History of Quaternary volcanism and lava dams in western Grand Canyon based on lidar analysis, $^{40}\text{Ar}/^{39}\text{Ar}$ dating, and field studies: Implications for flow stratigraphy, timing of volcanic events, and lava dams

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ABSTRACT

A synthesis of the geochronology on basalt flows from the southern Uinkaret volcanic field indicates that basalts erupted within and flowed into Grand Canyon during four major episodes: 725–475 ka, 400–275 ka, 225–150 ka, and 150–75 ka. To extend the usefulness of these dates for understanding volcanic stratigraphy and lava dams in western Grand Canyon, we analyzed light detection and ranging (lidar) data to establish the elevations of the tops and bottoms of basalt-flow remnants along the river corridor. When projected onto a longitudinal river profile, these data show the original extent of now-dissected intracanyon flows and aid in correlation of flow remnants. Systematic variations in the elevation of flow bottoms across the Uinkaret fault block can be used to infer the geometry of a hanging-wall anticline that formed adjacent to the listric Toroweap fault.

The 725–475 ka volcanism was most voluminous in the area of the Toroweap fault and produced dike-cored cinder cones on both rims and within the canyon itself. Mapping suggests that a composite volcanic edifice was created by numerous flows and cinder-cone fragments that intermittently filled the canyon. Reliable $^{40}\text{Ar}/^{39}\text{Ar}$ dates were obtained from flows associated with this period of volcanism, including Lower Prospect, Upper Prospect, D-Dam, Black Ledge, and Toroweap. Large-volume eruptions helped to drive the far-traveled basalt flows (Black Ledge), which flowed down-canyon over 120 km. A second episode of volcanism, from 400 to 275 ka, was most voluminous along the Hurricane fault at river mile 187.5. This episode produced flow stacks that filled Whitmore Canyon and produced the 215-m-high Whitmore Dam, which may have also had a composite history. Basaltic river gravels on top of the Whitmore remnants have been interpreted as “outburst-flood deposit” but may alternatively represent periods when the river established itself atop the flows. Remnants near river level at miles 192 and 195, previously designated as Layered Diabase and Massive Diabase, have been shown by $^{40}\text{Ar}/^{39}\text{Ar}$ dating to be correlative with dated Whitmore flow remnants, and they help document the downriver stepped geometry of the Whitmore Dam. The ca. 200 and 100 ka flows (previously mapped as Gray Ledge) were smaller flows that entered the canyon from the north rim between river mile 181 and Whitmore Canyons (river mile 187.5); they are concordant with dates on the Whitmore Cascade as well as other cascades found along this reach.

The combined results suggest a new model for the spatial and temporal distribution of volcanism in Grand Canyon in which composite lava dams and edifices, that were generally leaky in proximal areas, were built from 725 to 475 ka near Toroweap fault and around 320 ka near Whitmore Canyon. New data on these and other episodes present a refined model for complex interactions of volcanism and fluvial processes in this classic locality. Available data suggest that the demise of these volcanic edifices may have involved either large outburst-flood events or normal fluvial deposition at times when the river was established on top of basalt flows.

Keywords: Grand Canyon region, Uinkaret, basalt flows, lava dams, volcanic history.

INTRODUCTION

The Uinkaret volcanic field in northwestern Arizona is a north-south-trending field of cinder cones and basalt flows that is situated between the Hurricane and Toroweap faults on the north edge of western Grand Canyon (Fig. 1). This study focuses on basalts that erupted within and flowed into western Grand Canyon. Although flows on the Uinkaret Plateau are as old as 3.7–3.4 Ma at higher elevation on Mount Trumble ($^{40}\text{K}/^{40}\text{Ar}$; Best et al., 1980), dated flows within Grand Canyon are Quaternary in age (Hamblin, 1994; Dalrymple and Hamblin, 1998; Fenton et al., 2001, 2004). Very recent volcanic activity on the north rim (ca. 1 ka) is indicated by the presence of pottery fragments in welded basaltic spatter (Ort et al., 2008) and by cosmogenic He dating (Fenton et al., 2001).

New $^{40}\text{Ar}/^{39}\text{Ar}$ results indicate that Quaternary basalts flowed into western Grand Canyon between ca. 725 and 100 ka (Karlstrom et al., 2007) and profoundly affected the erosional and geomorphic processes within Grand Canyon by forming lava dams and armoring terraces and hillslopes (Hamblin, 1994). As first reported by Powell (1895), it is clear that canyon incision, basaltic volcanism, and extensional faulting have all interacted here with interesting feedbacks between these processes (Hamblin et al., 1981;
Figure 1. True color Landsat image of the Grand Canyon showing the location of the Uinkaret volcanic field, Toroweap fault, Hurricane fault, and the Grand Wash Cliffs.

Bassalt remnants are present from river mile 177 to 254 (measured downstream from Lee’s Ferry). Spencer Canyon is located at river mile 246. Major Quaternary faults, including the Toroweap and Hurricane faults, are shown in red (from U.S. Geological Survey and Arizona Geological Survey, 2006).
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Jackson, 1990; Stenner et al., 1999; Fenton et al., 2001, 2002, 2004; Pederson et al., 2002). Earlier studies have suggested that these flows are over a million years old (based on 40K/40Ar dates; McKee et al., 1968; Hamblin, 1994), but new 40Ar/39Ar dates indicate that all dated intracanyon flows are younger than 723 ka (Karlstrom et al., 2007).

Flows from the Unkarek volcanic field traveled from vents in the Unkarek Mountains: eastward to fill the Toroweap paleocanyon, westward to fill the Whitmore paleocanyon, and southward to partially fill the Grand Canyon (Hamblin, 1994). The flows that cascaded into Grand Canyon poured into a canyon that had reached ~90% of its current depth, and they are hypothesized, according to the prevailing models (Hamblin, 1994; Fenton et al., 2004), to have built a series of major dams and related lakes. Hamblin (1994) proposed stable dams and large lake systems that lasted ~20 K.y., and Fenton et al. (2004) suggested that catastrophic dam failure may have occurred before dam overtopping in some cases. However the details of the lava-dam record remain controversial and are difficult to unravel. Basalts are preserved in Grand Canyon as patchy remnants of one or more continuous flows that have been dissected and eroded by the Colorado River, leaving only a fraction of the original volcanic products. Remnants take the form of: (1) dikes in areas of vents; (2) cinder-cone fragments; (3) stacks of numerous flows, locally interlayered with cinders in areas close to sources; (4) areas of multiple inset flows of different ages within the river corridor; (5) isolated single flows, often with a massive columnar-jointed colonnade base and entablature top, consisting of smaller, less organized columnar joints; and (6) cascades where basalt was frozen on canyon walls during descent.

The goals of this study are to summarize all existing geochronology in the context of a new spatial analysis of remnants using light detection and ranging (lidar) data obtained by the Grand Canyon Monitoring and Research Center (www.gcimrc.gov). We also present results of new field studies of volcanic units along the river corridor. The combined data lead to a refined model for the history and processes of formation of this classic landscape, including a markedly different new model for the geometry and history of lava dams and edifices. A companion paper (Karlstrom et al., 2007) presents 20 new 40Ar/39Ar dates and uses them to focus on the neotectonic faulting history and differential incision of Grand Canyon. Beyond its significance for Grand Canyon, the ultimate goal of our study is to evaluate far-traveled basalt flows in canyon settings, their interaction with incision and faulting, and arrive at an integrated model for interaction of Quaternary volcanism and landscape evolution in similar settings.

Previous Work on Basalt Stratigraphy

Powell (1895, p. 275) was the first to report: “What a conflict of water and fire there must have been here!” with “a river of molten rock running down into a river of melted snow.” He was also the first to postulate that high lava dams and extensive lakes may have resulted. Hamblin (1994) formalized an elegant model for lava dams and hypothesized a series of 13 major dams that were generally stable and relatively long-lived for dams on a major river (~20,000 yr). He envisioned dams, up to 700 m high, that backed up lake water as far as Moab, Utah, and deposited lake sediments in several localities. Much of the lacustrine evidence for large reservoir-sized lakes, cited by Hamblin (1994), has been questioned by Kaufman et al. (2002), who suggested that lakes in Grand Canyon may have been less extensive both spatially and temporally than previously thought. Fenton et al. (2002, 2004, 2006) revised Hamblin’s stable dam model by hypothesizing that the demise of some lava dams may have resulted in catastrophic failure and large-scale floods, recorded by basaltic gravel, which they interpreted to be “outburst-flood deposits.” The “outburst-flood deposits” are greater than 82% basalt boulders and cobbles, lack quartz river sand, are generally more poorly sorted and less rounded than Holocene river gravels (Fenton et al., 2004). Our data suggest that both of these appealing models need refinement.

Hamblin (1994) proposed a temporal sequence for Grand Canyon basalts and lava dams based on a combination of superposition (e.g., Lower and Upper Prospect flows) and inset relationships (Fig. 2). This stratigraphy and nomenclature were developed in the context of a model for formation and destruction of lava dams, so names were presented for different “dams.” Here, we retain these names in part, but we modify the nomenclature where necessitated by new dates (shown in black on Fig. 2). Problems with Hamblin’s flow chronology were apparent even with the 40K/40Ar dates of Dalrymple and Hamblin (1998). Dams that were inferred to be quite young stratigraphically (Layered and Massive Diabase) gave similar 40Ar/39Ar dates to dams inferred to be much older (Fig. 2). New 40Ar/39Ar dates (Karlstrom et al., 2007) show that named flows, such as those identified by Hamblin as “Black ledge,” give disparate dates due to miscorrelation of remnants (see following). This paper presents a new synthesis of all existing geochronology on the basalts and adds new lidar and field data on the geometry of basalt remnants. We propose a testable new model that takes an important first step toward understanding the timing and volcanic stratigraphy of basaltic volcanism and lava dams in Grand Canyon.

Synthesis of Basalt Dating

In spite of an increasingly large number of dated flow remnants, the basalt stratigraphy and the geometry of lava dams in Grand Canyon remain difficult to unravel because of the multiple eruptions, extreme topography, complex inset

Figure 2. Hamblin’s nomenclature for dams and volcanic stratigraphy and the inferred relative ages of each dam, based largely on inset relationships (Hamblin, 1994). The 40K/40Ar dates are in gray from Dalrymple and Hamblin (1998). New 40Ar/39Ar dates (see Table 1 for references) do not substantiate the proposed age sequence.
relationships, long transport distance, and incomplete preservation. Available geochronology is of variable quality, and often contradictory ages result from different dating techniques, each of which has its own limitations. Published ages are principally $^{40}\text{K}/^{40}\text{Ar}$ and $^{40}\text{Ar}/^{39}\text{Ar}$ basaltic groundmass dates and cosmogenic $^3\text{He}$ dates on olivine phenocrysts. We rely primarily on $^{40}\text{Ar}/^{39}\text{Ar}$ ages and various correlation techniques to present what we consider to be the most reliable synthesis of the previously reported dates (reliable dates shown in black in Table S1).

This study considered 183 dates (Table S1, Fig. S1 [see footnote 1]). Age-probability plots, sorted by dating method, of all geochronology deemed reliable (105 dates) are shown in Figure 3. Large peaks on the age-probability plots, which are often consistent between dating methods, represent the episodes of volcanism that will be explained in detail later. The $^{40}\text{K}/^{40}\text{Ar}$ dating was conducted by several workers (McKee et al., 1968; Damon, in Hamblin, 1994), but the main campaign was reported in a paper by Dalrymple and Hamblin (1998) based on samples collected in 1971–1972. The $^{40}\text{K}/^{40}\text{Ar}$ dates of 1.16 ± 0.36 Ma were initially obtained on the Toroweap flow near Lava Falls (McKee et al., 1968), and Damon (in Hamblin, 1994) reported ages of 990 ± 180 ka and 550 ± 60 ka on the Whitmore and Black Ledge flows, respectively. Additional $^{40}\text{K}/^{40}\text{Ar}$ results, reported by Lucchitta et al. (2000), Pederson et al. (2002), Fenton et al. (2004), and Raucci (2004) are incorporated into Figure 3, Table 1, Table S1, and Figure S1. The $^{40}\text{K}/^{40}\text{Ar}$ dating is considered here to provide the most reliable age constraints because it allows for the detection of excess argon while not being affected by burial or surface degradation.

All radiometric and cosmogenic dates are reported with $2\sigma$ errors. The oldest basalt flows (dating from 725 to 475 ka) are interpreted to have mainly originated along the Toroweap fault near river mile 179 (Fig. 4). Flows from this age range constitute the farthest-traveled flows, traveling over 120 km down river. Stacked basalt flows filled both paleo–Toroweap Canyon from the north and paleo–Prospect Canyon from the south (Fig. 4). The presence of dikes within the canyon (dated at 521 ± 59 ka, $n = 2$, $^{40}\text{Ar}/^{39}\text{Ar}$) that are the same age (within error) as the Upper Prospect basalt flows (518 ± 22 ka, $n = 5$; Pederson et al., 2002) and Raucci (2004) are combined with the presence of numerous dikes and cinder deposits under the Upper Prospect flows (Hamblin, 1994; Fig. 5) that rest on tephra at river mile 176.9 (613 ± 38 ka, $n = 2$, $^{40}\text{Ar}/^{39}\text{Ar}$; referred to as the “high remnant” in Table 1; Fig. 4; Fig. S2 [see footnote 1]) to allow for comparison between dates from different methods on the same flow. Fenton et al. (2001, 2002, 2004) reported mean ages on single flows as arithmetic means. When different from the recalculated value, the originally reported mean ages are shown in Table S1 in parentheses.

**TEMPORAL AND SPATIAL DISTRIBUTION OF VOLCANISM**

The available geochronology (105 reliable radiometric and cosmogenic ages) suggests that volcanic rocks can be grouped temporally into four episodes of volcanism (colored bands of Fig. 3): 725–475 ka, 400–275 ka, 225–150 ka, and 150–75 ka. The next section summarizes the spatial distribution and character of basalt flows from each of these episodes. The volcanic products of these four episodes have marked differences in their point of origin, volcanic structure, and effect on Grand Canyon. Additional dating of remnants may indicate more continuous volcanism and/or help refine multiple eruptive peaks within these broad episodes, but the compilation presented here markedly alters the conventional view of the volcanic history of western Grand Canyon.

**Episode 1: 725–475 ka Volcanism**

The oldest basalt flows (dating from 725 to 475 ka) are interpreted to have mainly originated along the Toroweap fault near river mile 179. Field measurements indicate that vents and cinder cones were present within Grand Canyon at this time. Field measurements indicate that the Upper Prospect flow dips to the northeast and flowed away from what is now a cinder-cone fragment at the western edge of Prospect Canyon, which is cored by Prospect dikes of similar age.

The presence of high flows (~300 m above river level) that rest on tephra at river mile 176.9 (613 ± 38 ka, $n = 2$, $^{40}\text{Ar}/^{39}\text{Ar}$; referred to as the “high remnant” in Table 1; Fig. 4; Fig. S2 [see footnote 1]) requires that some flows traveled upstream from the Toroweap fault area at very high levels as the canyon filled with volcanic...
Figure 3. (A) Plot of 105 dates that we consider to be the most reliable ages on basalt remnants in western Grand Canyon. Age ranges reflect the 2σ error on each date. The episodes of volcanism (based on available data) are color coded. (B) Cumulative probability plot of the reliable ⁴⁰Ar/³⁹Ar ages. (C) Cumulative probability plot of the reliable cosmogenic ³He ages; reliable cosmogenic ³He dates are younger than ca. 275 ka. This dating method is best applied to young features that have not been eroded or experienced burial. (D) Cumulative probability plot of the reliable ⁴⁰K/⁴⁰Ar ages. Reliable ⁴⁰K/⁴⁰Ar dates are older than ca. 200 ka. The ⁴⁰K/⁴⁰Ar dates are often too old due to undetected excess argon. The relative height of the peaks is a function of both the precision of the date and the number of samples within an age range, so a highly sampled flow will result in high peaks. Ages from Dalrymple and Hamblin (1998), Lucchitta et al. (2000), Fenton et al. (2001), Pederson et al. (2002), Fenton et al. (2002), Fenton et al. (2004), Raucci (2004), and Karlstrom et al. (2007) were included in the analysis.
<table>
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<tr>
<th>Weighted Mean Ar/Ar Age (ka)</th>
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<th>Weighted Mean K/Ar Age (ka)</th>
<th>Weighted Mean Ar/Ar Age (ka)</th>
<th>Weighted Mean He Age (ka)</th>
<th>Weighted Mean K/Ar Age (ka)</th>
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<tr>
<td>Prospect Cone (Rim - RM 179.6)</td>
<td>38 ± 3 (F01)</td>
<td>323 ± 141 (K07)</td>
<td>Whitmore (RM 188.2)</td>
<td>38 ± 3 (F01)</td>
<td>323 ± 141 (K07)</td>
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<td>Vulcan's Throne (Rim - RM 178.7)</td>
<td>72 ± 4 (F01)</td>
<td>332 ± 39 (K07)</td>
<td>Layered Diabase of Hamblin, 1994 (Correlative with Whitmore) (RM 192)</td>
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<td>Bar Ten Basalt Flow (Rim - Whitmore Valley)</td>
<td>87 ± 6 (F01)(F02)</td>
<td>Mile 177 Flow (RM 177.3)</td>
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<td>87 ± 6 (F01)(F02)</td>
<td>Mile 177 Flow (RM 177.3)</td>
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<td>Upper Gray Ledge (RM 188.1)</td>
<td>97 ± 26 (P02)</td>
<td>424 ± 136 (Dh98)</td>
<td>Upper Gray Ledge (RM 188.1)</td>
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<td>424 ± 136 (Dh98)</td>
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<td>Older Esplanade Cascade (Rim - RM 182.8)</td>
<td>432 ± 8 (F04)</td>
<td>137 ± 20 (F04)</td>
<td>Toroweap Flow C (RM 178.5-179.6)</td>
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<td>Younger Cascade lava flow (RM 179.1-179.3)</td>
<td>107 ± 9 (F02)</td>
<td>487 ± 48 (K07)</td>
<td>Upper Prospect (RM 179-179.6)</td>
<td>107 ± 9 (F02)</td>
<td>487 ± 48 (K07)</td>
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<td>Upper Gray Ledge (RM 189.1)</td>
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<td>Toroweap Terrace (RM 178.9)</td>
<td>137 ± 20 (P02)</td>
<td>627 ± 117 (Dh98)</td>
<td>Toroweap Terrace (RM 178.9)</td>
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<td>521 ± 59 (K07)</td>
<td>Whitmore Cascade Flow (RM - Whitmore Valley)</td>
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<td>521 ± 59 (K07)</td>
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<td>186 ± 26 (R06)</td>
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<td>Lower Prospect (RM 179-179.6)</td>
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<td>Lower Gray Ledge (Mapped as Black Ledge Hamblin, 1994) (RM 184.6L)</td>
<td>251 ± 59 (PO2)</td>
<td>557 ± 109 (DH98)</td>
<td>Lower Gray Ledge (Mapped as Black Ledge Hamblin, 1994) (RM 184.6L)</td>
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<td>Esplanade cascade (RM 182R) (Fenton et al., 2004 correlates with Older Esplanade Cascade)</td>
<td>210 ± 80 (H94)</td>
<td>602 ± 37 (K07)</td>
<td>Ponderosa (RM 181.6)</td>
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<td>208 ± 28 n=1 (F01)</td>
<td>Ponderosa (RM 181.6)</td>
<td>Flow north of Vulcan's Throne (Rim-RM 178.6)</td>
<td>208 ± 28 n=1 (F01)</td>
<td>Ponderosa (RM 181.6)</td>
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<td>Vulcan's Footrest (Rim - RM 178.6-178.8)</td>
<td>218 ± 28 n=2 (F04)</td>
<td>613 ± 38 n=2 (K07)</td>
<td>High Remnant (RM 176.9)</td>
<td>218 ± 28 n=2 (F04)</td>
<td>613 ± 38 n=2 (K07)</td>
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<td>Whitmore Sink basalt (Rim - Whitmore Valley)</td>
<td>219 ± 28 n=3 (F04)</td>
<td>723 ± 31 n=1 (K07)</td>
<td>Whitmore Sink basalt (Rim - Whitmore Valley)</td>
<td>219 ± 28 n=3 (F04)</td>
<td>723 ± 31 n=1 (K07)</td>
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<td>Massive Diabase of Hamblin, 1994 (Correlative with Whitmore) (RM 194.7)</td>
<td>298 ± 57 n=1 (P02)</td>
<td>766 ± 277 n=2 (F04)</td>
<td>Massive Diabase of Hamblin, 1994 (Correlative with Whitmore) (RM 194.7)</td>
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<td>Whitmore (RM 189.6)</td>
<td>318 ± 69 n=1 (P02)</td>
<td>390 ± 26 n=7 (F01)</td>
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Note: Mean ages shown in blue include ages considered unreliable for our compilation. See Table S1 (text footnote 1) for a list of all dates (both reliable and unreliable) along with sample numbers, river miles, and exact locations. (K06)—Karlstrom et al. (2007); (P02)—Pederson et al. (2003); (DH98)—Dalrymple and Hamblin (1998); (L00)—Lucchitta et al. (2000); (R06)—Raucci (2004); (F04)—Fenton et al. (2004); (F02)—Fenton et al. (2002); (F01)—Fenton et al. (2001); (H94)—Hamblin (1994); and (M68)—McKee et al. (1968). RM—river mile.
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Figure 4. Map of the southern Uinkaret volcanic field showing the location of all reliable dates between 800 and 475 ka. Lava flows of this age are interpreted to have entered the canyon at around river mile 179, near the Toroweap fault. Numerous dates on Black Ledge remnants at Granite Park and a single date from a remnant (Spencer Canyon) at river mile 246 indicate that this oldest stage of volcanism was the most voluminous and far-traveled. A 540 ± 30 ka 40Ar/39Ar date in Whitmore Canyon indicates that volcanism likely occurred along the Hurricane fault at this time as well but may not have resulted in intracanyon flows.

Figure 4. Map of the southern Uinkaret volcanic field showing the location of all reliable dates between 800 and 475 ka. Lava flows of this age are interpreted to have entered the canyon at around river mile 179, near the Toroweap fault. Numerous dates on Black Ledge remnants at Granite Park and a single date from a remnant (Spencer Canyon) at river mile 246 indicate that this oldest stage of volcanism was the most voluminous and far-traveled. A 540 ± 30 ka 40Ar/39Ar date in Whitmore Canyon indicates that volcanism likely occurred along the Hurricane fault at this time as well but may not have resulted in intracanyon flows.
material. This, combined with the large volume of Toroweap and Prospect valley-fill flows, is the best evidence for a large volcanic edifice or dam in this reach. The Black Ledge flows of Granite Park (572 ± 31 ka, n = 9; Lucchitta et al., 2000; Pederson et al., 2002; Karlstrom et al., 2007) near river mile 208 are examples of similar-age flows that traveled great distances down the river, probably from the Toroweap-Prospect Canyon area.

Other intracanyon flows from the 725–475 ka episode of magmatism are the Lower Prospect flows, which have been dated at 552 ± 33 ka (n = 6, 40Ar/39Ar) and the probably related D-Dam (602 ± 37 ka, n = 1, 40Ar/39Ar). A single 40Ar/39Ar date of 540 ± 30 from the “Older Whitmore flow,” ~2 miles up Whitmore Canyon (Raucci, 2004; Fig. 4), indicates that volcanism of this age was not restricted only to the Toroweap fault area. However, no direct evidence exists that this flow reached the Grand Canyon.

It is important to note that the Black Ledge flows were originally thought to have been among the youngest flows in the canyon (Fig. 2; Hamblin, 1994). The 40Ar/39Ar dating indicates that they are, instead, some of the oldest (Lucchitta et al., 2000; Pederson et al., 2002; Karlstrom et al., 2007). A new 40Ar/39Ar date of 487 ± 48 ka on the Toroweap C flow is significantly younger than the 1.16 ± 0.36 Ma 40K/40Ar date initially obtained on the Toroweap flow near Lava Falls, which has been used for decades to determine the minimum age of canyon excavation (McKee et al., 1968; Hamblin, 1994).

Figure 5. Photo looking south, up Prospect Canyon, showing thick tephra deposits under the Upper Prospect flow. Cinder-cone remnants, seen perched on the canyon’s rim (right side of image), may indicate a possible source for this 518 ± 12 ka (n = 5) flow (Pederson et al., 2002).
While the analysis of weighted mean ages points to correlation between the Prospect and Black Ledge flows (Table 1), a closer look at individual ages (for any dating method) indicates that there is insufficient temporal resolution in the ages for certainty in such fine-scale correlations. While mean ages are likely good approximations, individual ages from the Upper Prospect and Lower Prospect flow stacks are not entirely consistent with the stratigraphy of the flows. A sample from the middle of the Upper Prospect stack gives an age over 40 k.y. younger than flows both above and below it, overlapping within error with three of the four remaining dates (Karstlom et al., 2007). Similarly, dates on two samples from the Lower Prospect flow stack give ages of 632 ± 45 ka and 541 ± 22 ka \((n = 5)\). The \(^{40}\text{Ar}/^{39}\text{Ar}\) age \((723 ± 18\text{ ka})\) on the Spencer Canyon flow, which traveled 108 km downstream and almost certainly resulted from voluminous eruptions that would have left remnants throughout the canyon, does not agree with other \(^{40}\text{Ar}/^{39}\text{Ar}\) dates on the Black Ledge flows or Upper or Lower Prospect. While the Spencer Canyon flow may represent a separate volcanic episode distinct from other dated flows, it may also represent a statistical outlier that overestimates the true age of this flow. Because of these inconsistencies, we prefer to group together the 725–475 ka ages into an as-yet undifferentiated episode of volcanism.

**Episode 2: 400–275 ka (Whitmore Area and 177-Mile Flow)**

Another major period of volcanism occurred from 400 to 275 ka. The map of dated remnants from this episode (Fig. 6) shows that most of these remnants are present downstream from Whitmore side canyon, which parallels the Hurricane fault. Lavas traveled down Whitmore Valley, filling the tributary, and ultimately poured into the Grand Canyon at river mile 187.5, where a giant plug of basalt filled both paleo–Whitmore Canyon and a 6.5 km \((4\text{ mi})\) reach of Grand Canyon. Hamblin referred to this collection of 50 thin flows as the “Whitmore Dam,” which he mapped as being covered with a younger cascade in Whitmore Valley (Hamblin, 1994). Fenton et al. (2004) noted that at least five lava flows from Hamblin’s “Whitmore Dam” and the younger cascade have different ages and geochemical signatures. They identified two “Whitmore Sink” flows and two “Whitmore Cascade” flows on the north rim of the canyon (Whitmore Valley) and a “hyaloclastite dam” located within the canyon on river left at river mile 188.

For the 6.5 km \((4\text{ mi})\) reach of the Colorado River below the mouth of paleo–Whitmore Canyon \((\text{river mile 187.5})\), Hamblin (1994) mapped a series of high Whitmore remnants \((\text{these include the hyaloclastite dam of Fenton et al., 2004})\). New \(^{40}\text{Ar}/^{39}\text{Ar}\) dates on the base of two Whitmore remnants at river miles 189.6 and 188.2 \((318 ± 69\text{ ka and 323 ± 141 ka})\;\text{Pederson et al., 2002; Karlstrom et al., 2007}\) indicate that the lowest flows formed at this time, and we refer to these as the Whitmore flows. However, the upper flows in the stack appear to be considerably younger, as discussed in the following section. Cosmogenic dates on the Whitmore Sink basalt flow \((262 ± 26\text{ ka, n = 2, \(^{3}\text{He}\)) indicate a possible source for the ca. 320 ka intracanyon Whitmore flows, if the cosmogenic dates are considered to be minimum ages \((Fenton et al., 2004)\). The Older Whitmore Sink flow \((360 ± 50\text{ ka, n = 1, \(^{3}\text{He})\; Fenton et al., 2004\)}\) was proposed as a source for the Whitmore flows, but new \(^{40}\text{Ar}/^{39}\text{Ar}\) dates of 540 ± 30 ka \((Raucci, 2004)\) indicate that it is too old. Further work is needed to determine which, if any, of the Whitmore Sink flows correlate with intracanyon flows. Flows previously designated as Layered Diabase and Massive Diabase \((Hamblin, 1994)\) are also considered here to be part of the Whitmore flows, based on new \(^{40}\text{Ar}/^{39}\text{Ar}\) ages of 332 ± 39 ka \((n = 2)\) and 298 ± 57 ka, respectively \((\text{Fig. 6})\).

Well upstream of both Whitmore Canyon and the Toroweap fault, at river mile 177.3, there is a small remnant dated at 351 ± 25 ka \((n = 3)\) by the \(^{40}\text{Ar}/^{39}\text{Ar}\) method \((Pederson et al., 2002; Karlstrom et al., 2007)\). The river mile 177 remnant lies 34 m above the current river level and is underlain by 2 m of mainly nonvolcanic mainstem river gravels that rest on a bedrock strath \((Pederson et al., 2002)\). The base of the flow shows pillow structures, indicating eruption of basaltic magma into water or water-saturated river sand and gravel. The top of the flow remnant at river mile 177 slopes upstream, indicating an unknown downstream source.

**Episode 3: 225–150 ka (Lower Gray Ledge and Whitmore Cascade)**

The Gray Ledge remnants were assumed by Hamblin \((1994)\) to be remnants of some of the youngest flows in the canyon. Comparisons of \(^{40}\text{Ar}/^{39}\text{Ar}\) dates on four remnants partially confirm this interpretation but indicate that they reflect two distinct periods of intracanyon basalt flows instead of one, at ca. 200 ka \((\text{lower})\) and 100 ka \((\text{upper})\; \text{Fig. 3}\). A Gray Ledge remnant at river mile 187.7 and a remnant originally mapped as Black Ledge at river mile 184.6 \((Hamblin, 1994)\) give ages of 194 ± 39 and 200 ± 72, respectively \((\text{Fig. 7; Pederson et al., 2002; Karlstrom et al., 2007)\) and are referred to here as parts of the Lower Gray Ledge flow.

The Whitmore Cascade in Whitmore Valley has been extensively sampled and dated \((\text{Fig. 7; Fenton et al., 2002, 2004})\). The mean age of 179 ± 9 ka \((n = 8, \text{cosmogenic \(^{3}\text{He}\)}\) dates) is generally accepted, but the \(^{40}\text{Ar}/^{39}\text{Ar}\) dates from a single new sample have a mean age of 186 ± 26 ka \((n = 2; Raucci, 2004)\). In agreement with the cosmogenic ages, Whitmore Cascade flows appear to have capped the earlier ca. 320 ka Whitmore flows that plugged paleo–Whitmore canyon, cascading into the main canyon at river mile 187.5. Cosmogenic helium dates on a flow north of Vulcan’s Throne \((208 ± 28\text{ ka, n = 1 and Vulcan’s Footstep (218 ± 28 ka, n = 2; Fenton et al., 2004)})\), on the north rim near the Toroweap fault, are concordant with \(^{40}\text{Ar}/^{39}\text{Ar}\) dates on the Lower Gray Ledge remnants \((ca. 200\text{ ka})\), but they may or may not have resulted in intracanyon flows \((\text{Fig. 7}; Fenton et al., 2004)\). These \(^{40}\text{K}/^{39}\text{Ar}\) ages on a cascade that Fenton et al. \((2004)\) also reported a \(^{3}\text{He}\) cosmogenic age of 138 ± 13 ka \((n = 2)\) for their Esplanade cascade \((Qbe2 in their nomenclature)\), which lies on the north rim between river miles 184 and 185 \((\text{Fig. 8})\). While their Qbe1 underlies this flow, “it gives a younger age” \((102 ± 8\text{ ka, n = 3, \(^{3}\text{He})\)}\).

This inconsistent relationship was explained in terms of erosion of the surface or unresolved juxtaposition \((Fenton et al., 2004)\). Hamblin \((1994)\) cited a \(^{40}\text{K}/^{39}\text{Ar}\) date of 210 ± 80 ka on a cascade that Fenton et al. \((2004)\) correlated to their Qbe1 flow \((see their Table 1)\), indicating that cinder cones on the north rim between river miles 181 and 188 may have been active during this time period. Our best interpretation of flow sources and paths is shown in Figure 7, although uncertainty remains about which cascades were active at ca. 200 ka, 100 ka, or both.

**Episode 4: 150–75 ka (Upper Gray Ledge)**

Samples from other remnants originally mapped as Gray Ledge at river miles 188.1 and 189.1 give \(^{40}\text{Ar}/^{39}\text{Ar}\) ages of 97 ± 26 ka and 127 ± 27 ka \((n = 2)\) \((\text{Fig. 7; Pederson et al., 2002; Karlstrom et al., 2007})\). These are the youngest reliable \(^{40}\text{Ar}/^{39}\text{Ar}\) ages on intracanyon flows. Other features of similar age include: Fenton et al.’s \((2004)\) Younger Cascade \((107 ± 9\text{ ka, n = 6})\), and possibly the Esplanade flow. A \(^{40}\text{K}/^{39}\text{Ar}\) date of 110 ± 106 ka on the Esplanade flow was reported by Dalrymple and Hamblin \((1998)\), who considered it to be unreliable because it was a single age and not verified by replication. Fenton et al.’s \((2004)\) Older Esplanade cascade \((their Qbe1)\) that caps the Esplanade flow has been dated by both the \(^{40}\text{K}/^{39}\text{Ar}\) \((Hamblin, 1994)\) and cosmogenic \(^{3}\text{He}\) methods with inconsistent results: 210 ± 80 and 102 ± 8 ka \((n = 3)\), respectively \((\text{see previous})\). While Fenton et al. \((2004)\) correlated the 110 ± 106 ka \((^{40}\text{K}/^{39}\text{Ar}; Dalrymple and Hamblin, 1998)\)
Figure 6. Map of the southern Uinkaret volcanic field showing the location of all reliable dates between 425 and 250 ka. Circa 320 ka lava Whitmore flow(s) are interpreted to have entered the canyon at river mile 187.5, where they filled paleo-Whitmore Canyon. Similar 40Ar/39Ar ages have been obtained for a small remnant at river mile 177, which probably traveled upriver based on the dip of the flow’s top and the lack of upstream sources. Two 40K/40Ar dates on Massive Diabase remnants are included in this group, even though their correlation is questionable.

Explanation
- Ar/Ar dates (Karlstrom et al., 2007; Pedersen et al., 2002)
- Cosmogenic He dates (Fenton et al., 2004; Fenton et al., 2002; Fenton et al., 2001)
- K/Ar dates (Dalrymple and Hamblin, 1998)

Fill colors refer to the age of the flows:
- Green 425-250 ka
- Orange 250-150 ka
Figure 7. Map of the southern Uinkaret volcanicfield showing the location of all reliable dates between 225 and 160 ka. Lava flows of this age are interpreted to have entered the canyon near river mile 187.5 (Whitmore Wash) and possibly at river mile 182. Cosmogenic dates on a flow north of Vulcan’s Throne and on Vulcan’s Footrest indicate volcanism along the Toroweap fault during this time period; however, it is unclear if these flows entered the canyon.
<140 ka flows and flow directions (red)

Figure 8. Map of the southern Uinkaret volcanic field showing the location of all reliable dates younger than 140 ka. Ages younger than 51 ka are shown in yellow. Circa 100 ka lava flows are interpreted to have entered the canyon between river miles 182 and 185 and flowed downriver to at least river mile 192. Cosmogenic dates on the Toroweap Terrace and Vulcan’s Throne indicate volcanism along the Toroweap fault during this time period; however, it is unclear as to what distance (if any) these flows traveled downriver.
Esplanade Dam remnant with their Younger Cascade on the basis of field evidence, we consider the age of the Esplanade flow to be poorly constrained. The cosmogenic \(^{4}He\) dates on the Younger Cascade and Younger Esplanade Cascades give the best available indication of the source for the Upper Gray Ledge flows as cinder cones on the north rim between river miles 182 and 185. Unfortunately, available geochronology and field studies of the ca. 100–200 ka basalt cascades are insufficient for good resolution of this volcanic episode.

**Episode 5: Younger than 75 ka Volcanism**

Three cosmogenic dates from the Prospect cone give a mean age of 38 ± 3 ka \((n = 3;\) Fenton et al., 2004). Vulcan’s Throne cinder cone also gives a minimum age of 72 ± 4 \((n = 3;\) Fenton et al., 2004). The Little Spring Flow, north of the study area, gives a cosmochemical age of 1.3 ± 1 ka \((n = 2;\) Fenton et al., 2001). Pottery shards preserved in basaltic spatter (Ort et al., 2008) further support the young age of this feature. These dates indicate that the Uinkaret volcanic field is geologically active. However, no evidence exists that any basalt flows entered Grand Canyon after ca. 100 ka.

**LIDAR METHODS FOR CORRELATING FLOW REMNANTS**

An efficient and powerful supplement to the geochronology, geochemical correlation, and field work is lidar (light detection and ranging), which, along with aerial photography, can be used to map locations and geometry of basalt remnants in three dimensions. This method has the advantage of measuring heights in terms of an absolute datum (sea level) instead of the river level, which fluctuates, and, more importantly, it can be done accurately for almost every flow remnant.

The lidar data used in this study were collected by the Grand Canyon Monitoring and Research Center (GCMRC) in the spring of 2000. Complementary color infrared (CIR) aerial photographs were collected at the same time and orthorectified to the lidar data. The ground-truthed lidar data have a nominal point spacing of 4 m and a vertical accuracy of 3–17 cm. The data were processed to remove noise, nonterrain data points, and erroneous data points at the base of cliffs. The lidar point cloud was then converted to a triangulated irregular network (TIN) and finally to a digital elevation model (DEM). The DEM has a pixel size of 4 m, and the CIR orthophoto graphes have a pixel size of ~0.3 m.

Geographic information system (GIS) software was used to digitize the top and bottom of each flow remnant based on the CIR orthophotograph (Fig. 9A). Because of the resistant nature of the basalt flows, the remnants typically have relatively flat tops and form steep cliffs facing downslope, toward the river, that can be mapped relatively easily and accurately on the photos. A grid of slope, derived from the lidar data, was used to verify the expected changes in slope at the top and bottom of flow remnants (Fig. 9B). Elevation values along the digitized line (derived from the photo, as verified by the lidar slope map) were extracted from the lidar-derived DEM (Fig. 9) and plotted on Figure 10 for every tenth of a river mile. This figure is best viewed with 2x enlargement, as different areas are discussed (see following sections).

The lidar heights to the top and bottom of remnants were compared to measured heights obtained with a Jacob Staff at 22 locations (Fig. 11). On average there was an excellent agreement (~4 m discrepancy) between the field measurements and lidar values. This level of accuracy in plotting flow tops and bottoms is excellent for the correlation analysis discussed next. In areas where faults offset flows, lidar elevations agree well with larger offsets (Toroweap fault) and show subtle offsets not easily seen in the field (Hurricane fault; Karlstrom et al., 2007).

**RESULTS OF LIDAR CORRELATIONS COMBINED WITH GEOCHRONOLOGY**

The lidar data greatly extend the usefulness of the \(^{40}Ar/^{39}Ar\) dates and allow us to build on Hamblin’s (1994) and Fenton et al.’s (2001, 2002, 2004, 2006) work to refine models for the timing, geometry, and stratigraphy of intra-canyon flows. Lidar analysis allows us to make inferences about the original shape and structure of flows and potential dams and edifices. The results are plotted on a longitudinal river profile, extending from river mile 176 to 224 (Fig. 10). The approximate canyon rims, locations of cinder cones, and major faults are also shown. The inset shows a simplified summary of the volcanic edifices (dams) and cascades inferred for each episode. The average top (triangles on Fig. 10) and bottom (squares on Fig. 10) elevations of each remnant (from lidar) were projected onto the profile at every tenth of a river mile (using Stevens’s [1983] river miles, measured downstream from Lee’s Ferry). In many cases, well-defined flow tops could be used to correlate remnants. The longitudinal profile (Fig. 10) summarizes many of the results of this study, and we present it in detail in terms of the temporal evolution of volcanic activity in western Grand Canyon.

**Lidar Insights on Episode 1: 725–475 ka Prospect Edifice and Black Ledge Flows**

The oldest basalt remnants are shown as orange units on the longitudinal profile (Fig. 10); dark fill colors show remnants dated by the \(^{40}Ar/^{39}Ar\) method, and lighter colors represent our correlations based on lidar heights. The varied heights of flows tops from remnants of this age range, and field studies indicating basaltic gravel within flow stacks (Hamblin, 1994), indicate that multiple large volcanic edifices were constructed and removed from the canyon during this period. Stacked flows mixed with cinder-cone fragments that were cored by concordant dikes (red vertical lines in Fig. 10) indicate volcanism emanating from within the canyon. While the original shape of individual dams has not been resolved, the collective remains of these dams (Fig. 10) suggest that the canyon was mostly filled with basalt flows and cinders at least once during this episode. As a major departure from Hamblin’s stratigraphy, we infer that the large volume of basaltic magmatism plus the gravitational potential from this edifice likely facilitated the far-traveled flows of about the same age (Black Ledge). This interpretation is also consistent with studies of Hawaiian basalt flows that show a correspondence between flow length and total volume of material erupted (Walker, 1973; Malin, 1980).

Some of the early (725–475 ka) flows overlie several meters of river gravel with little or no basalt debris, which, in turn overlie elevated bedrock straths. At these locations, bedrock incision rates can be calculated by dating the basalt flow, measuring its height above the river, and estimating the current depth to bedrock (Pederson et al., 2002; Karlstrom et al., 2007). The base of the 725–475 ka flows, as defined by lidar data, can thus be used to determine the maximum elevation of paleo–Colorado River bedrock straths at the time of initiation of volcanism; this is shown by the lower bold orange line on Figure 10. Interestingly, the connected surface (Fig. 10) is ~60 m above the present river level at river mile 188 compared to only ~15 m at mile 179. While this surface currently slopes 0.0003 in the upstream direction based on lidar data, it must have sloped downstream, subparallel to the current river gradient, at the time of the intracanyon basalt flow. Hence, we infer a 0.1° rotation of the strath within the Uinkaret fault block (bounded by the Toroweap and Hurricane faults) due to formation of a hanging-wall anticline during listric faulting on the Toroweap fault (Karlstrom et al., 2007).

Numerous other flow remnants are also correlated with the 725–475 ka flow group based on the position of their flow tops and bottoms.
Figure 9. Light detection and ranging (lidar) interpretation method: example from three inset flows at river mile 188. The Colorado River is flowing to the south. (A) Top and bottom of each flow is digitized based on 0.3 m resolution near-infrared aerial photographs. The digitized top and bottom are shown as black lines. (B) Grid of slope (derived from lidar) is overlaid over the aerial photographs. Pink areas denote cliffs where the slope is over 75°. Lidar data are then used to calculate top and bottom elevations for each remnant along its length. The data from Figure 9 are shown as three inset flow remnants of different ages on Figure 10 at river mile 188: Whitmore (green), Black Ledge (Orange), and Gray Ledge (blue). Shown in purple is the Whitmore Cascade, which is interpreted to overlie the Whitmore flow locally.
Geometry and Duration of 725–475 ka Lava Dams

The edifice postulated in Figure 10 is compatible in height with the highest and oldest lava dam inferred by Hamblin (1994), the Prospect Dam. However, as mentioned earlier, unlike Hamblin (1994), we envision that the minuscule Prospect flows (and others from this period) resulted in far-traveled flows (Black Ledge) found over 120 km downstream from this location. The Prospect Dam was envisioned by Hamblin (1994) to have formed a lake larger than present-day Lake Powell or Lake Mead, that backed water up past Moab, Utah, and that was stable for up to 20,000 yr. We support the notion of a very high edifice of basalt based on new dates from the “high remnant” flows (Fig. S2) and on the massive amount of basalt in Prospect Canyon. However, we do not envision a stable dam edifice and large lake. Instead, it seems likely that the Colorado River would have exploited weaknesses (lava tubes, tephra stacks, bedrock contacts, cinder deposits, and basal river gravels) in the proximal parts of this porous volcanic edifice. This is supported by field evidence that indicates the source of the Prospect flows flowed from the south side of the Grand Canyon rather than flowing across from the north, and by evidence that dike-fed vents and cinder cones were present inside the Grand Canyon at this location. This interpretation of a large composite volcanic edifice within the Grand Canyon is an important departure from previous models.

Denise of 725–475 ka Dams and Possible Outburst-Flood Deposits

While large reservoirs need not form behind “leaky” dams in the case of persistent edifice infiltration, the model for outburst-flood deposits (Fenton et al., 2004) proposes that at least some dams of this age did impound water and fail catastrophically. Fenton et al. (2004) identified the oldest “outburst-flood deposits” (their Qfd1) as a 92% basalt cobble and gravel deposit at river mile 198.5. They reported that its stratigraphic position is between flows dated at 483 ± 80 ka (40Ar/39Ar age; Fenton et al., 2004) and 318 ± 69 ka (40Ar/39Ar age; Pederson et al., 2002; Fenton et al., 2004), and that the Qfd1 basalt-rich flood deposit may have been formed by the failure of a dam created by the Upper Prospect flows (518 ± 22 ka, n = 5, 40Ar/39Ar; Pederson et al., 2002), which have similar rare earth element (REE) patterns to glasses and whole-rock basalt samples from the Qfd1. There are also other basalt-rich gravels that were deposited during the 725–475 ka episode, as shown by interflow basalt-rich gravels present between the Toroweap flows and on top of the Buried Canyon flows (Hamblin, 1994; Fig. 10). While these and the Qfd1 basalt-rich gravels are compatible with a model for catastrophic failure of unstable dams (Fenton et al., 2002, 2004, 2006), they alternatively could represent basaltic alluvium deposited by normal fluvial processes at times when the river was established on top of basalt flows during dam spillover, as suggested by Lucchitta et al. (2000). In our view, the location(s) and nature of any individual lava “dams” created during this episode of volcanism remain poorly constrained, and the evidence for outburst-flood events of this age is equivocal. Sedimentological differences between Holocene and “outburst-flood deposits,” including differences in rounding and sorting (Fenton et al., 2004), may be permissive, but are not compelling arguments for outburst-flood events based on the current level of documentation, as these differences could also be due to the proximity to their source.

The Qfd3 outburst-flood deposits of Fenton et al. (2002) are preserved between river mile 203 and 222 (Fig. 10) and have been reported to be 155–525 ka based on cosmogenie dating and overlying stage-V soil carbonates (Fenton et al., 2004; Lucchitta et al., 2000). Geochemical correlation has indicated that glasses in the deposits may be related to the Toroweap Dam (487 ± 48 ka, n = 1, 40Ar/39Ar), while basalt clasts are most probably related to the Whitmore Cascade (186 ± 26 ka, n = 2, 40Ar/39Ar; Raucci, 2004; Fenton et al., 2004). Based on lidar heights, stage-V carbonates, and their position atop the far-traveled Black Ledge flows (572 ± 31, n = 9, 40Ar/39Ar; Lucchitta et al., 2000; Pederson et al., 2002; Karlstrom et al., 2007), these deposits are younger than 572 ka, but, like the other proposed outburst-flood deposits, it is not clear to us when they formed and whether they represent dam-failure deposits versus more normal volcanic-rich river alluvium.

Lidar Insights on Episode 2: 400–275 ka Whitmore Flows

For a 6.5 km (4 mi) reach of the Colorado River below the mouth of paleo–Whitmore Canyon (river mile 187.5), Hamblin (1994) mapped a series of high flow remnants that he named the Whitmore Dam. Within this reach, the base of the ca. 320 ka Whitmore remnants are tens of meters above and stratigraphically overlie older remnants (Hamblin’s [1994] Black Ledge lava flow). The Whitmore flows clearly filled an already existing main-stem canyon that had been cut to within tens of meters of its present-day position, as shown by bedrock straths between 40 and 55 m height beneath the Black Ledge and an older remnant in the mouth of Whitmore Canyon that Hamblin (1994) called Massive Diabase, but that we consider to be part of the Black Ledge flows (Figs. S3 and S4, see footnote 1). Other evidence that the flows filled an already deep canyon include a dated Whitmore flow (316 ± 69 ka) at river mile 189.6, the base of which is 122 m above current river level and which overlies a travertine-cemented colluvial drape that extends to within 68 m of the present river level (Fig. S4). Based on a bedrock incision rate of 140 m/m.y. for this part of the canyon (see Karlstrom et al., 2007), the 320 ka bedrock strath should have been ~20 m above river level rather than the observed 120 m height of the base of the 316 ± 69 ka flows (Fig. 10). Thus, we infer that the Whitmore flows poured into a reach of the canyon (river miles 187.5–192) that was already choked with a mixture of sediment, cinders, and other volcanic debris almost 100 m above the estimated bedrock strath height.

Downstream of river mile 192, west of the Hurricane fault, no high remnants of the Whitmore flow are found, but two low remnants (flow bases at 18–22 m and tops at ~30 m above current river level) give 40Ar/39Ar ages of 332 ± 39 ka and 298 ± 57 ka (n = 2), respectively. We correlate these flows with the Whitmore flows. These were previously named Layered Diabase (at river mile 192) and Massive Diabase (at river mile 194.7; Fig. S3; Pederson et al., 2002; Karlstrom et al., 2007). The low elevations of the tops and bottoms of these flows indicate that the top of the Whitmore Dam stepped down over 100 m west of river mile 192, where it continued for an undetermined distance within tens of meters of the present river level (Fig. 10). This down-stepping of the top of the Whitmore flows in map view (Fig. 6) occurs both across the Hurricane fault and where the river begins a regional westward bend.

It is possible that there were normal fluvial aggradational channel fills on which the Whitmore flows were emplaced. Pederson et al.
Figure 10 (continued on following page). Longitudinal profile of the Colorado River from river mile 176 to 200 (A) and 200 to 224 (B). The Spencer Canyon flow at river mile 246 is shown as an inset in part B. Schematic synthesis showing the extent of different-aged intracanyon basalt flows from river mile 176 to 246 is shown on top of part A. Remnants are projected onto the profile based on their lidar heights and color coded based on their age (solid fills show remnants with $^{40}$Ar/$^{39}$Ar dates). Note that the ca. 100 ka (blue) and ca. 200 ka flows (purple) are interpreted to have entered the canyon at similar places. These flows exhibit some of the best-defined flow tops. The ca. 320 ka Whitmore flows (green) are interpreted to have originated from Whitmore Canyon and to have a high surface that existed from river mile 187 to 192. The bold lower orange line between river mile 179 and 191 shows where the orientation of the 725–475 ka maximum strath surface indicates fault block rotation (see text). Figure is vertically exaggerated 13 times.
Figure 10 (continued).
Crow et al.

(2006) reported that, in eastern Grand Canyon, a 380–300 ka gravel aggradation event filled the canyon with up to 60 m of alluvium. Such an aggradational event could in part explain the presence of high Whitmore flows above older Black Ledge flows, and almost 100 m above the height of the estimated bedrock strath, but it would not explain the change in height (of ~100 m) to the base of the ca. 320 ka flows across the Hurricane fault. Alternatively, fault offset along the Hurricane fault (after ca. 320 ka) could be invoked to explain the stepped top of the Whitmore flows, but the needed offset (~80 m) is more than four times what is observed in well-exposed areas across the fault (Fenton et al., 2001; Raucci, 2004; Karlstrom et al., 2007). Perhaps the best explanation involves combined effects, where the reach from river mile 187 and 191 was choked locally with volcanic debris due to high volumes of cinder input from cones up Whitmore Canyon, superimposed on a regional climate-driven aggradational event. This could explain why low, ca. 320 ka Whitmore-aged remnants are found immediately downstream of the reach. Thick piles of cinders (~40 m thick) under the flow stack filling Whitmore Canyon support this idea.

Downstream of river mile 192, two well-defined flow tops are seen in the lidar data (Fig. 10). The upper flow top (orange) is interpreted to be related to the 725–475 ka flows. The lower flow top likely represents different-aged flows (ca. 320 and ca. 200 ka) that converge downstream from river mile 192 and are indistinguishable based on their heights.

Whitmore Lava Dam: 400–275 ka

The dam created by the Whitmore lava flows was proposed as a type-example by Hamblin (1994), where both the paleo-Whitmore side stream and the main stem got completely filled with a series of flows (over 50 flows) that were considered to represent a single eruptive “event.” However, like the Prospect Dam, new 40Ar/39Ar dates show a range in ages from ca. 320 to ca. 180 ka and a composite history that is only partly unraveled. The five dated 332–298 ka remnants (Fig. 6) and their excellent lidar correlation between river miles 187 and 191 (Fig. 10) make the early history of the Whitmore Dam one of the better understood dams. The top of the dam was on the order of 215 m high (about the same height as Glen Canyon Dam).

Demise of the Whitmore Dam and Possible Outburst-Flood Deposits

Fenton et al. (2002, p. 197) proposed a conceptual model for lava-dam failure involving “high pore pressures or flow under the base and abutments of the dam or by piping through fracture planes in the basalt.” If the Whitmore Dam was underlain by 100 m of volcanic debris and gravel, the processes of piping river water through the unstable volcanic edifice (Fig. 12B) may have significantly decreased the life span of the dam.

Figure 11. Light detection and ranging (lidar) and field measurements obtained with a Jacob Staff generally agree within <4 m. Increasing error with height may indicate that compounding error associated with Jacob Staff measurements may be the largest source of error. Other sources of error include: river-level variations, spatial resolution of the lidar data, and inaccurate placement of remnant contacts on aerial photography.
Of the “outburst-flood deposits” cited by Fen-ton et al. (2004, 2006), their Qfd4 deposits, which are found up to 200 m above the current river level (Fig. 10; Fig. S3), are the best preserved and perhaps most easily correlated. As of yet, only the Qfd4 and the “hyaloclastite dam” (see Fig. 10 for locations) have been found to have tholeiitic signatures. These very coarse river-rounded basalt-boulder and cobble deposits rest on top of Whitmore flows (bases dated at ca. 320 ka), between river mile 189 and 192, and the surfaces of large boulders have been dated at 165 ± 36 ka (3He; Fen-ton et al., 2004). While the possibility that these deposits record paleofloods cannot be discounted, it seems equally possible that they were deposited when the river was established at a higher level, atop basalt flows that had filled the canyon bottom.

The presence of interbedded gravels in the upper Whitmore flows (Hamblin, 1994) and the almost ubiquitous presence of Qfd4 deposits on top of Whitmore flows suggest to us that the deposits may have formed during development, overtopping, and erosion of the later stages (ca. 180 ka) of a Whitmore Dam that had begun to form much earlier (ca. 320 ka). This may be in conflict with the interpretation that Qfd4 (165 ± 36 ka, 3He), which contains tholeiitic clasts, correlates to the only known tholeiitic “flow” remnant, a slumped block at river mile 188.5 called the “hyaloclastite dam” (Fenton et al., 2004). The Fenton et al. (2004, 2006) model that the “hyaloclastite dam” was the site of the dam failure event that deposited the 165 ka Qfd4 deposits seems unproven to us. Instead, we suspect that the hyaloclastite deposits are a slumped block that may correlate with lower portions of the 320–180 ka flow stack (Fig. 13), but the age of the hyaloclastite outcrop remains unknown (cf. Fenton et al., 2004). Further geochemical work needs to be done to evaluate how unique the proposed tholeiitic geochemistries may be, as both the Whitmore and Whitmore Cascades are composed of multiple thin flows that have not been fully characterized.

Lidar Insights on Episode 3: 225–150 ka Lower Gray Ledge Flows

Lidar analysis of remnants interpreted to be correlative with the ca. 200 ka event(s) shows a well-defined flow top between river miles 182 and 188 (Fig. 10). This top surface slopes 0.0108

Figure 12. Conceptual model for the various types of dams and edifices that may have formed in western Grand Canyon. The incorporation of volcanic debris into dams would add instabilities that would lead to more rapid destruction of that part of the dam but not necessarily cause catastrophic failure before overtopping. The presence of lava tubes would allow for infiltration of the edifices and cause rapid destruction. In this depiction, the stability of dams is shown by the degree to which they are preserved.
in the downstream direction and can be used to correlate associated remnants (Fig. 10). A dated Upper Gray Ledge remnant (originally mapped by Hamblin [1994] as Black Ledge) that yields a $^{40}$Ar/$^{39}$Ar date of 200 ± 72 ka provides the best example of this flow. A flow directly across the river and at the same height is probably correlated, but it has yielded two $^{40}$K/$^{40}$Ar dates of 496 ± 114 ka and 291 ± 226 ka (Massive Diabase of Dalrymple and Hamblin, 1998) (Fig. 10) that we suspect are too old. Similarly, Layered Diabase flows at river miles 183.2 and 183.3, which were dated by the $^{40}$K/$^{40}$Ar method at 620 ± 104 ka ($n = 4$; Dalrymple and Hamblin, 1998), appear to be part of this same, much younger, flow. These $^{40}$K/$^{40}$Ar dates do not seem to accurately reflect crystallization ages. Instead, based on the $^{40}$Ar/$^{39}$Ar dates and spatial analysis of flow tops, we interpret these remnants to correlate with the Lower Gray Ledge flows (Fig. 10).

At river mile 187.7, a $^{40}$Ar/$^{39}$Ar date from a single basalt block at river level gives an age of 194 ± 39 ka (Fig. 13; Pederson et al., 2002). The block, which has a highly irregular top and is eroded, is covered by ~4–8 m of basaltic gravel, which is in turn covered by an undated massive Gray Ledge flow (Fig. S5, see footnote 1). About 3.2 km (2 mi) upstream from this location, at river mile 184.6, the previously mentioned Lower Gray Ledge flow (200 ± 72 ka, $^{40}$Ar/$^{39}$Ar) has a flow top that is ~100 m above river level. This discrepancy in flow top heights and the eroded nature of the 187.7 river mile outcrop indicate that the dated outcrop there may be out of place, as shown in Figure S5.

Fenton et al. (2004) completed cosmogenic dating and geochemical characterization of the Whitmore Cascade, which tops the flow stack that fills paleo–Whitmore Canyon and extends at least 5 km up Whitmore Valley (Fig. 7). This ca. 180 ka lava flow seems to have topped the ca. 320 ka Whitmore flows, which also emanated from upper Whitmore Canyon. Lidar heights indicate that the top of the paleo-Whitmore flow stack (river mile 187.5) and a remnant on river right at river mile 188.2, the base of which is dated at 323 ± 141 ka, are at least 50 m higher than other Whitmore remnants in the area (Fig. 10). These and possible other Whitmore remnants in the canyon may be locally topped by the Whitmore Cascade, such that better understanding of the composite history of the Whitmore Dam will require more refined differentiation between the ca. 320 and ca. 180 ka flows.

**Lidar Insights on Episode 4: 150–75 ka Upper Gray Ledge Flows**

Lidar analysis of remnants correlated with the Upper Gray Ledge flow shows a well-defined
flow top from river mile 188 to 192 (Fig. 10). At river mile 191, lidar analysis indicates that a Gray Ledge remnant may be cut by the Hurricane fault. This is in contrast to Hamblin (1994) and Pederson et al. (2002), who suggested that there was no Quaternary movement on the Hurricane fault, but it supports the findings of Fenton et al. (2001) and Raucci (2004), who estimated the Quaternary displacement rate of the Hurricane at a minimum of 70–100 m/m.y. (see Karlstrom et al., 2007). Offset observed in the lidar data is west side down, with a throw of ~4 m, and the slope of the upper surface of the 100 ka basalt flow is about 0.0038.

Lidar analysis does not resolve questions regarding the age of the Esplanade flow, which could be related to the 725–475 ka, 225–150 ka, or 170–75 ka episodes based on the position of the main Esplanade remnant at river mile 182.

Speculation on 225–75 ka Lava Dams and Their Demise

The Gray Ledge flows represent the youngest known lava flows in western Grand Canyon and are hypothesized to have formed a major dam(s) (Hamblin, 1994). However, the ca. 200 ka and ca. 100 ka flows remain difficult to distinguish based on heights and geometry of flows. It remains unclear how many dams existed during this time period, where they were located, and how they may have failed. While it seems clear that the Whitmore Cascade flow poured into the Grand Canyon near river mile 187.5 at ca. 180 ka, no remnants of the resulting dam have been identified, making conclusions about its size and structure difficult. Similarly, proposed outburst-flood deposits are only permissively tied to specific dam-failure locations and events. Fenton et al. (2004) described at least three outburst-flood deposits (shown in Fig. 10) within or close to this 225–75 ka age range: Qfd3, Qfd4, and Qfd5, and they also speculated that the Qfd3 deposits may have been related to a dam formed by the Whitmore Cascade (186 ± 26 ka, n = 2). Qfd5 flood deposits (104 ± 24 ka, n = 8, 3He) overlie dated Gray Ledge remnants (97 ± 26 ka and 127 ± 27 ka, n = 2, 40Ar/39Ar; Karlstrom et al., 2007). Fenton et al. (2004) suggested that the “Younger Cascade” (107 ± 9 ka, n = 6, 3He) was a likely source for these deposits. The similar ages and the almost ubiquitous presence of Qfd5 deposits on top of Upper Gray Ledge flow remnants (Fig. 10) may indicate that the “flood” deposits were preserved shortly after overtopping of the Upper Gray Ledge Dam, when the river had established itself on top of the Gray Ledge flows. This does not preclude the possibility that the Qfd5 “flood” deposits are related to the “Younger Cascade,” since dates on it are concordant with those on the Upper Gray Ledge, which indicates that the two may be correlative.

In summary, neither dating nor geochemical correlation have yet elucidated the location, geometry, or duration of any of the dams that may have resulted from the youngest flows (Gray Ledge flows) in Grand Canyon, and, in our view, none of the proposed outburst-flood deposits can be tied to known dams or failure events.

Models for Dam Stability Based on Field Evidence

If large stable dams existed in Grand Canyon for up to 20,000 yr, as proposed by Hamblin (1994), lake deposits should exist, either within the main canyon or flooded tributaries, but no such deposits have been positively identified (Kaufman et al., 2002). The locations originally cited by Hamblin (1994) have been reinterpreted as slack-water deposits in spring-fed travertine pools and as fluvial, colluvial, or paleoflood deposits (Kaufman et al., 2002). Many of these deposits have also been shown by Kaufman et al. (2002) to be significantly younger than the proposed lava dams. While hillslope instability and erosion would lead to incomplete preservation of lake deposits in the Grand Canyon, it seems unlikely that all evidence for large reservoir-sized lakes could have been removed in the last 725–100 k.y. if the lakes had existed. For example, the late Pleistocene McKinney basalt flows, which dammed the Snake River near Bliss, Idaho, show evidence for impounded lakes in the form of abundant thick lacustrine clays that in places directly overly pillow basalts (Malde, 1982). Similarly, Pleistocene basalt flows from the La Jara shield volcano in western Mexico dammed the Atenguillo River and produced a paleolake, the extent of which can be determined by well-defined pillow basalts at its shoreline and 10 m of lacustrine sediments (Righter and Carmichael, 1992).

The flow of basalts >120 km down the canyon from their sources seemingly necessitates lava tubes if low effusive rates are assumed (Cashman, 1998; Keszthelyi and Self, 1998; Keszthelyi, 1998), yet none has been identified to date in the Grand Canyon. Similarly, analogous lava dams on the Boise (Howard et al., 1982) and Snake (Stearns et al., 1938) Rivers also lack lava tubes within the canyon but show evidence that lava tubes on the rim drained into the canyons. The lack of preserved lava tubes associated with lava dams may indicate that these features were quickly removed as river water infiltrated the dam and funneled into partially emptied lava tubes (Fig. 12C). As a possible analogy, in the spring of 1983, massive amounts of water, resulting in discharges of 97,000 cfs (2750 cm/s), were released through diversion tunnels from Glen Canyon Dam in order to prevent its overtopping and destruction (Collier and Webb, 1997). Cavitation in the spillway tubes was severe and required their reconstruction. Similar processes could cause the rapid destruction of lava dams with lava tubes during spring floods. Further study of the morphology of far-traveled flows could lead to a better understanding of the processes that insulated and allowed for far-traveled flows and would have important implications relating to models for dam geometry and stability.

Implications for Lava-Dam Models

A lack of evidence for large-scale reservoir-sized lakes in Grand Canyon suggests that many of the basalt edifices may have been “leaky” in proximal areas and unable to impound significant amounts of river water, or, alternatively, they may have been short-lived (Fenton et al., 2002). Indirect evidence for leaky dams exists in the morphology of flow remnants (and the presumed necessity for lava tubes), in the reconstructed structure of original basalt edifices, the large volumes of tephra found below, within, and above flow stacks, and in the presence of dikes, which suggest that cinder cones were built in the canyon.

Basalt-rich gravels between and atop basalt flows (outburst-flood deposits or not) require some damming of river water. The stability of the distal far-traveled parts of the lava flows may be the biggest unknown, because while a cinder-cone fragment incorporated in the upstream part of an edifice would imply instabilities in that area, it would not necessarily lead to the rapid destruction of downstream flows. At river mile 246, across from Spencer Canyon, well-defined channels and potholes have been carved into the top of a Black Ledge flow, clearly indicating that the river was once established on top of this distal flow (Fig. 14). This indicates that at least some of the distal flows may have been quite stable. If lava tubes were present, it seems clear that at least some may have never emptied.

Lava dams likely varied in both form and stability, and we envision a continuum of volcanic edifices that ranged from dams to sieves (Fig. 12). Unlike the Hamblin model for massive basalt plugs in the canyon (Fig. 12A), we envision that the Whitmore Dam had a composite history, including early (ca. 320 ka) flows built atop cinders and volcanic debris (Fig. 12B) and later ca. 180 ka Whitmore Cascade components that likely overtopped some of the earlier Whitmore flows. Likewise, we envision the 650–500 ka
Prospect edifice to have been a composite feature that was likely leaky throughout much of its history (Fig. 12D).

DISCUSSION AND CONCLUSIONS

Reliable dates on basalts from the Uinkaret volcanic field have been difficult to obtain. Because the $^{40}$Ar/$^{39}$Ar method provides a way of detecting excess argon while not being affected by burial or surface degradation, we consider these ages to be the most reliable age determinations and use them to assess the reliability of other dates and the chronology of volcanism in western Grand Canyon. The $^{40}$K/$^{40}$Ar dates are often inconsistent and are typically too old due to undetected excess $^{40}$Ar. Cosmogenic helium dates only accurately reflect the crystallization age of basalt flows when the surface being dated is uneroded and has not been shielded from cosmogenic rays by burial. We consider the cosmogenic dates to be minimum ages that accurately reflect the crystallization ages only for younger volcanic features (younger than 200 ka), as also noted by Fenton et al. (2001).

Analysis of 105 reliable dates (including $^{4}$He, $^{40}$K/$^{40}$Ar, and $^{40}$Ar/$^{39}$Ar dates) indicates at least four major periods of volcanism in the southern Uinkaret Mountains that resulted in intracanyon flows: 725–475 ka, 400–275 ka, 225–150 ka, and 150–75 ka. A main conclusion of the geochronology synthesis is that all of these new $^{40}$Ar/$^{39}$Ar dates are significantly younger than the 1.16 ± 0.36 Ma $^{40}$K/$^{40}$Ar date initially obtained on the Toroweap flow near Lava Falls rapid, which has been used for decades to determine the minimum age of canyon excavation (McKee et al., 1968).

Figure 15 shows a revised model for lava episodicity, origin of flows, and resulting intracanyon distribution of volcanics. The $^{40}$Ar/$^{39}$Ar dating shows that the 725–475 ka volcanic events were most voluminous and produced the Upper Prospect (518 ± 22 ka, n = 5; Pederson et al., 2002), Lower Prospect (552 ± 33 ka, n = 6), D-Dam (602 ± 37 ka), Toroweap (487 ± 48 ka), and the far-traveled Black Ledge flow at Granite Park (572 ± 31 ka, n = 9; Lucchitta et al., 2000; Pederson et al., 2002; Karlstrom et al., 2007) and Spencer Canyon (723 ± 31 ka). Earlier $^{40}$K/$^{40}$Ar dating combined with lidar analyses suggest that the Ponderosa (607 ± 48 ka, n = 2), Lava Butte (557 ± 109 ka, n = 7), and Buried Canyon flows also formed during this episode. Most of the 725–475 ka flows entered the canyon near river mile 179, with flows from both the north and south rims and from vents within the canyon. The presence of the Prospect Dike (521 ± 59 ka, n = 2, $^{40}$Ar/$^{39}$Ar) and other intrusive rocks, as well as the northeast-dipping Upper Prospect...
flow ($518 \pm 22\text{ ka}, n = 5$), indicates that some of these flows may have also emanated from cinder cones constructed in the river. We agree with Hamblin (1994) that eruptions from within the canyon were more likely to result in far-traveled flows, as the full volume of the eruption would be funneled into the canyon. The “high remnant” at mile 176.9 ($613 \pm 38\text{ ka}, n = 2$, $^{40}\text{Ar}/^{39}\text{Ar}$) probably flowed east (upstream) from the edifice (Fig. 15), and it supports the basic idea of the Prospect Dam of Hamblin (1994). However, we view the resulting edifice as likely a mix of cinder-cone fragments, stacked flows, and river alluvium. Weaknesses in such an edifice would have been rapidly exploited by the Colorado River possibly resulting in a “leaky dam” and rapid failure during annual spring floods (Fenton et al., 2002, 2004, 2006).

The 400–275 ka volcanism was centered on the Hurricane fault, and the majority of flows entered the canyon at river mile 187.5, where stacked flows filled paleo–Whitmore Canyon. Some of these side-canyon flows appear to be correlative with high ca. 320 ka Whitmore remnants in a 6.5 km (4 mi) reach of Grand Canyon below the confluence with Whitmore Canyon. These intracanyon flows were likely deposited on an elevated aggraded surface (not a strath), possibly caused by interactions between climate-driven aggradation and the influx of volcanic material from the rim (via Whitmore Canyon). Flows previously designated as Layered and Massive Diabase are found to be the same age as the ca. 320 ka Whitmore flows. A step in the top surface of the Whitmore Dam at river mile 191 is interpreted to be a relic of the original geometry of the early part of the Whitmore Dam.

Volcanism from 225 to 150 ka, and 150 to 75 ka produced the Lower and Upper Gray Ledge flows, respectively, and likely emanated from cinder cones on the north rim between river miles 182 and 188. At ca. 180 ka, the Whitmore Cascade flowed atop Whitmore flows from at least river mile 188 to 189.

New $^{40}\text{Ar}/^{39}\text{Ar}$ dates require both general and specific changes to the terminology for basalts of western Grand Canyon. In terms of specific flows: (1) The Black Ledge far-traveled flows are considerably older (725–475 ka) than initially thought. Black Ledge flows are not interpreted to be separate flows but rather the distal parts of large-volume named flows that originated near river mile 179 and hence are likely correlative with the Prospect and/or Toroweap flows. Lava tubing via roofed of channels is postulated to connect far-traveled flows to the high-volume canyon edifice. (2) Whitmore flows as mapped by Hamblin (1994) include a lower ca. 320 ka part that is correlative with flows named as Layered and Massive Diabase. Upper parts of the Whitmore flow stack are younger and called Whitmore Cascade (ca. 180 ka). The composite history of this dam needs to be unraveled before lava-dam geometries and outburst-flood models can be proven. (3) Gray Ledge remnants mapped by Hamblin (1994) reflect two distinct periods of volcanism at ca. 200 and 100 ka. $^{40}\text{Ar}/^{39}\text{Ar}$ dating on a remnant at river mile 184.6, previously mapped as Black Ledge, indicates that it correlates with the older Lower Gray Ledge flow.

Hamblin’s (1994) correlations were based largely on flow morphology, cooling structures, color, and igneous textures. While important, these characteristics are not necessarily expected to remain constant throughout the flow. This may be especially true in

Figure 15. New testable intracanyon flow stratigraphy and model for composite volcanic edifices. Note that the flows from the Prospect flow stack are correlated with downstream Black Ledge remnants. Whitmore remnants are correlated to downstream remnants originally mapped as Layered Diabase (and Massive Diabase). Absolute ages from Karlstrom et al. (2007) are given for the closest remnant dated by the $^{40}\text{Ar}/^{39}\text{Ar}$ method. Inset relationships are depicted to show relative ages. Figure is not to scale.
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the Grand Canyon where topography and interactions with water are likely to affect a flow’s appearance. Miscorrelation of remnants between key outcrops where inset relationships were observed likely accounts for the need to revise the intracanyon flow stratigraphy. Available geochronostratigraphy is neither accurate enough nor voluminous enough to create a finished model for Quaternary volcanism in Grand Canyon. However, our new model for timing and sources of flow “groups” (Fig. 12) is well defined by new 40Ar/39Ar data and is further testable with additional dating and geochemical correlation, which may eventually allow for corollation of all individual flows.

Spatial analysis of flows using lidar is presented here as another correlation tool that allows for a precise evaluation of the geometry of contemporaneous cascades, flows, and dams. Well-preserved Upper and Lower Gray Ledge flow tops can be used to correlate associated remnants. The upstream-sloping 725–475 ka flow bottom indicates fault-block rotation and supports the differential incision model of Karlstrom et al. (2007).

Grand Canyon may be one of the best field laboratories for understanding interactions of volcanism, lava dams, extensional faulting, and canyon incision in the world. An over 700,000 yr record of interactions between these processes is beginning to be resolved (this paper; Karlstrom et al., 2007) with provocative new findings that can be further tested.

ACKNOWLEDGMENTS

We thank Grand Canyon National Park and the Hualapai Nation for cooperation in the form of a research permit that made field work in the river corridor a possibility and the Grand Canyon Monitoring and Research Center for making the lidar data available. Financial support for this study came from National Science Foundation grant EAR-9706541 (to Karlstrom and Pederson) from the Tectonics Program, EAR-0612310 (to Karlstrom) from the Instrumentation and Laboratory Improvement Program, and a Geological Society or America (GSA) student grant (to Crow). We thank Laura Crosse, Joel Pederson, Mike Timmons, Shari Kelly, Stacy Timmons, Matt Heizler, Lynn Heizler, Jason Raucci, Paul Umhoefer, Kimberly Samuels, Scott Miner, Austin Zinner, Adam Read, Tony Salem, and many other members of the broader University of New Mexico Grand Canyon collaboration for help with the field work and informal discussions of the manuscript. This manuscript was improved by reviews from Noah Snyder, Cassandra Fenton, and Kenneth Hamblin.

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