Evidences for Rapid Formation and Failure of Pleistocene "Lava Dams" of the Western Grand Canyon, Arizona

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Abstract

Over two hundred isolated outcrops of horizontally stratified, basaltic lava flows within the inner gorge of western Grand Canyon indicate that several natural "lava dams" blocked the flow of the Colorado River during the Pleistocene, resulting in the formation of several lakes within the canyon. The largest lake was 90 m above the high water level of present-day Lake Powell and backed up a distance of over 480 km to Moab, Utah. Although early studies indicated that three or less dams once blocked the inner gorge, work completed in 1994 indicated that at least thirteen distinct lava dams may have blocked the Colorado River. Comparison with modern erosion rates of cliff retreat (Niagara Falls) indicate that the thirteen dams would have required a minimum of 250,000 years to erode during the Pleistocene. However, geologic features and relationships not previously considered indicate that the dams formed rapidly (hours, days, or months) and failed catastrophically soon after formation. Excess radiogenic argon is contained within many basalts of Grand Canyon. This initial argon invalidates K-Ar model ages which are assumed by many geologists to require an age of more than one million years for the oldest lava dams. We envision that the entire episode of the lava dams can easily be reconciled within a time frame of less than two thousand years. Our observations and interpretations reveal serious flaws in the current long-age timescale of the Pleistocene Epoch.

Keywords

Arizona, Grand Canyon, Catastrophic Erosion, Dam Breachment, Lava Dam, Geomorphology, Excess Argon, K-Ar Dating, Pleistocene Epoch

Introduction

The western Grand Canyon contains a unique and spectacular sequence of Pleistocene volcanic flows. The basaltic flows are particularly captivating because of their stark contrasting jet-black color against the light brown and red hues of the underlying Paleozoic sedimentary rocks. The Pleistocene flows appear as "frozen" lava falls cascading down the walls of the inner gorge to the Colorado River below. They also have a much more unique aspect which was first observed by John Wesley Powell in 1887. Powell noted that many of the inner gorge flows are horizontally bedded, indicating that they once extended across the entire width of the inner gorge, damming the Colorado River and forming an immense lake within the Grand Canyon. Later geologic studies showed that there were possibly several separate lava dams within the western Grand Canyon during the Pleistocene. Recently, W. Kenneth Hamblin (1994) evaluated over 200 lava-dam remnants within the inner gorge between miles 177 and 254 (river miles measured downstream from Lee's Ferry, Arizona (Figure 1) and concluded that at least thirteen separate and distinct lava dams once blocked the Colorado River spanning a length of time between approximately 1.8 Ma (million years ago) to as recently as 0.45 Ma.

The remnants of lava dams outcrop at elevations from river level (500 m) up to near the top of the inner gorge rim (1200 m),and vary in size from a few meters to over 2.5 km long. The tallest and oldest lava dam had a crest of 700 m above the Colorado River and backed up a lake to near Moab, Utah (a distance of over 480 km) which would have been 90 m above the high water level of present-day Lake Powell. The dams were all at least several kilometers long, with the longest extending a total distance of over 138 km. Based on present rates of retreat of Niagara Falls, Hamblin (1994) suggested that the individual dams required from 10,000 to 40,000 years to erode. Using an intermediate value of 20,000 years, Hamblin

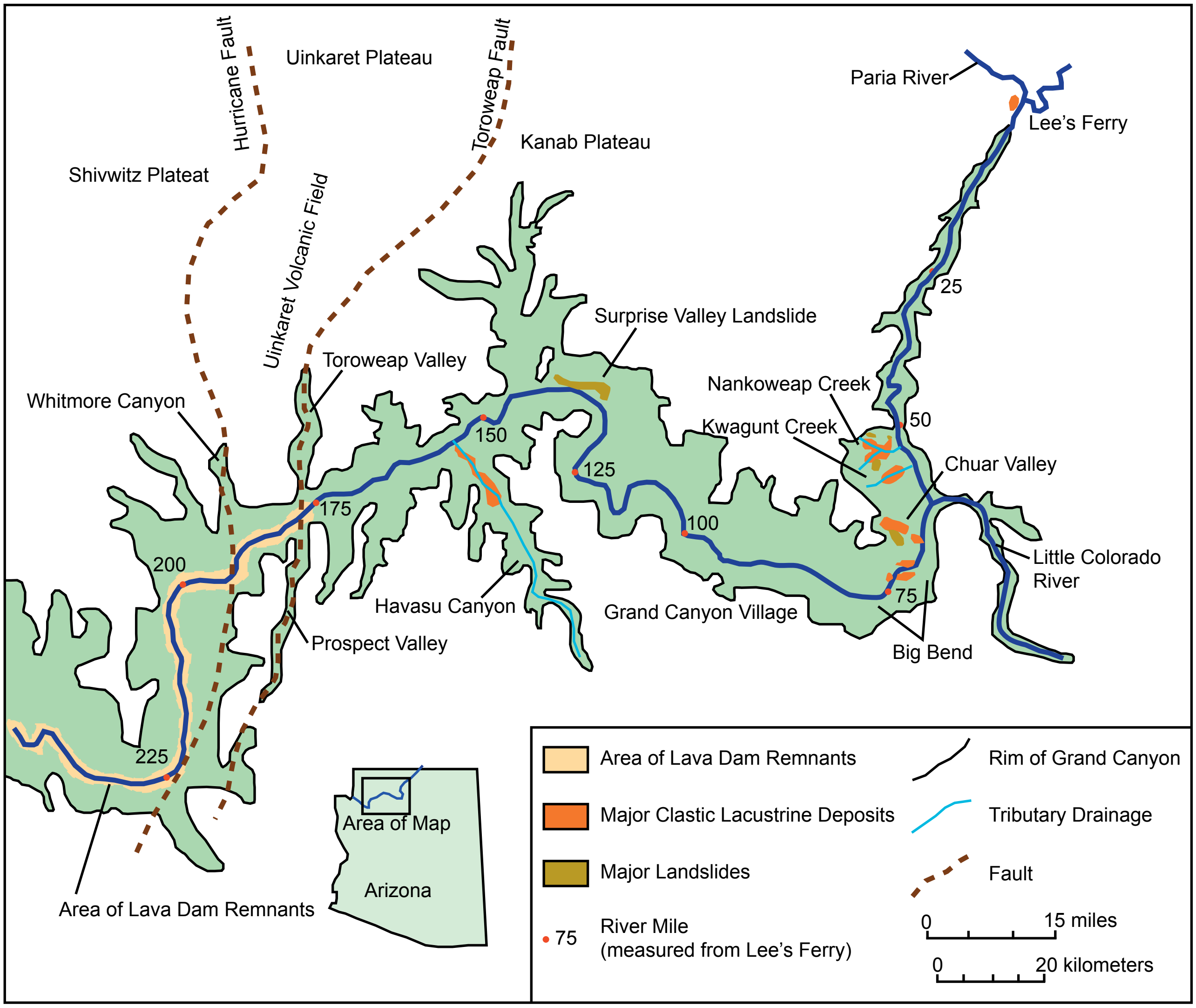


Figure 1. Location and geologic map of Grand Canyon, Arizona.

concluded that the Colorado River would have been dammed a total of up to 250,000 years during the period between 1.8 Ma to 0.45 Ma of the Pleistocene.

Lava dams figure prominently in the rendition of Grand Canyon in the popular press. Hamblin & Hamblin (1997) have recounted the naturalist's common perception of Grand Canyon's lava dams being "more than one million years old." Davis Young (1990), a Christian geologist writing about Noah's Flood, has reiterated the notion that Noah's Flood could not have been involved in forming the Grand Canyon, because the canyon was already present "1.16 million years ago" when lava flowed in and blocked the river. Young's very precise "age" for the lava dam comes from potassium-argon (K-Ar) dating of the basalt (McKee, Hamblin, & Damon, 1968).

This long time frame potentially presents a problem to those who hold to a biblical view of a young earth and a short time frame for earth history. If the Pleistocene is a post-Flood epoch, then the episode of the volcanic dams needs to be reconciled within only a several-thousand-year time frame, and not the "more than one million years" of the uniformitarian timescale. Does the geologic field evidence support a short or long time frame scenario for the development and subsequent erosion of the Pleistocene lava dams? We believe that the evidence overwhelmingly supports a short time frame, and we will examine several important details not previously considered.

Geologic Setting

The volcanic rocks of the western Grand Canyon are part of the Uinkaret Volcanic Field. This volcanic field extends northward from the Colorado River approximately 80 km to near the Vermilion Cliffs, and contains up to 160 volcanic cones (Koons, 1945). The cones range from 15 to 250 m in height. The volcanic flows are generally less than 8 m thick and cover an area of several hundred km^2.

Maxson (1949) noted that the volcanic rocks consist of olivine basalt flows and basaltic cinders. The flows erupted in association with two north/south trending fissures on the Uinkaret Plateau which extend north from near the rim of the inner gorge. Only a few relatively small eruptive sources occur on the platform south of the inner gorge. The flows average between approximately 1 to 2 meters thick. Some individual flows cover areas of up to several square kilometers. The thin and extensive lateral coverage of the flows indicates that they were highly fluid upon eruption. Many of the flows poured southward into the inner gorge as lava cascades. The most spectacular cascades occur between miles 179 and 182 on the north wall of the inner gorge. One cascade (near mile 181) almost reaches the bank of the Colorado River (Billingsley & Huntoon, 1983).

The classic Grand Canyon sequence of Paleozoic rocks (Tapeats Sandstone through Kaibab Formation) all outcrop in the western Grand Canyon. The rim of the inner gorge is composed of the Esplanade Sandstone (Supai Group). The wall of this inner gorge exposes strata as deep as Tapeats Sandstone. The broad Esplanade Platform occurs above the inner gorge and is overlain by the Hermit through Kaibab Formations.

The Toroweap and Hurricane faults are the most prominent structural features of this region of the western Grand Canyon. The Toroweap Fault, which crosses the Colorado River near mile 179, displays about 250 m of displacement and has controlled the development of Toroweap Valley on the north side of the inner gorge and Prospect Valley on the south. The Hurricane Fault exhibits up to 400 m of offset. The fault runs parallel with the Colorado River starting at mile 188 (Whitmore Canyon) where the river makes a southward bend, and eventually crosses the river near mile 191, where the river makes another turn toward the west. Like Toroweap Valley, Whitmore Canyon has allowed the lava flows on the Esplanade to be channeled southward toward the inner gorge.

Lava Dams

McKee & Schenk (1942) first studied the lava-dam remnants and concluded that they were part of a large solitary dam structure. After a more detailed study, Maxson (1949) concluded that up to three separate dams, two of which coexisted, once filled the inner gorge. Hamblin (1994) has concluded, in the most detailed study to date, that at least thirteen separate lava dams, none of which coexisted, filled the inner gorge during a period between 1.8 Ma to 0.45 Ma of the Pleistocene. Hamblin noted that the remnants displayed several distinctive types of depositional features (texture and flow thickness) which he relied upon to correlate the individual dam remnants.

One of the most interesting aspects of the remnants is that many, including some of the oldest, occur near the present elevation of the Colorado River. For example, a large outcrop of Toroweap Dam occurs within only 15 m of the present river level. This shows that there has not been significant additional downcutting of the canyon in this area since the time of formation of even the oldest dams. The pattern of preservation of dam remnants also shows that the inner gorge has not undergone noticeable widening during the Pleistocene.

Concepts of uniformitarian geologists regarding the very long ages of the lava dams within Grand Canyon come from three areas:

1. the stratigraphic relationships of the different flow remnants of ancient dams,
2. the durability of slopes within the canyon against which these dams have accumulated, and
3. K-Ar dating of the basalt.

The first two methods are strongly tied to the geomorphic presuppositions of the geologist making the interpretation. For example, were multiple dams each eroded slowly at the rate at which the Niagara River of New York is now eroding back the falls? The third (K-Ar dating) appears to be less dependent on geomorphic presuppositions.

K-Ar Dating of Lava Dams

The first basalt dam to be dated using the K-Ar method was Toroweap Dam by McKee et al (1968). The lowest part of that dam gave a K-Ar model age of 1.16±0.18 Ma (million years). These earliest workers admitted that their age could be in error because of "excess argon," a process whereby the magmatic argon is occluded within basalt as it cools making the sample appear exceedingly old. Other investigators since have also dated basalts within Grand Canyon. Hamblin [1989, p. 199] described numerous basalt samples collected during 1972 and dated by G.B. Dalrymple. Concerning these rocks, Hamblin noted that four basalt flows gave "reliable dates" (0.14, 0.57, 0.64, and 0.89 Ma). However, Hamblin noted "many had excess argon" (1989, p. 199). The "ages" for those with "excess argon" have not been reported in any publication. Also, there has been no publication of which criteria were used to select the "reliable" from the more-frequently occurring "unreliable" ages. Recently, Wenrich, Billingsley, & Blackerby (1995, p. 10421) reported other "ages" for basalt dams within Grand Canyon, but none exceeds the "age" of Toroweap Dam (supposedly 1.16±0.18 Ma).

In order to test the K-Ar dating of the lava dams, we collected another sample of the Toroweap Dam about 300 m downstream from the site sampled by McKee et al (1968). Our new sample of Toroweap Dam (called QU-16) comes from the north side of the river just above Lava Falls Rapid (mile 179.4) at somewhat higher elevation than the sample of McKee et al. This

Table 1. Potassium and argon data for Toroweap Dam.

	%K	^{40}K ppm	% ^{40}Ar*	^{40}Ar* ppm	^{40}Ar*/^{40}K	"Age" Ma
A-Flow	0.9475	1.130	3.1	0.780×10^{-4}	0.690×10^{-4}	1.19±0.18
QU-16FG	1.468	1.751	5.9	3.49×10^{-4}	2.00×10^{-4}	3.4±0.2
QU-16HM	0.693	0.826	5.0	1.49×10^{-4}	1.80×10^{-4}	3.1±0.3
QU-16HN	0.253	0.302	5.0	3.65×10^{-4}	12.07×10^{-4}	20.7±1.3

new sample is very fine-grained and uniform black, without phenocrysts and without xenoliths. It may be classified as a "basanite" (44.3 wt % SiO2, 5 wt% total alkalis and significant olivine). In every way it appears suitable for K-Ar dating. The one-kilogram sample was milled to −230/+270 mesh particles (63 to 53 microns) and separated into heavy and light fractions by centrifugation in methylene iodide, a heavy liquid "cut" to a specific gravity of 3.20 with ethyl alcohol. The float fraction (called QU-16FG) is dominated by plagioclase and glass. The sink fraction was separated magnetically into weakly magnetic olivine (called QU-16HN) and strongly magnetic orthopyroxene with some Fe-Ti oxides (called QU-16HM). The three new samples were submitted to Geochron Laboratories (Cambridge, Massachusetts) for conventional K-Ar analysis. The results are listed in Table 1 and plotted graphically in Figure 2.

New K-Ar analyses on the Toroweap Dam lava are listed with the sample "A-Flow" (our name for the published data of McKee et al (1968). We recalculated the abundance of ^{40}K and the resulting "model age" in "A-Flow" using the new constants (Steiger & Jager, 1977). The recalculated age is 1.19±0.18 Ma. However, the three mineral concentrates from sample QU-16 contain significantly more ^{40}Ar* than the whole rock analysis of "A-Flow". Mineral concentrates from QU-16 have 1.49 to 3.65×10^{-4} ppm ^{40}Ar*, whereas "A-Flow" has only 0.78×10^{-4} ppm ^{40}Ar*. "Model ages" for QU-16 are 3.4±0.2 Ma (feldspar-glass), 3.1±0.3 Ma (orthopyroxene+FeTi oxides), and 20.7±1.3 Ma (olivine). These ages are strongly discordant with that from the whole rock of "A-Flow" (1.19±0.18 Ma). Most interesting is the olivine in QU-16, which of all the analyses has the lowest ^{40}K (0.302 ppm), but has the highest ^{40}Ar* (3.65×10^{-4} ppm).

If "A-Flow" is actually 1.19±0.18 Ma, then the mineral concentrates from QU-16 should each lie on the line in Figure 2 describing an isochron through "A-Flow." The new data do not lie on that line, but significantly above that line. Why does the basalt of Toroweap Dam give discordant K-Ar "ages?" There must be "excess argon" in the olivine of QU-16. Are we sure there is not "excess argon" in the olivine in "A-Flow" sampled and analyzed as a whole rock by McKee et al (1968)? Because many basalts of Grand Canyon have been shown to contain "excess argon" (for example, admission by Hamblin (1989, p. 199), we can ask a more important general question. Has any Grand Canyon lava dam been demonstrated not to contain "excess argon?"

The ages of the remnants and dams were deciphered by Hamblin (1994) using both the relative dating method of juxtaposition and the "absolute ages" determined by K-Ar dating. However, the K-Ar dates in many cases do not match the relative sequence worked out by juxtaposition. This may be why most have been discarded after K-Ar analysis as containing "excess argon." The results of Hamblin's work concerning the relative sequence of development for his 13 dams, along with other important details, are listed in Table 2.

The tens of thousands of years Hamblin (1994) has interpreted for each of the 13 dams to form and then erode are seemingly impossible to reconcile within the several thousands of years of the post-Flood period. However, several geologic relationships indicate that the dams actually formed rapidly and failed catastrophically within a period of less than several hundred years. Furthermore, it is also evident that several of the 13 dams coexisted, as previously interpreted by Maxson (1949). We shall highlight these important conclusions in the following sections by addressing:

1. duration of dam formation (the amount of time required for each of the individual dams to form);

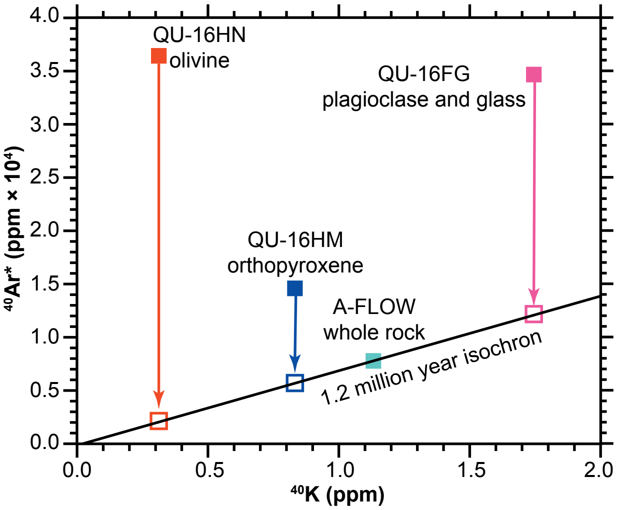


Figure 2. K-Ar plot for basalts of Toroweap Dam. If the lava dam has an "age" of 1.2 Ma, the three QU-16 mineral concentrates should plot as a line on the 1.2 Ma reference isochron with whole rock sample "A-FLOW" (arrows indicate where each mineral concentrate should plot). Instead the mineral concentrates plot significantly above the 1.2 Ma reference isochron, arguing that the lava dam contains significant "excess radiogenic argon." Can any basalt sample from the Toroweap Dam be assumed to be free of "excess radiogenic argon?"

Table 2. Characteristics of lava dams of the western Grand Canyon (after Hamblin, 1994).

Dam	Elevation (m)	Height (m)	K-Ar Age (Ma)	Number of Flows	Dam Length (km)	Lake Length (km)	Water Fill Time	Sediment Fill Time
Prospect	1200	699	1.8	3	?	518	23 yr	3018 yr
Lava Butte	1050	560	?	Several	?	?	?	?
Toroweap	927	424	1.2	5	16	283	2.6 yr	345 yr
Whitmore	750	270	0.99	40+	29	173	240 days	88 yr
Ponderosa	840	339	0.61	1	19	202	1.5 yr	163 yr
Buried Canyon	744	255	0.89	8	?	173	231 days	87 yr
Esplanade	780	288	?	6-8	13	174	287 days	92 yr
"D" Dam	689	191	0.58	40	?	123	87 days	31 yr
Lava Falls	678	180	?	1	35	123	86 days	30 yr
Black Ledge	610	111	0.55	1	138+	85	17 days	7 yr
Layered Diabase	581	89	0.62	20	22	67	8 days	3 yr
Massive Diabase	548	68	0.44	1	16	64	5 days	1.4 yr
Gray Ledge	544	61	0.78	1	21	59	2 days	0.9 yr

2. duration of the dams (the amount of time each dam was in existence after formation); and
3. the temporal relationship of dams (the amount of time that transpired between erosion of one dam and the formation of the next dam).

Duration of Dam Formation

Hamblin (1994) estimated that the total volume of all 13 lava dams was near 25 km^3. The flows are composed of olivine basalt, nearly identical to those expelled during the highly fluid, late Cenozoic eruptions of the western United States and other regions of the world. Fissure eruptions of the Columbia River Basalt resulted on occasion in the expulsion of hundreds and even thousands of cubic kilometers of lava in individual flow events (Tolan et al, 1989). During the historic Lakagigar eruption of June 8, 1783 in Iceland, a total volume of approximately 12.2 km^3 of olivine basalt lava was expelled over a period as short as eight months (Thorarinsson, 1969). This eruption resulted in a complex sequence of thin vertically stacked lava flows very similar to flows seen in the Uinkaret Volcanic Field.

The single flow lava dams of the western Grand Canyon (Table 2) could, therefore, have formed within periods as short as several hours or days. The most extraordinary example is Black Ledge Dam, which consists of a solitary flow up to 111 m thick and over 138 km long. The Black Ledge lava must have been fast flowing in order to spread over such a long distance. The appreciable thickness of the flow probably resulted from damming along the front edge of the flow as it cooled and hardened. Three other single flow dams (Lava Falls, Massive Diabase, and Gray Ledge) have been identified. Thickness are from 61 m to 180 m and lengths are between 16 km to 35 km. Obviously these dams also could have formed over a very short period of time.

Five dams (Prospect, Toroweap, Ponderosa, Buried Canyon, and Esplanade) where formed by as few as three to eight flows. Most of these flows are near 100 m in thickness. Prospect Dam consists of three major flows ranging from 180 to 250 m thick. The main remnant of Ponderosa Dam contains one major flow over 300 m thick. Esplanade Dam actually contains laminated tephra that passes laterally into at least three lava flow units. This shows that the tephra was deposited contemporaneously and at near the same rate of the adjacent flows. The multiple flow dams would have taken longer to form than the single flow dams, but could have still formed within a very short period of several months, as demonstrated by the development of stacked multiple flows in the Lakagigar eruption.

The remaining four dams (Lava Butte, Whitmore, "D," and Layered Diabase) are composed of numerous thin flows from ten to forty in number. These dams probably took the longest time to form. However, the total time required could have been still very short, probably as short as several years. Only a short amount of time (the time required for the upper surface of a flow to cool) is necessary before a subsequent flow covers the previous flow and creates a bedding plane between them.

Many of the dam remnants show evidence of erosion between flows, and also contain interstratified and capping gravel beds. Remnants of Whitmore Dam along the south wall of the inner gorge contain several interstratified gravel beds. Although many of the gravel beds lie on top of flows that exhibit little if any undulatory relief, areas of moderate scouring indicate erosion did occur. Similar patterns of interbedded gravels and moderate scouring are found in many of the other dam remnants, including Prospect Dam and Esplanade Dam. The main remnant of Buried Canyon Dam is capped with a massive stratified unit of coarse gravel 60 m thick and contains blocks up to 1 m in size. Remnants of Gray Ledge Dam are overlain with very coarse cross-bedded gravel deposits up to 45 m thick and contain clasts as large as 15 m.

Erosion and deposition are typically used as a uniformitarian indicator of the passage of a significant amount of time. Therefore, based on this interpretation, the dams would have taken at least several hundreds of years, if not thousands to build-up to account for such erosion and deposition within the dam structures. However, it is peculiar that thick gravel deposits are found at all within the dam structures, and we contend that this actually is an indicator for a rapid process of dam erosion and gravel deposition.

The addition of the volcanic flows into the course of the Colorado River would have raised the stream bed above the previously established base level. This would mean that the regions occupied by the dam would have been subjected to an interval of sustained erosion until the structure of the dam was worn down to the original base level. The dam structure could have grown only by the addition of lava, and not by gravel from stream bedload accumulation. The stream bed across the dam would have been relatively clean of gravel, except for relatively small quantities of gravel material in transport. Thick accumulations of gravel could not have occurred under normal stream flow conditions.

Clearly, the only process that could account for both the evidence of erosion, and, the accumulation of thick gravels, would be periodic catastrophic flooding. During the initial stages of the flooding episode, erosion of the dam would have been taking place by flood bedload scouring and cavitation. During the waning stages of the flood, the sediment load would have dropped out and accumulated on top of the dam structure, where it then could have been covered by subsequent lava flows. *Rogers and Pyles* [1979] have suggested that many of the gravels are the result of high energy/flow breachment or catastrophic breakout of a dam crest. The coarse cross-bedded gravel deposit with blocks of up 15 m seen on Gray Ledge flows was clearly formed by high energy water flow, probably resulting from a dam breachment event.

Duration of Dams

The best test to determine how long an ancient dam was in existence is to ascertain the degree to which the lake behind the dam was filled with sediment. The sediment that a river normally carries along its coarse will be caught and deposited within the lake created behind the dammed river. The length of time required for siltation can be determined if both the volume of the lake and the sediment transport load of the river are known. The larger the lake, the longer it will take for the sediment to fill completely that lake. This test can only be used to place a minimum number of years for dam longevity, because once the dam is completely silted-in, the sediment that the river is carrying will then be transported over the dam. The siltation time required for each of the lakes formed behind the 13 dams has been calculated by Hamblin (1994) and is based on the sediment load carried by the modern Colorado River into Lake Mead (Table 1).

Recent surficial deposits related to fluvial-type processes are relatively sparse within the Grand Canyon. *The Geologic Map of the Eastern Part of the Grand Canyon* (1996) identifies two main types of surficial deposits; river gravels and alluvium. The river gravels are limited to very recent deposition along the banks of the Colorado River. The alluvium occurs in isolated outcrops primarily within the broad valley floors of Nankoweap Creek, Kwagunt Valley, Sixtymile Creek, and Chuar Valley, and is found on terraces at elevations up to 1500 m (645 m above river level). Remnants of a thin gravel and boulder deltas are found on terraces at 930 m elevation on both sides of the Colorado River downstream of Comanche Creek (miles 67 to 73) (Machette & Rosholt, 1989). This was probably a temporary delta into the lake behind the Toroweap Dam. Other relatively large bodies of surficial-type alluvial deposits are found within Havasu Canyon, at Lee's Ferry, and at several locations in the Lake Powell region. Hamblin (1994) believed that this alluvium was derived from deposition within the larger Pleistocene lava-dam lakes. An extraordinary deficiency of lake sediments exists in the canyon of the Little Colorado River. Apart from these few areas, other significant deposits of supposed lake deposits are peculiarly absent.

The alluvium (lake sediments) in the eastern Grand Canyon consists of several small to large gravel deposits located mostly on the west (left) side of the Colorado River. The larger deposits consist of four outcrops within the upper basins of Nankoweap Creek, Kwagunt Valley, Sixtymile Creek, and Chuar Valley (Figure 1). These outcrops range in size from 2 km^2 to 5 km^2 and are up to several tens of meters thick, extending up-basin to elevations ranging from 1285 m to 1500 m. These elevations indicate that the gravel deposits are most likely related to Prospect Lake. Local uplift across one or several of the normal faults of the Grand Canyon, sometime after failure of Prospect Dam, has probably raised these deposits above the 1200 m level of Prospect Lake.

Typical gravels contain clasts derived locally from each particular depositional basin. Therefore, most deposits are the result of gravel deltas that built outward into the main lake body, and are not derived from material transported down the Colorado River. Elston (1989) believed that they may record aggradation by flash flooding. These gravels probably once extended all the way down to the Colorado River, where similar small isolated gravel deposits occur. One small outcrop, located where Nankoweap Creek enters the Colorado River, is overlain by silty alluvium material and underlain by gravel which contains exotic clasts derived well upstream of the Colorado River. Numerous other similar small isolated deposits occur downstream all the way to Big Bend (mile 75). West of Big Bend these types of alluvial gravels are not found. The lower gravel units containing exotic clasts may represent the initial lake deposits transported down the Colorado River into Prospect Lake.

The up-basin gravels are overlain along their edges by several small to very large units of talus and landslide debris. These debris deposits are not known to underlie the gravels in any significant quantities. The onlapping relationship of the talus and landslide debris indicates that mass wasting was a post-lake event and may have resulted from slope instability caused by rapid lake drawdown.

The next large lake sediment deposit occurs within Havasu Canyon. The main unit consists of a long thin deposit extending 8km up Havasu Canyon from Beaver Falls to the Havasupai Indian village. Smaller isolated outcrops occur both downstream and upstream of the main deposit. The sediments are composed primarily of silt and fine sand with interbeds of travertine. Travertine has also armored the surfaces of the deposits in many areas, particularly along the course of Havasu Creek. The main deposit reaches a high elevation at 960m, with small isolated outcrops preserved on the upper canyon walls at as high as 1032m. Hamblin (1994) believed that these deposits may include material from several lava-dam lakes, the highest from Prospect or Lava Butte Lake. The main deposit at 960m may be from Toroweap Lake. Hamblin stated that the sediment contains thin horizontal laminae similar to lake deposits in Lake Mead and Lake Bonneville. However, the sediments also contain medium- to micro-scale cross-bedding, showing that they were also influenced by current flow. This suggests that deposition may have occurred down Havasu Canyon as an aggrading delta, and not up canyon from material derived from down-river transport of the Colorado River. Therefore, the deposits at Havasu Canyon are an isolated, localized unit and not the result of the complete infilling of a large lava-dam lake.

A sequence of gravel, sand and silt occurs just west of Lee's Ferry, near the confluence of the Paria and Colorado Rivers. This deposit occurs at and elevation of 1080m and consists of an upper gravel unit with clasts over 6 inches in size overlying laminated sand and silt. Hamblin (1994) argues that the sand and silt are indicative of lake deposits and could not be the result of deposition from the high energy flow of the Colorado River. However, his explanation does not address the coarse gravel cap which would have required swiftly moving currents. We contend that the proximity of this deposit near the confluence of the Paria is no coincidence and that they are genetically linked. Swiftly moving currents from flash floods could have readily transported the entire unit (gravel, silt, and sand) in one or several phases of deposition. Here again, this material is the result of an aggrading delta fed by material down a tributary drainage (Paria River) into the lava-dam lake.

The water level of the lava-dam lakes ranged in elevation from a low of 544m (61m above the river) for Gray Ledge Lake to a high of 1200m (699m above the river) for Prospect Lake. The majority of these lakes would have been confined to the thin long channel of the steep sided inner canyon gorge. The exceptions would have been Prospect Lake, Lava Butte Lake, and Toroweap Lake. These three lakes would have been high enough to extend a considerable distance up many of the side canyons, including Havasu and Kanab Canyons. Prospect Lake was by far the largest and within the Grand Canyon it would have covered more than three times the surface area of Toroweap Lake and extended well up into all of the side canyons including those of the eastern Grand Canyon, all the way through the Little Colorado River gorge, and over three-quarters of the distance up Havasu and Kanab Canyons. Lake Prospect would have also extended past present day Lake Powell, approximately 90m higher then the present high water elevation of the lake. Below Grand Canyon Village, Prospect Lake would have completely inundated the Tonto Platform by over 90m up to the base of the Redwall Limestone. The sediment fill time for Prospect Lake (3,000 years) is well below the 10,000-year duration of Prospect Dam as determined by Hamblin (1994), and would therefore have had more than enough time to fill completely with sediment under uniformitarian conditions.

Prospect Lake sediments should have been preserved in literally thousand of locations, ranging from very small to large remnants, if in fact Prospect Lake was completely sediment filled. Likely areas of preservation would be within the myriad of protected pockets of small and large side canyons, and on top of elevated flat-lying surfaces such as the Tonto Platform where erosion is at a minimum within the canyon. Appreciable sediment preservation within protected areas would have also occurred from accumulation in Lava Butte and Toroweap Lakes. Because the remainder of the lakes were confined to the steep sided inner gorge, sediment preservation would have been less likely.

The most interesting characteristic of the lake deposits is that, nearly without exception, they all occur in low-lying drainages which are areas of the most active erosion (aside from the main Colorado River channel). Lake deposits are not found in areas protected from erosion such as within the thousands of tributary canyons or, most puzzling, on top of the Tonto Platform such as below Grand Canyon Village where sediment depths of over 90 m should have occurred. In fact, the pattern of occurrence of the lake sediments is exactly opposite of what would be expected. This pattern indicates that the lake deposits are not remnants left over from erosion of a sediment-filled lake, but are relatively intact uneroded depositional units formed by aggrading deltas building outward from the side canyon tributaries into the main lake body. This shows that the lava-dam lakes were never completely filled with sediments, and, therefore, were very short-lived features. We estimate that this relatively small quantity of lake sediment could have been deposited in a period of less than 100 years. Multiplying this value by thirteen for the number of total possible lava dams, we obtain a total of 1,300 years for the duration of lava dams blocking the flow of the Colorado River.

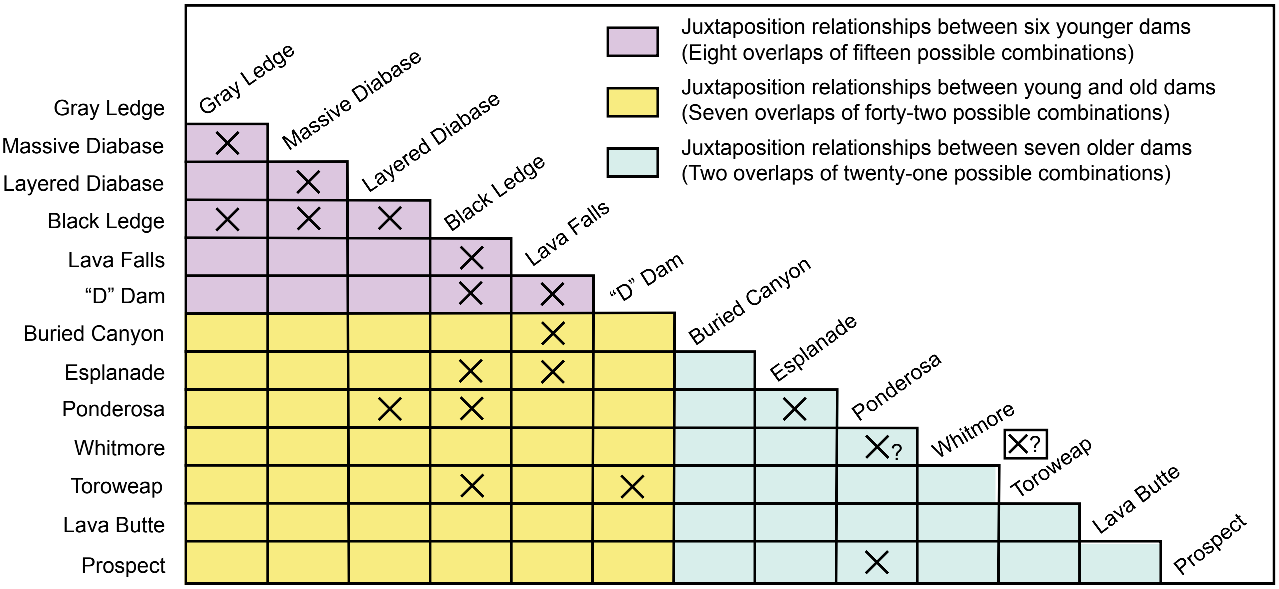
Temporal Relationship of Dams

Early investigators (McKee & Schenk, 1942; Maxson, 1949) concluded that only a small number (one to three) of dams blocked the Colorado River. Maxson determined that only three lava dams existed, based on the presence of finely laminated lake-deposited tephra interbedded with volcanic flows which strongly indicated dam coexistence (found between miles 180.5 and 194.5). Hamblin (1994) discounted Maxson's contemporaneous lava dam theory and proposed that the tephra developed within temporary lakes formed by landslide dams. Hamblin offered no substantive evidence for the landslide dams.

McKee & Schenk's (1942) and Maxson's (1949) premise that only a small number of lava dams once blocked the inner gorge was founded on the fact that nearly all lava remnants are composed of a similar olivine basalt. Although they undoubtedly noted the depositional and textural differences between individual outcrops, the compositional similarity obviously was paramount in their interpretation.

Hamblin's work does suggest strongly that there have been numerous lava dams within the inner gorge. However, his belief that all thirteen dams were separate and non-contemporaneous features is not necessarily supported by the data. First of all, the finely laminated tephra observed by Maxson (1949) is clear evidence of dam coexistence. Secondly, many of the remnants are compositionally and texturally similar, which underscores the potential for error in Hamblin's correlations. Finally, many of the K-Ar dates obtained from dam remnants are completely ambiguous and yield dates entirely out of sequence from that determined by the reliable relative dating method of juxtaposition. Referring to Table 1, the nine youngest dams (Ponderosa through Gray Ledge Dams) yield K-Ar dates that are out of sequence. Our own date determined from a remnant of Toroweap Dam is older than the oldest date determined for Prospect Dam. We believe that it is not only possible, but highly probable (based on tephra deposits and K-Ar dates), that several lava dams coexisted as either separate dam structures, or even overlapping dam structures.

Figure 3 is based on Hamblin's (1994) geologic map, and shows the overlapping relationships between different dam remnants that were observed in contact in at least one locality. For example, the first mark in the upper left of the table indicates that



🟪 Juxtaposition relationships between six younger dams (Eight overlaps of fifteen possible combinations)
🟨 Juxtaposition relationships between young and old dams (Seven overlaps of forty-two possible combinations)
🟦 Juxtaposition relationships between seven older dams (Two overlaps of twenty-one possible combinations)

	Gray Ledge	Massive Diabase	Layered Diabase	Black Ledge	Lava Falls	"D" Dam	Buried Canyon	Esplanade	Ponderosa	Whitmore	Toroweap	Lava Butte	Prospect
Gray Ledge													
Massive Diabase	X												
Layered Diabase		X											
Black Ledge	X	X	X										
Lava Falls				X									
"D" Dam				X	X								
Buried Canyon					X								
Esplanade				X	X								
Ponderosa			X	X				X					
Whitmore									X?		X?		
Toroweap				X		X							
Lava Butte													
Prospect									X				

Figure 3. Relative age/juxtaposition relationships of lava dams.

one or more remnant(s) of Gray Ledge Dam overlies a younger remnant(s) of Massive Diabase Dam. The table shows that there are a total possible 78 different combinations of dam remnant overlap. However, as the table also shows, only nineteen overlap combinations were actually found by Hamblin. Hamblin questioned two of these overlap relationships. These are indicated on the table by the queries. Therefore, only seventeen dam remnant overlap combinations are known with certainty. Hamblin worked out his interpretation of the relative sequence of lava dams from these seventeen dam remnant overlap combinations.

The upper section of the table shows the contact relationship between the six youngest dams (indicated on the table as: juxtaposition relationship between six younger dams—Gray Ledge through "D" Dam). Out of a total of 15 possible overlap combinations, there are eight (53%) found for the younger dam remnants. This is a high percentage and indicates that the relative sequence for the younger dams has a high degree of reliability. The lower section of the table shows the overlap relationship for the older dams (juxtaposition relationships between seven older dams—Buried Canyon through Prospect). Only two overlap contacts out of a total possible twenty-one combinations (10%) are found in the inner gorge. This is a very low percentage, and the only relative sequence that can be determined from these two contacts is that Esplanade Dam is older than Ponderosa Dam, which is older than Prospect Dam. Therefore, the relative ages of Buried Canyon, Whitmore, Toroweap, and Lava Butte Dams cannot be worked out amongst these older dams based on juxtaposition. Therefore, it is possible that these four dams could have been part of a one large single dam complex, or any other combination of one or more of these four dam units.

Other Evidences for Catastrophic Dam Failure

Slope Failures Upstream of Lava Dams

The majority of the slopes of the Grand Canyon are devoid of a notable build-up of talus from mass wastage or landsliding (slope failures). This general absence of talus deposits is an indicator of the long term stability of the Grand Canyon slopes. Several large deposits of talus do occur and are primarily isolated at two localities. The first location is at Surprise Valley between miles 134–139, and the second is the eastern Grand Canyon in the same areas of the previously described lake deposits. Only a few mappable talus deposits are found in the region between these two localities.

The Surprise Valley landslide, which is the largest slope failure in the Grand Canyon, stretches along the Colorado River for over 8 km and is over 2 km wide. It is estimated that the slide has a volume of over 5.5 billion cubic yards.

The slope failures in the eastern Grand Canyon, although much smaller then the Surprise Valley landslide, are also enormous in dimension. The largest occurs along the south wall of Chuar Valley, and is 5 km long and up to 1 km wide. Other large slope failures occur in Unkar Creek, Kwagunt Valley, and Nankoweap Creek.

Rogers & Pyles (1979) assert that water saturation from the Pleistocene lava-dam lakes was the instrumental factor in the failure of these large slope areas. Although rapid drawdown of the lake waters was not necessary for slope failure to occur, it would have facilitated failure if drawdown occurred prior to complete slope saturation. The failure would result from what Rogers & Pyles describe as the development of large hydrostatic forces that act on the free face of a slope as the water tries to reestablish equilibrium conditions after a sudden lowering of the water level by dam failure.

The slope failure talus is almost without exception always overlying the lacustrine deposits where they occur together. In relation to this, Elston (1989) makes the following statement:

> The relations thus seem to indicate that gravel had accumulated along the course of the river prior to the episode of catastrophic landsliding, and that it was a time that the Colorado River was not actively removing detritus from the area. The pre-landsliding episode of aggradation thus appears to parallel the episode of aggradation seen in the eastern Grand Canyon, and landsliding can be inferred to have occurred during the episode of aggradation.

This relationship, therefore, shows that landsliding occurred only after deposition of the isolated lake deposits and that it is related to rapid lake drawdown.

Inner Gorge Widening from Flooding

The inner gorge of canyon widens noticeably at mile 181 and again at mile 187.5. The widening at mile 181 is directly downstream of the larger and older dams (Prospect, Toroweap, Ponderosa, Lava Butte). The widening at mile 187.5 is also downstream of these four dams, as well as the Buried Canyon, Whitmore, and Esplanade Dams. The widening can be easily explained by catastrophic dam failure and subsequent flooding.

Near mile 183, a large side canyon on the south side of the inner gorge opens along an upstream alignment at the first bend in the river downstream of the older dams. This upstream alignment is anomalous to the normal alignment of side canyons, which is typically perpendicular to the inner gorge. The upstream side canyon alignment is probably the result of flood waters impinging upon the outer inner gorge wall of the river bend, causing erosion and formation of the side canyon.

Mechanism of Catastrophic Dam Failure

Natural dams are typically prone to catastrophic failure by overtopping. Costa (1988) gives two examples of historical breakouts (1982 in Mexico and 1912 in Alaska) from failure of volcanic dams. In both of these cases, the dams failed within a year of formation. The flood from failure of the Alaskan volcanic dam caused scouring of 1 to 2 m and transported coarse gravel with clasts up to 50 cm diameter over a 20 km distance.

Catastrophic overtopping or breachment of the lava dams was probably caused by movement on the Toroweap and Hurricane Faults. Movement along these faults could have caused both mechanical fracturing of the dam structures leading to failure, and lake seiches resulting in dam overtopping. The main remnant of Toroweap Dam shows a decreasing amount of up-section fault offset across the Toroweap Fault, showing that the fault was active during the formation of Toroweap Dam. In fact, both the Toroweap and Hurricane Faults are probably still active today (Hamblin, 1994, p. 4).

Conclusions

Several important geologic features, which have been previously overlooked, give strong indication that the Pleistocene lava dams of the western Grand Canyon formed rapidly and were destroyed catastrophically within several tens to hundreds of years after formation. We believe that the entire span of time from the formation of the first dam to the destruction of the last dam could have transpired over a time frame of less than 2000 years. We consider our time estimate to be generous, leaving open the probability that the total time frame could have been considerably less.

It is undisputed, by even uniformitarian geologists, that the several single flow lava dams formed in a length of time as little as several hours to days. The larger multiple flow dams (consisting of three to over forty flows) are commonly stacked one atop the other with no signs of significant erosion. Although it is clear that in many instances interflow erosion has occurred, we have shown that the presence of interflow gravels actually indicates catastrophic flooding, rapid erosion, and deposition, and, therefore, does not require us to accommodate hundreds to thousands of years for these erosional features. Catastrophic flooding is clearly represented by the coarse cross-bedded gravel on top of Gray Ledge remnants.

The most convincing evidence that the dams where short-lived structures is the presence of relatively small isolated depositionally-intact aggraded delta deposits within tributary drainages of the eastern and central Grand Canyon. The fact that these relatively uneroded deposits occur within the most active erosive areas, and the absence of lake deposits on the least erosive areas (Tonto Platform and protected side canyons), reveals that the larger lava-dam lakes were not in existence long enough to allow for complete sediment infilling. The small quantity of delta deposits that are present could have accumulated easily in less than one hundred years.

Hamblin (1994) believes that thirteen separate lava dams once blocked the inner gorge. The relative age of the seven older dams were determined by only two overlap relationships. This allows for the possibility that several of these dams may have coexisted as a complex mega-dam structure. The presence of tephra deposits within several dam remnants is hard evidence that several of the dams coexisted.

K-Ar dates for many of the lava dams are out of sequence from that determined by juxtaposition. These essentially “impossible” dates show the difficulty in assessing the sequence of the dam remnants, and reveals the possibility that many of the correlations proposed by Hamblin may be in error. Furthermore, a sample of Toroweap Dam retrieved and dated in this study yielded dates of 3.1, 3.4, and 20.7 Ma, which are significantly older then the date (1.8 Ma) of the oldest dam (Prospect) determined in Hamblin’s study. Either Hamblin’s dates should be much older or the samples of Toroweap dam contain excess argon. In any case, the K-Ar dates obtained in this and Hamblin studies reveal the inherent problems of this dating method, casting doubt on the standard interpretation of 1.8 Ma for the Pleistocene Epoch.

The presence of lava-dam remnants near the present level of the Colorado River reveals that the canyon has undergone only negligible deepening since the time the dams originally formed. Furthermore, the normal flow of the Colorado River has not appreciably widened the inner gorge. Under a uniformitarian interpretation, this means that the Grand Canyon has not undergone appreciable erosion at least for the 1.8 million year period of the Pleistocene. A better interpretation (Austin, 1994) would be that the Grand Canyon is a relic flood-formed feature, and, likewise, that the lava dams were short-lived, catastrophically formed and eroded features.

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