subdivided their outburst-flood deposits on the basis of age, total alkali–silica classifications from major-element analyses on quenched glass, and REE signatures from both clasts and vitroclasts. Although some deposits, such as Qfd4, are easily identifiable because they contain fairly unique tholeiitic clasts (Fenton et al., 2004; Fenton et al., 2006), other flood deposits, such as Qdf1, Qfd3, and Qfd5, have nearly identical total alkali–silica compositions and were differentiated by Fenton et al. (2004) on the basis of REE signatures. However, large variations in the REE composition of clasts from the same deposit (i.e., >100% different in Qfd5; Fig. 21) indicate incorporation of older remnants during dam failure and/or large analytical uncertainties (see Results section); this makes absolute correlations to a specific dam difficult. Nonetheless we will investigate possible correlations of each of the outburst flood deposits for which geochemical data exist.

Deposit Qfd1 is only known from a single outcrop 1.5 km downstream from Whitmore Wash (RM 189L). Based on the outcrop that we visited there (Fig. 15), we reinterpret it as a mass-failure deposit overlain by rounded basaltic gravels unrelated to catastrophic failure of a dam (see above). The basaltic gravels are unlike other outburst-flood deposits in that they are moderately sorted, well rounded, and contain no clasts greater than ~1 m. Since the deposits overlie Upper Black Ledge and underlie Lower Whitmore, their age is bracketed at ~550–250 ka. Of the known lava dams within this age range, the 177-mile flow is most similar geochemically to the alkali basalt clasts and glasses within the deposit (Fig. 21A). Although the deposit may also be related to Upper Prospect

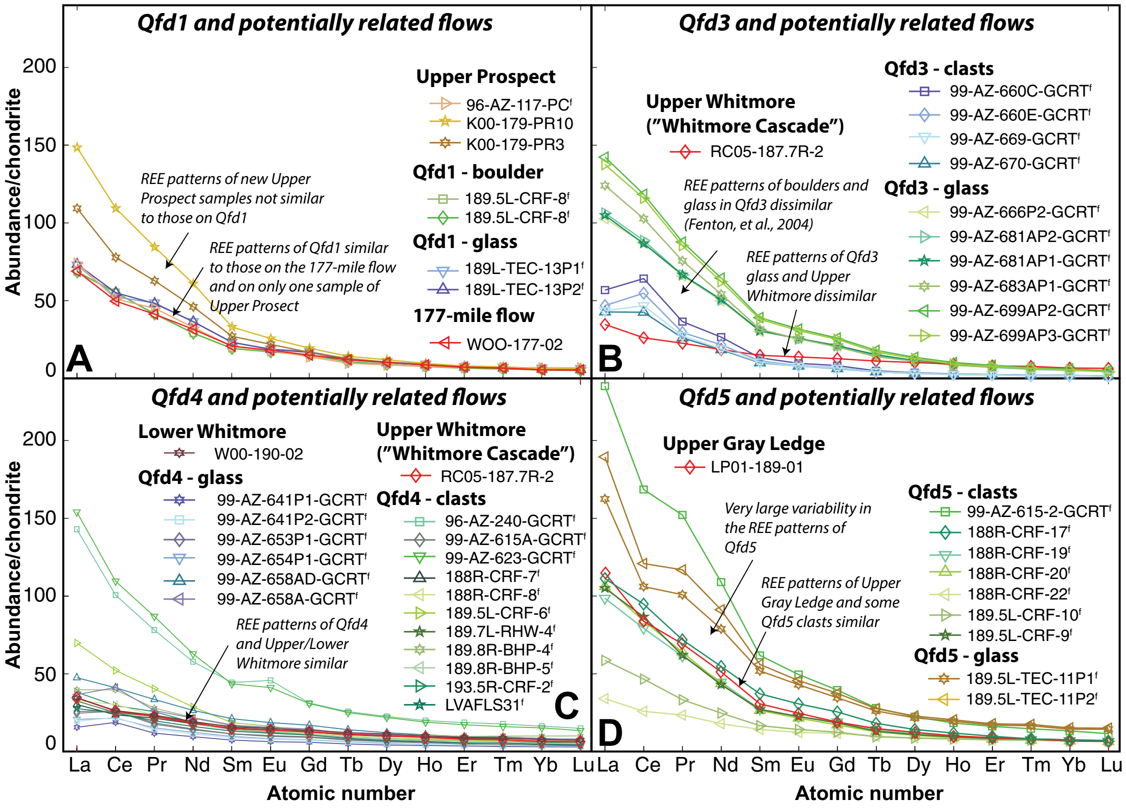

Figure 21. Rare-earth element (REE) plots of outburst-flood deposits and dam remnants that have been proposed as being related. Superscript "f" indicates analyses from Fenton et al. (2002) and Fenton et al. (2004).

as suggested by Fenton et al. (2002), new analyses of flows in that sequence show substantially different compositions that are unlike Qfd1 (Figs. 6E and 21A; Supplemental Fig. SF5E [see footnote 1]).

Deposit Qfd2 was not considered, because no REE data are available for it, and we have not examined it in detail. Deposit Qfd3 has been mapped by Fenton et al. (2004) in the Granite Park area, between RM 203 and 214. Stratigraphic relationships indicate that it is younger than Upper Black Ledge and older than Qfd4 or ~525–200 ka (Fenton et al., 2004). The clasts and vitroclasts in the deposit have separate REE signatures, which, along with the presence of the far-traveled clasts in the deposit, indicate that it has likely been reworked (Fig. 21B; Fenton et al., 2004). Although Fenton et al. (2002) related the glasses to Toroweap A and the clasts to their "Whitmore Cascade," we suggest that given the large uncertainty in the measurements and the large range in both clast and glass REE signatures, meaningful correlations cannot be made. Too many remnants of similar age overlap with the analyses on the glasses, and new analyses on Upper Whitmore ("Whitmore Cascade" of Fenton et al., 2004) do not agree with the analyses on the clasts in the gravel (Fig. 21B).

Deposit Qfd4, present between RM 186 and 193, is perhaps the best understood of the outburst-flood deposits (Fig. 2A). It is mapped easily from images and shows up as a high collar or bathtub ring of rounded basalt boulders. Not only is Qfd4 the best preserved and most continuous of the outburst-flood deposits, but it is also fairly distinctive in the fact that its clasts are dominantly tholeiitic (Fenton et al., 2004). The only other known flows with tholeiitic compositions are Lower and Upper Whitmore, which are ca. 250 and 200 ka, respectively. Rare-earth element profiles from Qfd4 compare well with both Lower and Upper Whitmore (Fig. 21C). Cosmogenic ^{3}He dating of Qfd4 gives a mean age of 162 ± 10 ka (n = 9) with individual ages as old as 201 ± 28 ka, suggesting a ca. 200 ka age (Fenton et al., 2004). This is confirmed by ^{40}Ar/^{39}Ar dating of a large alkali basalt boulder in the Qfd4 deposit (RM 191.6L) at 180 ± 20 ka. In the reach between paleo–Whitmore Wash (RM 187.6) and RM 190.5, Qfd4 is mapped as occurring almost entirely on top of the tholeiitic 200 ka Upper Whitmore remnants.

Fenton et al. (2006) modeled the failure of their "Hyaloclastic Dam" (located at RM 188L), which they thought produced the Qfd4 deposit, estimating discharges of ~10^5 m^3/s (3,500,000 cfs). This is about an order of magnitude greater than the largest prehistoric flood, which had a discharge around 1.4 × 10^4 m^3/s (500,000 cfs) (O'Connor et al., 1994). However, their model, which was dependent on dam breach geometry, was not able to fully account for the geometry of the Qfd4 flood deposits. At the time of their study, the "Hyaloclastic Dam" and the related flood deposits (Qfd4 of Fenton et al., 2004) were the only known tholeiites in Grand Canyon; however, this study shows that tholeiitic remnants related to our Lower and Upper Whitmore flows are common in the reach below Whitmore Wash. Their distribution shows that the dam that failed to produce the modeled flood deposits was almost certainly much longer longitudinally (>5 km) than the dam failure they model, which had a geometry similar to a modern constructed dam. A plausible explanation for the inability of any of their models to explain *both* the high flood deposits in the reach where related dam remnants are present *and* lower flood deposits in downstream reaches (below the dam) is that the flood was smaller than they modeled and occurred when the distal parts of the dam were still in place. This would explain why the flood deposits are almost always found on top of Upper Whitmore remnants, which have similar chemistry and age.

Deposit Qfd5 is present between RM 187 and 194 (Fig. 2B), has a mean cosmogenic ^{3}He age of 104 ± 24 ka (Fenton et al., 2004), and contains sedimentary features unambiguously indicating catastrophic failure. In almost all cases, the flood deposit directly overlies Upper or Lower Gray Ledge remnants, which are indistinguishable in terms of height and only distinguishable by ^{40}Ar/^{39}Ar dating. Only in distal areas, after RM 192, where the height to the top of all far-traveled flows converge (Crow et al., 2008), does it overlie other remnants (Fenton et al., 2004). Although the REE signatures of clasts and vitroclasts in the Qfd5 deposit are amongst the most variable (Fig. 21D), four samples have consistent values that are similar to Upper Gray Ledge (Fig. 21D). The correlation to the ca. 100 ka Upper Gray Ledge dam is supported by the fact that the dam and flood deposit have statistically indistinguishable ages. Fenton et al. (2002) suggested Qfd5 was related to the Younger Cascade, which we believe may have been the source of Upper Gray Ledge dam (see above). The fact that Qfd5 almost always overlies the related Gray Ledge remnants suggests that the flood deposit may have been deposited on top of its far-traveled and longer-lived distal end.

A New Model for Dam Longevity and Failure Mechanisms

Based on the combined data summarized below, we suggest that many of Grand Canyon's dams had a multi-staged failure where the upstream parts of dams failed quickly, in some cases catastrophically, while the downstream far-traveled parts of the dams lasted long enough (tens to hundreds of years and in some cases perhaps millennia) to impound short-lived lakes that backed water up throughout much of Grand Canyon. This is in contrast to earlier models that suggested either long-lived stable lava dams that lasted for tens of thousands of years (Hamblin, 1994) or alternatively that dams failed catastrophically and completely within years of formation, prior to being overtopped (Fenton et al., 2004; Fenton et al., 2006).

The combined observations require that: (1) most dams were overtopped with water during solidification, based on the two-tiered cooling structures; (2) lakes formed behind most of Grand Canyon's lava dams as indicated by basaltic gravels within and on top of flow remnants; (3) at least the Black Ledge dam(s) and Buried Canyon A were overtopped by a free-flowing Colorado River, transporting far-traveled clasts as evidenced by the discovery of those clasts on top of those dams; (4) at least part of some dam failed catastrophically, based on the occurrence of at least one unequivocal outburst flood deposit and possibly many more (Fenton et al., 2002; Fenton et al., 2004); and (5) many monomictic basalt gravels (e.g., outburst-flood deposits) were likely deposited on the distal parts of the failing dam, based on geochemical and geochronological similarities and a suggestion that that might better explain the hydrologic modeling of the "Hyaloclastite Dam" failure.

The simplest model that satisfies these requirements is a hybrid of the end-member models of Hamblin (1994) and Fenton et al. (2002, 2004, 2006) (see Figure 22). We suggest that most dams quickly blocked the river with far-traveled flows pouring down a mostly dry river bed (stages 1 and 2 of Fig. 22). This is indicated by the lack of features indicative of lava-water interactions at the base of far-traveled distal flow remnants. The analogous modern Laki eruptions, in Iceland, completely dammed the Skaftá River within days of entering the Skaftá River Gorge (Thordarson and Self, 1993). Overtopping of Grand Canyon's intracanyon flows must have occurred quickly because two-tiered cooling structures indicate that water flowed over the solidifying flows for months to years (stage 3 in Fig. 22). Based on historical pre-dam discharge records, 100- to 400-m-high dams would have been overtopped with water in days to years. If lava dams were leaky as suggested on the Boise, Snake, and McKenzie rivers (Taylor, 1965; Howard et al., 1982; Malde, 1982), the overtopping may have taken longer, but the cooling structures indicate it took place quickly, before the lava had completely solidified. After being overtopped with Colorado River water, the upstream parts of most dams failed quickly (stage 4 of Fig. 22) due to the weakening of those parts of the dams by lava-water interactions and piping, leakage, or seeping of river water through brecciated basalt, incorporated cinder and/or gravels, and unconsolidated colluvial material at the margins of the dam (Fenton et al., 2004). In at least some cases, this initial failure of the upstream portion of the dam was catastrophic; however, other dams may have failed more progressively due to overtopping by river water, hydraulic erosion, and entrainment of colluvium and dam debris. Either process would produce largely monomictic basaltic gravels with isolated colluvial clasts, if failure occurred before complete filling of the lava dam lake with sediment. Careful study of the sedimentary structures in the monomictic gravels is needed to differentiate between these processes. In this model, the monomictic gravel would be deposited on the longer-lived distal portion of the failing dam and downstream from it. The distal portions of the

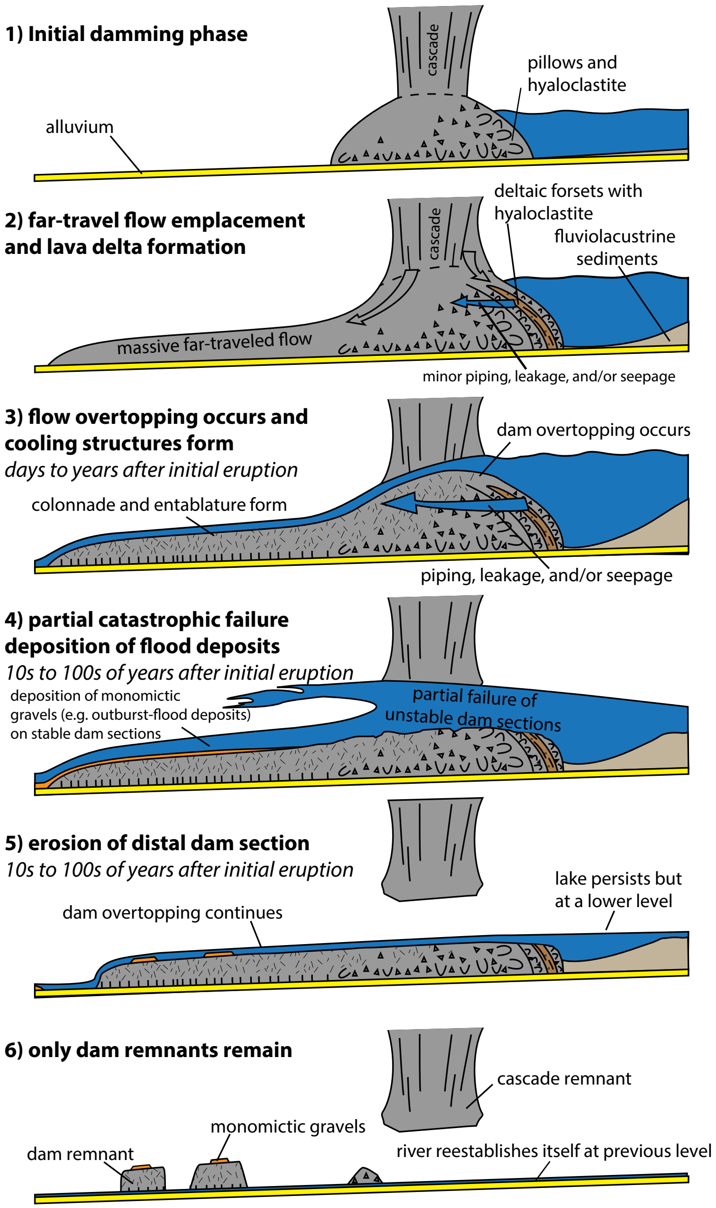

Figure 22. Conceptual model showing the inferred stages of dam failure for those dams that are overlain with monomictic basaltic gravels. The Black Ledge and Buried Canyon A dams, which are overlain by far-traveled gravels, failed only after the related lakes completely filled with fluviolacustrine sediments, allowing far-traveled sediments to overtop them; they likely persisted for longer than those overlain with only basaltic gravel.

dams were likely longer lived due to the fact that they flowed down a mostly dry river bed and were not pervasively brecciated by rapid quenching. Finally, the remaining portion of the dam was removed more slowly due to bed-load abrasion, lateral disaggregation, and plucking of basalt columns as the Colorado River continued to flow over it (stage 5 of Fig. 22). The lack of verifiable lake deposits suggests that many dams may have failed prior to the related lakes filling with sediment, which would have occurred within 10–250 years for 100- to 400-m-high dams. This is especially true for dams whose remnants are currently overlain by monomictic basalt gravels. Dams that are overlain by far-traveled gravels must have remained for significantly longer—long enough for the related reservoirs to completely fill with fluviolacustrine sediments and allow far-traveled sediment to be transported over the dam. From 600 to 400 ka, at least ten separate lava dams formed in Grand Canyon. The heights to the bases of these dams are subequal indicating that each was mostly removed before the next was emplaced. This requires an average lifespan of *less* than 20,000 years and indicates the longest lived dams may have remained for millennia at the most.

Unfortunately, in most cases, $^{40}Ar/^{39}Ar$ geochronology on stacked flows in a single dam is not sufficiently precise to determine the duration over which a dam was constructed. Exceptions are Buried Canyon and Toroweap. At Buried Canyon, the weighted mean ages for flows A through G overlap at two sigma; however, the individual ages indicate that flow I is at least 5 ka younger than A. Flow I overlaps in age with the 183.4-mile flow and is permissively part of that same dam. The geochronology at Toroweap is suspect because dates do not agree with the stratigraphic sequence, thus making determinations of dam longevity there difficult.

CONCLUSION

The combined geochronologic and geochemical data sets presented here define a new basalt-flow stratigraphy for Grand Canyon's intracanyon basalt flows and a new model for Grand Canyon's lava dams. We identify 17 separate flows or series of flows, most if not all of which produced significant impoundments of the Colorado River (lava dams). Although uncertainties in flow correlation and dam geometry persist, the new data indicate that significant revisions need to be made to both the remnant correlations and flow sequence of Hamblin (1994) (Table 2) and to the conceptual framework of high stable dams (Hamblin, 1994) and catastrophic dam failure (Fenton et al., 2002; Fenton et al., 2004; Fenton et al., 2006). Major changes to flow stratigraphy and nomenclature are as follows: (1) Black Ledge remnants of Hamblin (1994) are dominantly composed of two Black Ledge flows that are among the oldest in Grand Canyon; (2) the High Remnant is not related to the Toroweap flows as evidenced by significant differences in major- and REE composition; (3) the 177-mile remnant is correlative with Massive and Layered Diabase remnants of Hamblin; (4) Gray Ledge flows are probably two flows (upper and lower) the older of which is correlative with Hamblin's main Lava Falls remnant and the younger to Esplanade and the Younger Cascade. New names for previously unidentified flows include: the 188.7-mile, High Remnant, Whitmore Rapid, 183.4-mile, and 180.8-mile flows. Of the 17 intracanyon flows, we have identified sufficient remnants to reconstruct much of the original extent of six flows, including: Upper and Lower Gray Ledge, Upper Whitmore, 177-mile flow, and Upper and Lower Black Ledge. Dam thickness varied from 35 m to at least 330 m and possibly as much as 640 m. Dam run-out lengths varied from >5 to >135 km.

From 850 to 400 ka, at least 11 eruptions occurred, resulting in lava dams in the Lava Falls area. The plethora of large remnants and dikes of this age in the Lava Falls area (Fig. 1) indicates that most of these flows likely originated from either volcanoes centered within the canyon there (i.e., Upper Black Ledge and Upper Prospect) or from cascades that entered the canyon in that area. Although most originated from sources on the north rim, at least one cascade of this age has been found on the south rim, and the Upper Prospect volcano likely formed at this time on the southern flank of the canyon. The 177-mile flow was emplaced at ca. 320 ka. Although we do not know its exact source, dam reconstructions suggest it likely entered the canyon near the Lava Falls area. At ca. 250 and 200 ka, the locus of volcanism shifted to the Whitmore Wash area and sent a series of thin flows down that tributary creating the Upper and Lower Whitmore dams. The Lower Gray Ledge and 180.8-mile dams formed during this same period, and they were likely sourced from north-rim cascades between Whitmore Wash and the Lava Falls area. The last of Grand Canyon's lava dams, Upper Gray Ledge, formed at ca. 100 ka and is likely related to the Younger Cascade, which also entered the canyon around Lava Falls.

Evidence for lava-water interactions only in upstream-most parts of lava dams suggests that most dams likely dammed the river quickly. Two-tiered cooling structures present within almost all of Grand Canyon's lava dams indicate that dams were overtopped by the Colorado River soon after emplacement and that the river flowed on top of them for months to years as they solidified. Outburst-flood deposits indicate that parts of some dams failed catastrophically, possibly due to piping, leakage, or seepage through and around the unstable heads of dams where lava-water interactions and incorporated debris would have created instabilities. However, in contrast to earlier models, we suggest that these flood deposits, and the river itself, were in many cases deposited and/or established on top of the still stable downstream sections of the same dam. This is supported by geochemical and age similarities between floods deposits and the flows they overlie. The relative stability of the far-traveled part of lava flows is expected because they likely flowed down a mostly dry river bed and would have been less fractured. A lack of verifiable lake deposits suggests that many dams, especially those overlain by basaltic gravels, were removed by abrasion and plucking of columns before the resulting lakes were fully filled with sediment. Exceptions are the Black Ledge dams and Buried Canyon A, which were overtopped with mainstem river gravels, including far-traveled clasts foreign to Grand Canyon, indicating that the resulting lakes were filled with sediment, thus allowing sediment transport through the lake and over the dam. The Lower Black Ledge flow was over 135 km long and may have persisted as a convexity in the river profile for hundreds to thousands of years, whereas smaller dams were likely removed in tens to hundreds of years.

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