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Geology

K-Ar ages of Pleistocene lava dams in the Grand Canyon in Arizona

(radiometric dating/volcanism/basalt/potassium-argon)

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ABSTRACT **At least 13 times during the Pleistocene Epoch lava flowed into the inner gorge of the Grand Canyon and formed lava dams, as high as 600 m, that temporarily blocked the flow of the Colorado River. K-Ar ages on these lava dams indicate that the seven youngest formed within a short period of time between about 0.6 and 0.4 mega-annum (Ma). The physiography of the lava dam remnants within the canyon shows that each dam was destroyed by erosion, the Colorado River rapidly reaching its pre-existing grade level, before the next dam was emplaced by new eruptions. The total time for emplacement and destruction for an individual lava dam was probably as little as 0.01–0.02 million years. The K-Ar ages of the two oldest dams, the Lava Butte dam (0.577 ± 0.054 Ma) and the Prospect dam (0.684 ± 0.051 Ma) are somewhat younger than the physiography of their remnants suggest.**

One of the most significant recent events in the history of the Grand Canyon was the formation of a series of basaltic lava dams in the area of Toroweap Valley, Prospect Canyon, and Whitmore Canyon approximately 200 km west of the national park headquarters (Fig. 1). More than 150 lava flows poured into the canyon during the Pleistocene and formed a series of 13 major dams ranging from 60 to 600 m high. The lava dams impounded the water from the Colorado River to form a series of temporary lakes upstream. The shorelines of the deeper lakes were located near the base of the Redwall Limestone in the area of the park headquarters and extended far upstream into Utah beyond the present shores of Lake Powell. These lakes were larger in areal extent and impounded more water than Lake Mead and Lake Powell combined. Sediment deposited in these lakes still remain as isolated exposures, the largest being the silt deposits that fill Havasu Canyon. The lava dams have been described by previous workers, including Powell (1), Dutton (2), Moore (3), and McKee and Schenk (4), and discussed in detail by Hamblin (5–8); we include only a summary description in this paper.

Numerous remnants of the lava dams are preserved from Vulcan's Throne (mile 179) downstream to mile 263, a distance of 135 km. (Locations along the Colorado River in the Grand Canyon traditionally are measured in miles downstream from Lee's Ferry and nearly all of the relevant literature uses this location system. We also use the mile system for location.) Remnants range from a few kilometers long to small patches a few meters thick clinging precariously to the near vertical cliff of the inner gorge. Some dams were formed from a single lava flow, others were composed of multiple flows, some of which are interbedded with river gravel.

Hydrologic data from Lake Mead surveys suggest that both the formation and destruction of the lava dams occurred in a remarkably short period of time (9). The small single-flow dams were formed in a matter of days. Larger complex dams involving multiple flows may have required several thousand years to form and undoubtedly included several cycles of partial erosion between periods of lava extrusion and dam reconstruction. The lakes behind the dams were formed in a matter of years and probably filled with sediment in several hundred years. Destruction of the dams was also rapid. The overflow of the Colorado River at the downstream end of the dam undoubtedly formed rapids and waterfalls that quickly migrated upstream. After the lakes filled with sediment the normal traction load transported over the dam must have resulted in vigorous downcutting.

The relative ages of most of the lava dams are clearly expressed by juxtaposition (Fig. 2). Remnants of older basalt flows are adjacent to the canyon walls with succeeding younger units stacked in sequence side by side, with the youngest flows closest to the river channel. In addition, some expression of relative age is seen in the degree of erosion of remnants of dams that fill tributary valleys. Older remnants that fill major tributary valleys have been dissected by renewed side-canyon cutting whereas younger remnants that fill similar side valleys are only slightly modified.

Despite the importance of these lava dams to the recent history of the Grand Canyon, there have been few attempts to determine their age. McKee and others (10) obtained a K-Ar age of 1.16 ± 0.18 mega-annum (Ma) (1 σ) for the basalt at the base of the Toroweap Dam. Their age was based on three Ar analyses whose radiogenic ^{40}Ar content varied by 79% and whose atmospheric ^{40}Ar content ranged from 0.7 to 3.1%. Paul Damon (personal communication, quoted in ref. 8) measured K-Ar ages of 0.993 ± 0.097 Ma on one of the middle flows in the Whitmore Dam, and one of 0.549 ± 0.032 Ma on the flow that formed the Black Ledge Dam. Some of our preliminary results were referred to briefly by Hamblin (7, 8), but this is the first paper to document our radiometric ages for the lava dams.

During field work in 1971 and 1992 we collected samples for dating from more than 80 flows representing 13 of the major lava dams. The purpose of this paper is to present K-Ar ages for some of these samples and to relate these data to the Pleistocene history of the Grand Canyon.

Analytical Methods

Samples consisted of both hand samples and one-inch cores. All samples were examined in thin section and many were rejected as unsuitable for K-Ar dating, a few because of alteration but most because of large amounts of glass in the ground mass. Those samples that were selected for dating were free of alteration and were either holocrystalline or contained relatively small amounts of isotropic ground-mass glass.

Two methods of sample preparation were used: small blocks cut with a diamond saw and 0.5–1.0 mm crushed material. For the former, small chips were sawed from each end for the K_2O analyses whereas for the latter an aliquant was taken with a sample splitter. The material taken for the K_2O analyses was

Abbreviations: Ma, mega-annum; MSWD, mean square of the weighted deviates.

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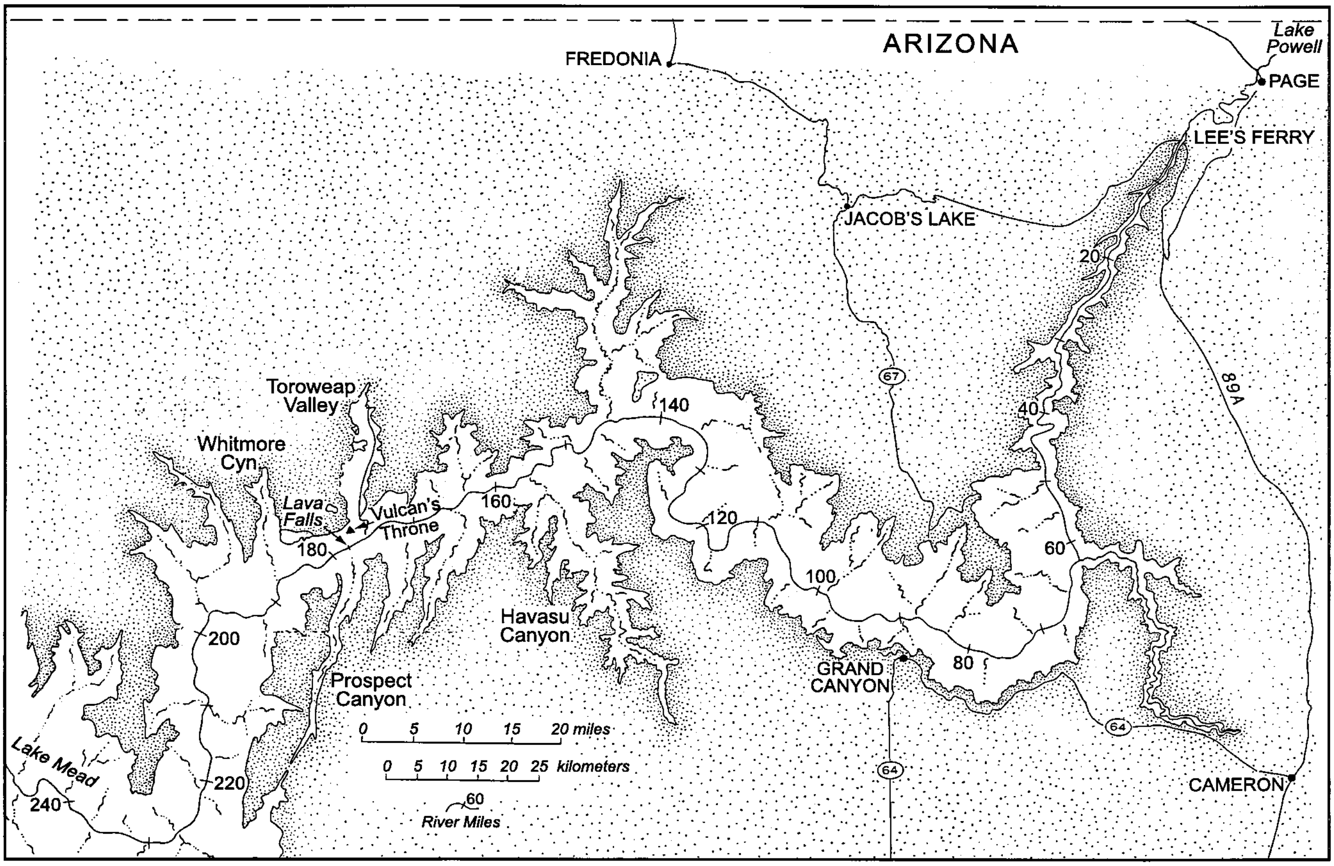

FIG. 1. Map showing general locations of Pleistocene lava dams in the Grand Canyon in Arizona, and the locations of places mentioned in the text. Mile markers, measured downstream from Lee's Ferry, are the traditional way to locate features along the Colorado River in the Grand Canyon. After Hamblin (8).

further crushed to -75 μm before analysis. Many of the basalts contain xenoliths (primarily dunite) and carbonate and as much care as possible was taken during sample preparation to avoid incorporating either of these into the sample analyzed. Both the carbonate, which interferes with the clean-up process during Ar extraction and whose results are unpredictable, and the older inclusions, which contribute unknown and varying amounts of inherited ^{40}Ar, would be expected to result in calculated ages that are inconsistent and, where inherited ^{40}Ar is present, too old. Despite our precautions, the inconsistency of the results for several of the samples suggests that we were not entirely successful for several of the flows.

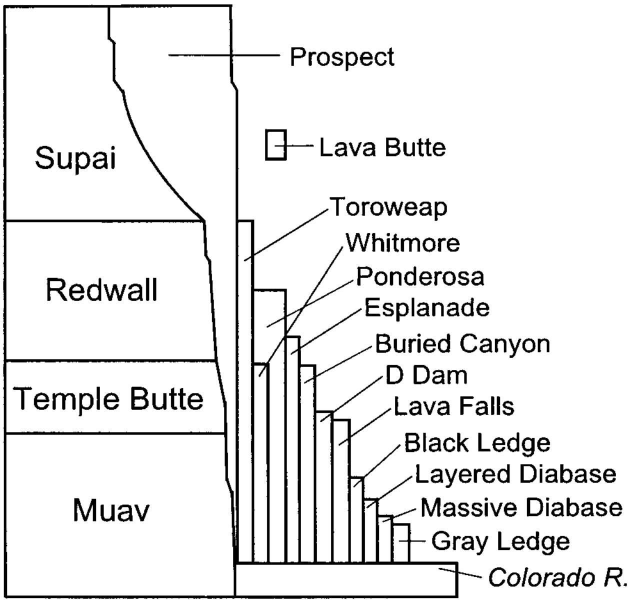

FIG. 2. Relative age of major dams as indicated by juxtaposition insofar as known. Paleozoic sedimentary units that form the walls of the Grand Canyon in the vicinity of the lava dams are shown on the left. This is a composite diagram constructed from numerous exposures between miles 179 and 207. After Hamblin (8).

Potassium analyses were by flame photometry using a lithium metaborate flux (11). Argon analyses were by isotope dilution using ^{38}Ar tracers calibrated with our intralaboratory standard biotite SB-3 (162.9 Ma) and methods described previously (12). Errors assigned to the individual ages are SDs of precision unless specified otherwise. Weighted means and weighted SDs (σ_{best}), were calculated following Taylor (13). For some samples the dispersion of the measured ages is greater than expected from random analytical errors, i.e., the mean square of the weighted deviates (MSWD) is greater than one. This finding indicates that "geological" error, perhaps because of carbonate, xenoliths, or other factors, is present. For these samples we have adjusted the uncertainties by multiplying each individual error by the square root of MSWD before calculating σ_{best} (14, 15). In general, our results are not sufficiently precise to distinguish differences in age between flows within a single dam, and so we treat all of the ages from such flows as a single population and use the weighted mean of the ages to represent the age of the dam.

Description of the Lava Dams and Their K-Ar Ages

The Prospect Dam. A single remnant of the Prospect Dam is preserved in a large alcove just east of the mouth of Prospect

Canyon on the south side of the river at mile 179. It consists of three exceptionally thick units of basalt preserved in the ancestral Prospect Canyon and is capped by a thick horizontal basalt layer that extends westward beyond the inner gorge of Prospect Canyon. The Prospect Dam had a height above the present Colorado River of 699 m and an estimated lava volume of 4.0 km^3 (7, 8). Younger flows believed to be equivalent to the Ponderosa and Toroweap dams are juxtaposed against the Prospect flows, but this correlation is not certain. The relative antiquity of the Prospect Dam is suggested by the degree of erosion of the flows in Prospect Canyon. A V-shaped gorge over 2 km long has been reexcavated into the basalt fill in Prospect Canyon whereas remnants of all of the other dams that fill tributary valleys, such as those preserved in Toroweap and Whitmore canyons, have been subjected to much less erosion. Thus, the physiographic evidence suggests that the Prospect Canyon dam is perhaps the oldest of the lava dams.

We measured K-Ar ages on all three of the flows that form the Prospect Dam (Table 1). The 1.86-Ma result from one sample of the oldest flow is clearly anomalous when compared with the results from the other two samples of this flow, and we suspect that the anomalous sample may have contained an undetected xenolith. If we exclude the one anomalous result the weighted mean age of the results from the three Prospect flows is 0.679 ± 0.047 Ma (MSWD = 6.057). If the anomalous result is included, the weighted mean age is 0.684 ± 0.019 Ma (MSWD = 7.099).

We also measured an age of 0.500 ± 0.047 Ma on a flow at the head of Prospect Canyon (Upper Prospect Canyon flow). There is no stratigraphic or geomorphic evidence to indicate whether this flow is part of the Prospect Dam or is a younger flow that flowed onto the surface of the dam at some later time. In view of its K-Ar age, however, we think that the latter explanation is most likely. In addition, this flow is cut by the Toroweap Fault, indicating that the fault was active less than about 0.5 Ma.

Lava Butte Dam. Several remnants of a sequence of thin flows interbedded with river sediment are preserved high on the north wall of the inner gorge at mile 180.8 about 4 km downstream from Vulcan's Throne. One remnant caps an isolated butte that stands approximately 130 m above the surrounding area. If this remnant was formed by topographic inversion, i.e., by erosion along the flow margins, it suggests that the Lava Butte Dam is one of the oldest dams preserved in the canyon. The remnants are not juxtaposed with other flows, however, so its relative age cannot be determined. The

Table 1. Analytical data for K-Ar ages on Pleistocene lava flows of the Grand Canyon, Arizona

Mile*	Flow	$^{40}Ar_{rad}$, %	Age†, Ma
Gray Ledge Dam			
187.2	—	6.5	0.788 ± 0.128
Massive Diabase Dam			
202.5N	—	5.5	0.421 ± 0.082
		3.9	0.430 ± 0.121
184.5N	—	9.0	0.496 ± 0.057
		2.8	0.291 ± 0.113
Layered Diabase Dam			
183.2S	Flow 2	6.9	0.542 ± 0.083
		6.4	0.729 ± 0.120
183.3S	Flow 7	5.7	0.657 ± 0.124
		6.3	0.636 ± 0.107
D Dam			
179.7N	Flow D	12.1	0.580 ± 0.049
		14.4	0.584 ± 0.040
Buried Canyon Dam			
183.1N	Flow I	2.7	1.190 ± 0.480
		1.7	1.410 ± 0.890
		1.6	0.469 ± 0.324
		12.3	0.992 ± 0.082
183.0N	Flow F1	1.5	2.240 ± 1.620
		4.0	0.921 ± 0.247
183.1N	Flow D	1.7	1.770 ± 1.140
		1.1	0.920 ± 0.890
		7.5	1.270 ± 0.180
183.1N	Flow D	3.1	0.838 ± 0.291
183.0N	Flow C	6.2	0.626 ± 0.107
		2.8	0.903 ± 0.355
183.1N	Flow A	2.4	4.780 ± 2.190
		4.3	1.020 ± 0.260
Esplanade Dam			
181.0N	Flow B	2.3	0.110 ± 0.053
Ponderosa Dam			
181.6N	—	7.2	0.591 ± 0.033
		7.2	0.625 ± 0.035
Toroweap Dam			
179.8S	Hi-remnant F	2.7	1.170 ± 0.470
		3.4	1.320 ± 0.420
		4.4	0.484 ± 0.119
179.8S	Hi-remnant F	6.1	1.180 ± 0.210
179.8S	Hi-remnant F	7.9	0.677 ± 0.090
		6.7	0.689 ± 0.109
178.5N	Flow E	2.2	1.200 ± 0.610
		4.1	1.730 ± 0.460
178.5N	Flow E	5.6	0.398 ± 0.075
		4.7	0.376 ± 0.086
		3.1	0.905 ± 0.318
Lava Butte Dam			
181.0N	Flow 1	6.3	0.659 ± 0.043
		5.4	0.511 ± 0.038
181.0N	Flow 2	4.4	0.581 ± 0.052
		7.2	0.840 ± 0.046
181.0N	Flow 3	3.7	0.569 ± 0.060
		6.1	0.408 ± 0.031
181.0N	Flow 4	7.2	0.652 ± 0.037
Upper Prospect Canyon flow			
—		6.8	0.524 ± 0.082
		8.9	0.488 ± 0.057
Prospect Canyon Dam			
179.0S	Youngest flow	18.7	0.653 ± 0.034
		13.9	0.596 ± 0.043
		6.6	0.416 ± 0.067
179.6S	Old fill	2.4	0.885 ± 0.410
		5.6	0.889 ± 0.170
179.0S	Oldest flow	6.2	1.860 ± 0.300
179.0S	Oldest flow	5.0	0.657 ± 0.052
		6.5	0.869 ± 0.052
179.0S	Oldest flow	5.0	0.946 ± 0.074
		3.1	0.745 ± 0.103
Toroweap Valley Fill			
—		3.8	0.780 ± 0.224
		4.7	0.774 ± 0.176
		4.7	3.770 ± 0.860
Dike, Prospect Canyon			
179.5S	Hi dike	12.7	0.851 ± 0.067
		12.6	0.750 ± 0.120

*The lava dams and the individual flows are listed in stratigraphic order, from youngest to oldest, where known. N, north side of canyon; S, south side of canyon.

†$^{40}K/K_{total} = 1.167 \times 10^{-4}$, $\lambda_\varepsilon = 0.581 \times 10^{-10} \cdot yr^{-1}$, $\lambda_\beta = 4.692 \times 10^{-1} \cdot yr^{-1}$. Errors assigned to individual ages are estimates of the analytical precision at the 68% confidence level.

Lava Butte Dam reached a height of 560 m above the present river but there are insufficient remnants to permit an accurate estimate of the original lava volume.

We were unable to sample the basalt on the lava-capped butte, but samples from four flows from the Lava Butte dam were collected from remnants on the north canyon wall and dated. The results are reasonably consistent with a weighted mean age of 0.577 ± 0.054 Ma (MSWD = 12.20).

Toroweap Dam. A remnant of the Toroweap Dam is juxtaposed against the lower basalt flows that fill Toroweap Valley and against the adjacent Paleozoic rocks between miles 178 and 180. This remnant, which consists of at least five major flows, is over 2 km long and indicates that the Toroweap Dam had a maximum thickness of 424 m. The Toroweap Dam is older than the Lava Falls dam and, if correlation with similar basalts across the river is correct, it is also younger than the Prospect and Ponderosa dams. The Toroweap Dam had an estimated volume of 3.7 km^3.

Several attempts were made to measure the age of the Toroweap dam by using multiple samples from two flows (E and F), but the results are highly inconsistent (Table 1), indicating that the analyses were affected by older inclusions, carbonate, or both. The weighted mean of all of our measurements is 0.557 ± 0.074 Ma (MSWD = 3.517), but in view of the poor reproducibility we do not consider this to be a reliable age. The age of 1.16 ± 0.18 Ma obtained by Damon (quoted in ref. 8) falls within the range of our ages but we consider it no more reliable than ours.

Whitmore Dam. A number of large remnants of the Whitmore Dam are preserved at the mouth of Whitmore Canyon and on both sides of the inner gorge of the Grand Canyon between miles 187 and 190. The Whitmore Dam consisted of more than 40 thin flows, commonly interbedded with river gravel. What appears to be a remnant of the Ponderosa flow (the identification is uncertain) is juxtaposed against, and therefore younger than, the basalt flows of the Whitmore dam as are the flows that formed the Black Ledge, Massive Diabase, and Gray Ledge dams.

We attempted to measure K-Ar ages on two of the older flows from the Whitmore Dam but the argon extracted in three attempts was all atmospheric and so it was not possible to calculate K-Ar ages. The age measurements on the stratigraphically older Lava Butte (0.577 ± 0.054 Ma) and the stratigraphically younger Ponderosa (0.607 ± 0.024 Ma) dams seem to indicate that the age of the Whitmore Dam is probably about 0.6 Ma. Damon (quoted in ref. 8), however, obtained a single K-Ar age of 0.993 ± 0.097 Ma from a Whitmore flow. We cannot explain this discrepancy, but it has been our experience in studying the Grand Canyon flows that consistency from multiple measurements, preferably on multiple flows, is necessary before a K-Ar age can be considered truly reliable. We hesitate, therefore, to place much significance on a single age measurement from a single flow and suggest that the age of the Whitmore Dam may be about 0.6 Ma.

Ponderosa Dam. A large remnant of the Ponderosa Dam, which was constructed by a single flow at least 300 m thick with a volume of 2.5 km^3, is preserved on the north side of the river at mile 182. The base of the flow is near river level, indicating that the Grand Canyon was cut to its present depth at the time the Ponderosa dam was formed. Remnants of the Esplanade Dam are juxtaposed against the Ponderosa flows, indicating that the Ponderosa is one of the older dams in the Canyon. Its age relative to the Prospect Canyon and Lava Butte dams, however, is unknown.

Only one sample from the Ponderosa dam was suitable for dating. That flow gave reproducible results with a weighted mean age of 0.607 ± 0.024 Ma (MSWD <1).

Esplanade Dam. Between miles 181 and 182 a large remnant of a sequence of basalt flows is preserved beneath younger lava flows (the Esplanade Cascades) that flow from the north canyon rim. The Esplanade dam was formed by 6–8 major flows, each over 50 m thick, and had an estimated volume of 1.8 km^3. Remnants of the younger Lava Falls dam (discussed below) are juxtaposed against the Esplanade, indicating that the Esplanade Dam is at least older than the five youngest dams in the Grand Canyon.

We made a single age measurement (0.110 ± 0.053 Ma) on one flow of the Esplanade dam but because the result is not verified either by replication or by an age on another flow we do not consider it to be reliable.

Buried Canyon Dam. At mile 183 a large exposure of a sequence of basalt flows fills an ancient canyon through which the Colorado River once flowed. This remnant is almost a perfect cross section through a complex dam and shows how the canyon was filled with basalt and river gravel during the construction of the dam. This dam consisted of eight major flows with a total volume of 1.7 km^3. The basalt flows of the Lava Falls Dam (discussed below) are juxtaposed against the flows of the Buried Canyon Dam but there is no evidence of the relative age between the Buried Canyon and Esplanade dams.

We attempted to measure K-Ar ages on six samples from five of the Buried Canyon flows, and the results are highly inconsistent, both within individual flows and between flows whose stratigraphy is known (Table 1, Fig. 3). The weighted mean of the results is 0.907 ± 0.066 Ma (MSWD = 1.474) but because of the lack of reproducibility and consistency we do not consider this age to be reliable.

D Dam. Several small remnants of a sequence of thin basalt flows are preserved on both sides of the canyon below Vulcan's Throne. McKee and Schenk (4) called these the D flows of their Lower Canyon Series. These basalt flows formed a dam 191 m high consisting of as many as 40 thin flows with a total volume of approximately 1.1 km^3. On the basis of juxtaposition the D Dam is clearly younger than the Toroweap Dam and older than the Lava Falls and Black Ledge dams.

We obtained reproducible K-Ar ages on a single sample from one of the flows that formed the D dam. The results have a weighed mean age of 0.582 ± 0.031 Ma (MSWD <1).

Lava Falls Dam. Several large remnants of a single basalt flow 191 m thick and with an estimated volume of 1.2 km^3 are preserved between Lava Falls Rapids and Whitmore Canyon. It is the oldest of the five most recent dams, whose relative ages

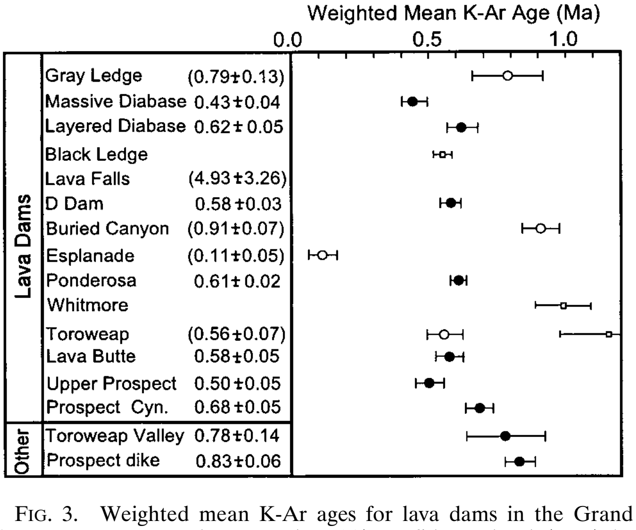

FIG. 3. Weighted mean K-Ar ages for lava dams in the Grand Canyon. Errors are shown at the 68% confidence level (σ_{best}) by vertical bars. ●, Ages considered reliable. ○, Ages considered unreliable. □, Ages from McKee and others (10) and Damon (quoted in ref. 8). The lava dams are shown in stratigraphic order, youngest at top, insofar as known. Numerical values are the data from this study with the unreliable data in parentheses.

are indicated by juxtaposition. Of the samples collected from this flow none was suitable for dating because of excessive amounts of glass. The Lava Falls Dam is thus not dated directly but it is tightly bracketed by indistinguishable ages for the D Flows (0.582 ± 0.031 Ma) and the Layered Diabase (0.620 ± 0.052 Ma, discussed below) dams.

Black Ledge Dam. One of the most distinctive remnants of basalt in the Grand Canyon is a dense black flow that typically forms a distinctive ledge along the canyon walls. This dam was 111 m high, was the longest flow in the canyon extending 135 km downstream from the Toroweap area, and had an estimated volume of 2.1 km^3. None of the samples we collected from the Black Ledge flow was suitable for dating because of excessive amounts of glass but, like the Lava Falls Dam, the age of the Black Ledge Dam is constrained by the ages of the flows of the D Dam (0.582 ± 0.031 Ma) and the Layered Diabase Dam (0.620 ± 0.052 Ma). The age of 0.549 ± 0.032 Ma obtained by Damon for the Black Ledge Dam (quoted in ref. 8) thus is consistent with, and not significantly different from, our ages for the two older and younger dams.

Layered Diabase Dam. A distinctive sequence of 15–20 flows of coarse-grained basalt formed the Layered Diabase Dam, which had a thickness of 89 m and a volume of only 0.3 km^3. Two flows, from near the bottom and top of the sequence exposed at mile 183.2 on the south side of the canyon, were analyzed. The results from the two flows are reasonably consistent and have a weighted mean of 0.620 ± 0.052 Ma (MSWD <1).

Massive Diabase Dam. This dam was formed by a single flow of very coarse-grained basalt. It was only 68 m high with a volume of 0.2 km^3 and had only a slight effect on the river compared with most of the other major lava dams. Two samples from two different localities were dated with reproducible results. The weighted mean age is 0.443 ± 0.041 Ma (MSWD <1).

Gray Ledge Dam. Remnants of a single basalt flow characterized by an abnormally thick basal colonnade structure commonly is juxtaposed against the remnants of the Black Ledge Dam. This flow is covered by a thick layer of coarse gravel and typically weathers into a distinctive gray ledge. The dam's height above the present river was 61 m, and its estimated volume was only 0.3 km^3.

A single age of 0.788 ± 0.128 Ma was obtained on one sample from this flow. Because this age is based on a single measurement we do not consider it to be reliable. The maximum age of the Gray Ledge Dam, however, is constrained by the age of 0.443 ± 0.041 Ma for the Massive Diabase Dam, which is stratigraphically older.

A Possible Dam at Toroweap Valley. The huge volume of basalt that fills Toroweap Valley suggests the possibility of an additional high-level dam in the inner gorge of the Grand Canyon. These flows are all relatively thin (4–5 m) and are similar in almost every way to the flows that form the Whitmore Dam. The cumulative thickness of these flows is 504 m. They apparently originated from lava that issued from vents on the Uinkaret Plateau and flowed into Toroweap Valley; many undoubtedly cascaded into the inner gorge. The eroded face of these flows in the inner gorge is slightly more than 600 m back from the river channel. Inasmuch as most flow units are nearly horizontal, it seems reasonable to suppose that they formed a barrier across the Grand Canyon. Without equivalent flows preserved on the south wall of the canyon, however, the existence of the dam cannot be demonstrated conclusively, but dikes cutting these flows suggest that the flows once filled the inner gorge and formed the country rock into which the dikes were injected. If a dam was constructed from these flows, it was older than the Toroweap Dam and was probably similar in geometry and internal structure to the Whitmore Dam.

We made three age measurements on a sample from the uppermost flow near the base of Vulcan's Throne. One of the ages is anomalously high, perhaps because of the inadvertent inclusion of a xenolith, but the other two are consistent with a weighted mean age of 0.776 ± 0.138 Ma (MSWD <1). Because of the relatively large analytical uncertainty, this age is not significantly different from the ages found for any of the other dated dams (Fig. 3), but the result is not inconsistent with the hypothesis that the Toroweap Valley fill is older than the Toroweap Dam.

Dike, Prospect Canyon. We also sampled and dated a dike that occurs at an elevation of 805 m at mile 179.5 on the south side of the Colorado River and in the west wall of Prospect Canyon. This dike is about 15 m thick and is one of a large number of similar dikes, some of which intrude remnants of lava dams. Lava remnants clearly show that the canyon was cut to its present depth before the oldest dams were formed (8). Because the dike had to have been intruded into some body of rock that since has been removed by erosion, it seems likely that the dike intruded lava flows that formed a dam in the canyon rather than the older sedimentary rocks. If this is so, then the top of the dam must have exceeded an elevation of 805 m.

The duplicate analyses of this dike are relatively reproducible with a mean age of 0.827 ± 0.058 Ma (MSWD <1). This age is significantly older, at the 95% level of confidence, than the age we obtained for the Prospect Dam and suggests the existence of volcanic activity, and perhaps even older dams, within the area of the present Grand Canyon before the formation of the 13 Pleistocene lava dams discussed above.

Discussion

We have obtained reasonably consistent K-Ar age data on lava flows from more than half of the 13 major lava dams that partly filled the Grand Canyon and temporarily blocked the flow of the Colorado during the Pleistocene Epoch (Fig. 3). Four of the six youngest dams (Ponderosa, D Flows, Layered Diabase, and Massive Diabase) have K-Ar ages that fall within a very narrow range, 0.61–0.43 Ma, indicating that these dams, as well as the Black Ledge, Lava Falls, Buried Canyon, Esplanade, and Toroweap dams, were formed within a very short period of time, probably 0.2 Ma or so. We did not obtain a reliable K-Ar age for the youngest (Gray Ledge) dam, but its flows are stratigraphically younger than those of the Massive Diabase dam and so it must be less than about 0.43 Ma in age, but not necessarily much less.

The K-Ar ages for the Lava Butte (0.574 ± 0.054 Ma) and Prospect Canyon (0.684 ± 0.051 Ma) dams, although stratigraphically and radiometrically consistent with the ages of the younger dams, pose somewhat of a problem. The physiography of these two dams suggests that they may be much older, rather than slightly older, than the younger dams. The remnant of the Prospect Dam that partly fills Prospect Valley has been eroded into a V-shaped gorge nearly 2 km in length. Neither the Toroweap nor the Whitmore dams, both of which also fill major tributary valleys, have been eroded similarly. This finding suggests that the Prospect Dam is much older than the K-Ar ages indicate. An alternate explanation is that preexisting and temporary hydrologic conditions in Prospect Valley may have eroded the Prospect Dam preferentially.

The antiquity of the Lava Butte Dam is suggested by the degree to which it has been eroded by minor intermittent streams on the sides of the inner gorge. A remnant of a series of basalt flows at mile 180.5 caps a high butte rising 120 m above the surrounding area and 529 m above river level. The butte has been separated from the wall of the inner gorge by headward erosion of two short tributary streams. No other remnant of a lava dam has been eroded by tributary streams to such a degree that it forms an isolated butte separated from the canyon wall.

We cannot resolve the apparent conflict between the K-Ar data and the physiography of the Lava Butte and Prospect dams. Either the K-Ar ages are incorrect or the relative degree of erosion is an imperfect indicator of elapsed time for these lava dams. As discussed below, erosion in the Grand Canyon can be extremely rapid under certain conditions and it is possible that the physiography suggesting the passage of substantial time was produced, instead, in a very short interval of time. Because the K-Ar ages are consistent with the known stratigraphy and are the only quantitative measure of time available we adopt, with the reservations expressed above, the K-Ar ages for the Lava Butte and Prospect flows in the discussion that follows.

Based on the K-Ar data (Fig. 3) all 13 of the major lava dams, representing a minimum of 22 km^3 of lava and a cumulative vertical thickness of more than 3.5 km, were formed by copious eruptions and were rapidly destroyed by the Colorado River within a very short period of time. All available evidence indicates that before the extrusions of lava into the Grand Canyon the Colorado River had cut down to its present gradient and stratigraphic position and that the size and shape of the canyon walls at the time of basalt extrusions were essentially the same as those we see today (8). This is clear from the position of numerous thin remnants of various dams that remain as slivers next to the original canyon wall, some of which extend down to present-day river level. Thus, after each lava dam was formed, the Colorado River eroded through the dam down to its original profile, but no farther. This process of re-excavating the canyon took place at least 13 times during the Pleistocene Epoch.

The K-Ar ages are not sufficiently precise to permit an estimate of the times between the various episodes of dam formation, but the clustering of ages for the younger dams between about 0.6 and 0.43 Ma shows that dam erosion was very rapid. The data indicate that the nine younger dams that are either dated directly or bracketed by dated flows (Ponderosa through Massive Diabase) were erupted within a period of only about 0.2 million years. This finding suggests that on the average an individual dam was emplaced and destroyed by erosion in only about 0.01–0.02 million years. Apparently major rivers, like the Colorado River, are extremely efficient at removing blockage and re-establishing a former gradient, even when the blockage is by relatively resistant rocks like basaltic lava flows.

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