Cole Bishop
Volcanic lava flows of the Grand Canyon and their influence on river geomorphology
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Abstract

There is unambiguous evidence that the Colorado river was dammed repeatedly by Quaternary basaltic lava flows from the Uinkaret Volcanic Field in the western Grand Canyon. However, these lava dams are poorly preserved in the geologic record because they were deposited in highly erosional environments. What remains today is a patchwork of isolated remnants which can be difficult to correlate. A lack of modern analogs means the morphology, longevity, processes of failure, and effects on the river geomorphology of Grand Canyon lava dams remain somewhat poorly understood.

Reconstruction methods primarily involve genetic fingerprinting techniques including Ar-Ar geochronology, cosmogenic exposure dating, lidar, paleomagnetism, whole-rock geochemistry, and stratigraphic relationships. These reconstructions seek to characterize the timing, longevity, extent, and structure of dams and their methods of failure. While earlier characterizations focused on singular construction and failure mechanisms, more recent modeling work has concluded that a number of different processes were likely involved.

Background

There are few modern basalt-dammed rivers to serve as analogs to the ancient Grand Canyon lava dams. Examples include Lake Myvatan and Laki Fissure in Iceland and Aiyansh Dam in British Columbia, but all are much smaller and none are in a canyon-like setting (Roberts and Mccuaig, 2001; Thordarson and Self, 1993). Evidence does exist for ancient lava blockages of major rivers including the Yukon (Huscroft et al., 2004) and Snake (Malde, 1982) rivers that can serve as corollaries to the dams that formed in the Grand Canyon and provide additional geomorphic constraints on lava dam longevity and removal mechanisms.

Volcanism influencing the Grand Canyon is centered in the Uinkaret volcanic field located mostly north of river mile 180 in the vicinity of Lava Falls (**Figure 1**). The volcanic field has erupted more than a dozen times in the Quaternary period producing lava flows and cinder cones (e.g. Vulcan's Throne; Crow et al., 2008). Some of these lava flows cascaded down the side of the canyon walls, while some may have erupted directly in the canyon itself (Hamblin, 1994). Some of the plumbing of Uinkaret volcanoes including dikes, sills, and plugs are cut and exposed in the deeper parts of the canyon. Pyroclastic and hydroclastic deposits provide unambiguous evidence that active lava flows interacted with the Colorado river. These interactions are believed to have caused significant impoundments of river flow, but no verified lake deposits in the canyon have been identified thus far.

Because the dams were deposited in a highly erosive environment, little remains of them today. Basaltic lava flow remnants exist a few kilometers upstream of the Uinkaret volcanic field and downstream up to 135 kilometers underneath what is now Lake Mead. Multiple hypotheses have been suggested as to the prevalent dam failure mechanisms, ranging from slow overtopping to cataclysmic failure. There is currently no broad consensus, and a variety of failure mechanisms likely occurred. The presence of a 45-meter-tall cross-bed near river mile 188 entraining ~5m boulders is evidence of at least one large catastrophic outburst flood.

Dam Reconstruction Methods

Reconstruction efforts focus on constraining the source, timing, extent, and structure of the Grand Canyon's ancient lava dams. The process of dam reconstruction involves a number of geochemical and geophysical methods and extensive fieldwork. The primary aim is to correlate dispersed dam remnants based on geological and geochemical fingerprints. Dam remnants have been mapped with aerial photography and LiDAR to estimate the original thickness of lava flows based on remaining exposures. This can be challenging as the specific depth and geomorphology of the ancient canyon can be difficult to estimate.

^{40}Ar/^{39}Ar geochronology is the primary way that absolute dates for individual lava flows in the western Grand Canyon have been determined (Crow et al., 2015). This method uses the decay of naturally occurring ^{40}K which decays into ^{40}Ar with a half-life of 1.25 billion years. Upon cooling of a lava flow below a "closure temperature" of 300-500 °C ^{40}Ar is retained within mineral grains. By irradiating a sample in a nuclear reactor, ^{39}K is converted to ^{39}Ar through the ^{39}K(n,p)^{39}Ar neutron capture nuclear reaction (Dalrymple et al., 1981). The ^{40}Ar/^{39}Ar ratio of the sample is then measured on a noble gas mass spectrometer, which can be related to the original ^{40}K/^{40}Ar ratio. With the ratio of parent radioisotope to daughter product, the closure age can be calculated using the ^{40}K decay constant.

Cosmogenic exposure dating is a secondary method that has been used to obtain absolute dates of lava flows in the Grand Canyon. High-energy particles \ are constantly raining down on Earth's surface from space and forming exotic stable and radioactive nuclides (e.g. ^{26}Al, ^{10}Be) in rocks (Darvill, 2013). Work in the Grand Canyon has used primarily ^{3}He as a cosmogenic isotope (Fenton et al., 2002) and has resulted in age determinations concordant with ^{40}Ar/^{39}Ar geochronology results.

Paleomagnetism is a term for the study of rocks based on the record of the Earth's magnetic field. The strength and direction of the magnetic field has changed through time, and magnetic mineral grains (e.g. magnetite) tend to align with the field as they crystalize. Therefore the strength and orientation of a rock can be used as a geological fingerprint to show a genetic connection between two lava flow remnants in different parts of the Grand Canyon (Crow et al., 2015).

Whole-rock geochemistry through trace element analysis is another tool that has been utilized to determine genetic connections between flow remnants (Crow et al., 2015). This has been accomplished through chemical dissolution followed by inductively coupled plasma mass spectrometry (ICP-MS). The lava rock sample is dissolved in acid and ionized by an Ar gas plasma torch at 6000°C. The ions are accelerated by an electric field, separated by mass, and collected. This procedure establishes the relative concentrations of rare earth elements in the samples, which are fractionated during magmatic processes such as partial melting and crystallization. Thus, two basalt samples that share the same rare earth element signature profile are "genetically related" and are likely to be from the same flow and dam.

The final reconstruction method is traditional structural geologic fieldwork looking for inset and stratigraphic relationships. Combinations of these geological tools have been used to successfully determine the absolute ages and geographical extents of lava flows that caused significant disruption to the flow of the Colorado River in the western Grand Canyon. The following sections will outline the current best understanding of the timing, longevity, extent, structure, and failure mechanisms of Grand Canyon lava dams.

Timing and Longevity

$^{40}Ar/^{39}Ar$ ages for lava flows in the Grand Canyon rage from 829± 9 kyr to 82 ± 13 kyr (Crow et al., 2015; Dalrymple and Hamblin, 1998; **Figure 2**). Crow et al. (2015) used these thermochronometric dates to identify 5 distinct episodes of volcanism and 17 distinct lava flows. The authors hypothesize that each of these flows produced major disruption to the Colorado River, including the formation of rapids and lakes. The flow remnants that remain today show clear evidence of lava-water interaction including pillows, peperite, and hyaloclastite textures. In the upstream direction, massive basalt flows transition to deltaic foresets of hyaloclastite dipping 10° upstream (Crow et al., 2015). Similar deposits near other ancient lava dam sites have been interpreted as evidence of lava flowing into standing water (e.g. the Fraser river; Andrews et al., 2012) so a transient lake may have formed quickly during the eruption. However, the lack of verified lake deposits in the Grand Canyon supports models where dams failed quickly implying significant lakes were short-lived. The upstream basalt formed from quenching would have been pervasively fractured and therefore more easily eroded and removed when a dam failed.

Cooling textures in the upstream direction suggest solidification times of a few months to 3 years (Degraff et al., 1989). This is based on the ratio between the sizes of the well-ordered ~2 meter thick columnar joined colonnade at the base of the flows and the chaotic, disordered overlying entablature (~26m; **Figure 3**). The upper entablature is thought to have formed as the flow crystalized downwards due to convective cooling from Colorado River water. Similar textures have been observed due to interaction with rainwater, but the Grand Canyon is not believed to have experienced sufficient rainfall even during the last glacial maximum to form the observed textures (Marchetti et al., 2011). The lower colonnade formed from slow conductive cooling of the base of the lava flow over months to years.

The lack of widespread evidence for lava-water interaction (e.g. peperite, hyaloclastite) downstream of the eruptive vents has been interpreted as evidence for a nearly complete temporary blockage of the Colorado river during eruption events (Hamblin, 1994). The lava is thought to have flowed down a mostly dry river bed for up to 135km in the case of the longest flow (Crow et al., 2015). Newly emplaced lava dams were likely overtopped quickly, however. Using flow rates from before construction of the Glen Canyon Dam, lava dams at the modern day location of Lava Falls of 100 meters, 200 meters, and 400 meters height would fill with river water in 15 days, 13 weeks, and 1.8 years respectively (Pederson et al., 2006). Using pre-Glen Canyon Dam sedimentation rates, the same lava dams would fill completely with sediment in 6, 33, and 248 years respectively using Lake Powell and Lake Mead as analogs (Ferrari, 2008). These values should be considered maxima as higher sediment loads would be expected during glacial periods. Thus, the dams were almost certainly overtopped while the lava was still cooling but may have been partially or entirely removed before the impounded lakes filled with sediment. Although most of the dam remnants are overtopped by monomict basaltic gravels, two remnants are overtopped by far-traveled Colorado river clasts (Crow et al., 2008) implying that the river re-established normal flow before the dam was removed.

Estimates of dam longevity have spanned from less than 10 years to 20 kyr. Although previous work advocated for cataclysmic failure, Crow et al. (2015) supported a multi-staged failure model detailed below. However, the existence of several large cross-beds including a massive 45-meter-tall example near river mile 188 (**Figure 4**) is unambiguous evidence that major outburst floods occurred. It is likely that evidence of additional floods has been lost to erosion.

Extent and Structure

Lava flows in the Grand Canyon travelled up to 1-2 km upstream and up to 135km downstream on the canyon floor. The farthest-reaching downstream basalts erupted from Uinkaret Volcanic Field vents are now covered by Lake Mead to the west (**Figure 1**). The majority of the flows traveled approximately 15-20km down the Colorado River.

The height of the ancient lava dams and their structure has been debated extensively in the literature. Many dam remnants are topped by monomictic basalt gravels, thought to have been formed from lava-water interactions farther upstream. Some of these gravels are additionally topped by mainstem Colorado river gravels implying the river formed a lake and re-established itself over the dam. The basaltic gravels are geochemically and chronologically similar to the basaltic lava flow remnants they overlie (Crow et al., 2008).

Around river mile 189, rounded Colorado River-derived gravels appear 200-260 meters above mean river level, requiring that the river was impounded and raised to that level (Pederson et al., 2006). Crow et al. (2015) note that a 260-meter-high dam would back up water all the way to river mile 80, past the modern-day Phantom Ranch, and impound a 5 km^3 reservoir. No deposit from this or any other lake remains, although such evidence could be eroded or not yet found. Deposits previously identified as lake sediments by Hamblin (1994) are now thought to be regular river deposits and do not have geochronological dates concordant with known eruptions or dams.

There is evidence that far higher dams may have existed, if only ephemerally. Two lava dams at 330 m and 395 m above mean river level lack overlying river gravels but would still likely have had a major influence on river flow even if they were leaky. The thickest flow is 640 meters thick located at river mile 180 and dated at 535 kyr (Hamblin, 1994). This flow and most if not all of the 17 total intracanyon flows almost certainly created blockages in the Colorado River when they erupted.

Modeling Emplacement and Failure Mechanisms

Proposed models for dam removal span from catastrophic failure within a few years of formation (prior to overtopping; Fenton et al., 2006, 2004, 2002) to slow removal over tens of thousands of years (Hamblin, 1994). Crow et al. (2015) proposed a mixed model between these two endmembers with progressive multi-staged failures releasing outburst floods of varying severity (**Figure 5**). In their model, lava flowed into the Canyon and quickly dammed the Colorado river almost entirely. The lava flowed down a mostly dry riverbed, forming the observed dichotomy between water-influenced textures upstream and leaving a lack of such features downstream. Features left by lava-water interactions (**Figure 3**) imply that water flowed over the downstream flows for months to years while they solidified, which is in agreement with river flow estimates indicating dams would have been overtopped on a timescale of days to months. The upstream portions were fractured by river water infiltration creating piping and leakage due to brecciation of the basalt. These weakened sections of the flows failed relatively quickly depositing the monomict basaltic gravels and cinders on top of the downstream parts of the flow that are observed today. These failures were sometimes catastrophic (**Figure 4**) and sometimes slow and progressive.

The downstream far-traveled parts of the dams were stronger due to the lack of water-lava interactions and were removed more slowly by the Colorado river through plucking of basalt columns, sediment abrasion, and lateral disaggregation (stage 5 of **Figure 5**). Because of a lack of verifiable lake deposits, Crow et al. (2015) hypothesize that most lake-forming dams were removed before the lakes could fill with sediment, which would happen over tens to hundreds of years (Ferrari, 2008). However, in two cases where far-traveled river clasts overlie monomict basaltic gravels, the dam and associated lake may have filled with sediment, implying persistence for hundreds to a few thousand years. Field observations imply that the bases of subsequent flows are not at the same height, implying that previous dams were removed before subsequent dams were emplaced and bolstering the hypothesis that dams were short-lived.

Conclusions and Broader Implications

At least 17 lava flows (and likely more) from the Uinkaret volcanic field entered the western Grand Canyon mostly from the North Rim between 800 and 80 thousand years ago. Some volcanoes may have erupted inside the canyon itself. Most if not all of these flows interacted with the Colorado River and caused significant geomorphological effects. Cooling structures and evidence of lava-water interaction imply that the Colorado River re-established itself on top of these lava dams as they were still cooling over a period of months to years. Some upstream parts of some dams failed catastrophically resulting in outburst floods. These floods created deposits overlying downstream parts of the flows that can be observed in the Grand Canyon today. The downstream portions of flows traveled over a dry riverbed and therefore maintained a greater structural stability than upstream portions. Downstream flows survived for thousands of years, with some remaining today.

Broader implications of the study and reconstruction of Grand Canyon lava dams include constraining the hazards (e.g. water contamination and flooding) to communities from future interactions between lava and river waters near populated areas. New analytical and geochemical methods for establishing genetic relations between lava flow remnants will add to our understanding, as well increases in the accuracy and precision of methods currently in use today.

Figures

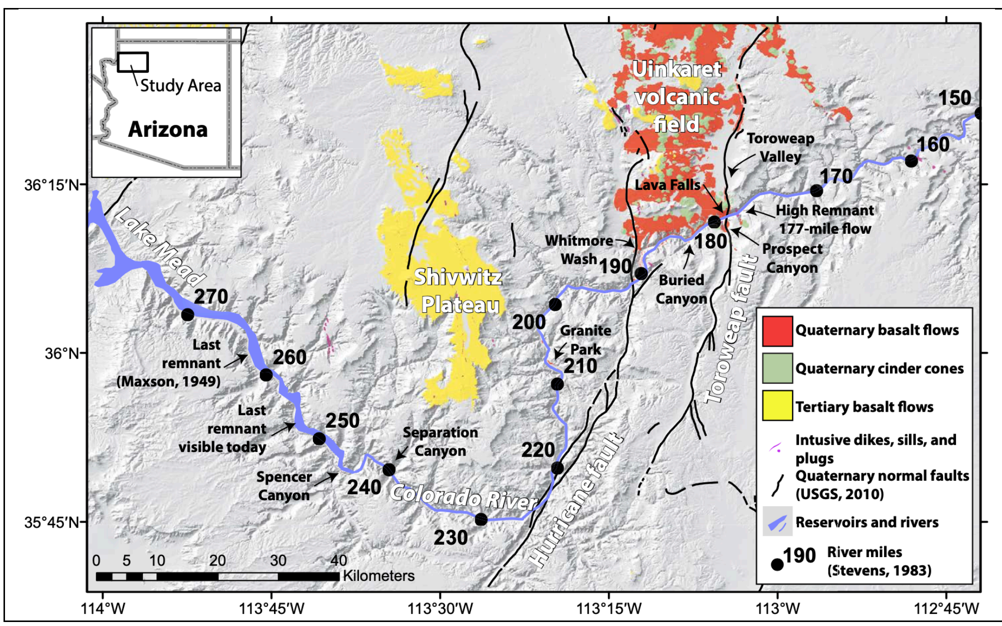

Figure 1: A simplified geologic map showing the extent of Quaternary volcanism in the western Grand Canyon. Adapted from Crow et al. (2015).

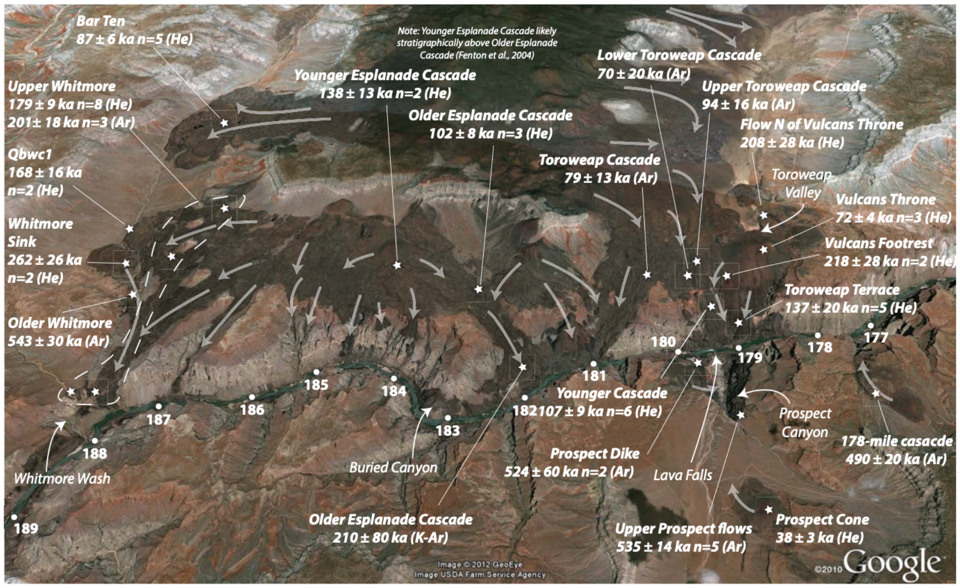

Figure 2: Satellite imagery of the Uinkaret Volcanic Field showing major flow names, morphology, direction, and Ar-Ar closure ages. Adapted from Crow et al., (2015).

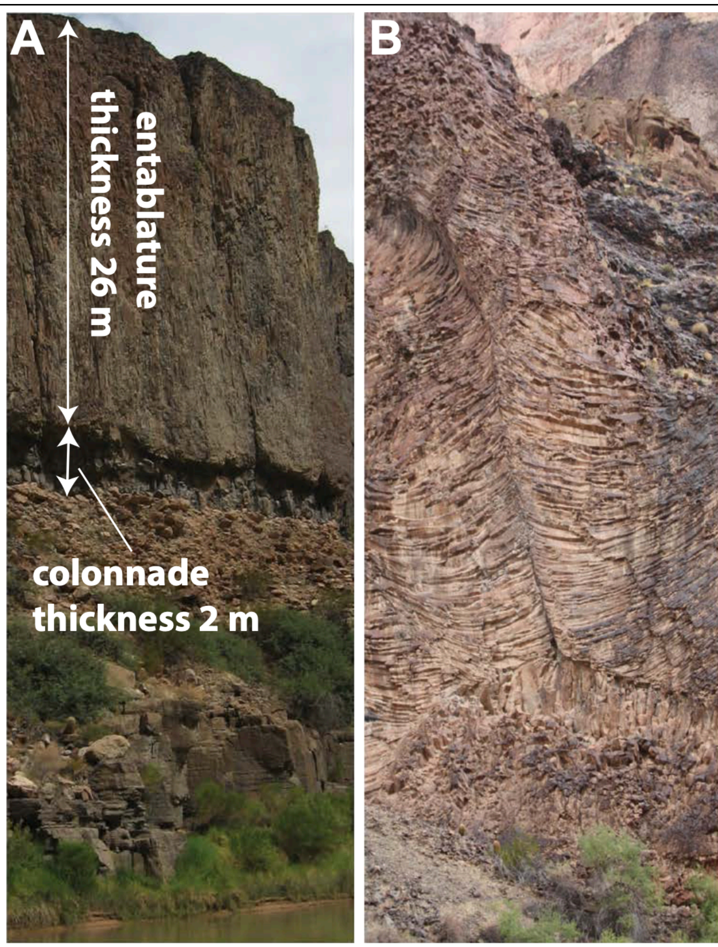

Figure 3: (A) A comparison of the colonnade and entablature thickness from a lava flow remnant at river mile 184. The ordered basal colonnade cooled from the bottom up due to conduction, while the disordered entablature cooled from the top down due to convection as Colorado River water flowed over it.
(B) Another example flow remnant showing similar morphology at river mile 194. The relationship between the thicknesses of these two layers can be used to determine the timescale over which the lava flow cooled and solidified. Adapted from Crow et al. (2015).

Figure 4: A 45 meter tall cross bed resulting from a catastrophic outburst-flood. It primarily consists of poorly-sorted sub-angular basaltic clasts and includes large several-meter scale limestone boulders. Adapted from Crow et al. (2015).

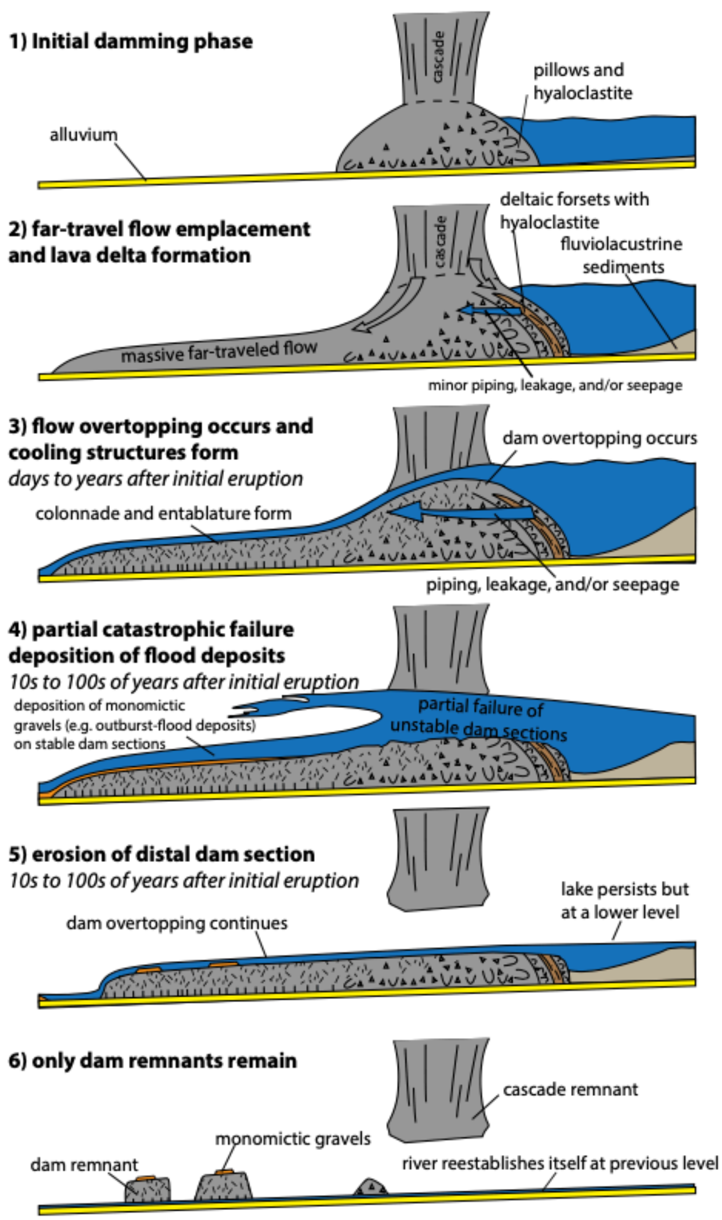

Figure 5: A graphical representation of the conceptual model of Crow et al. (2015) showing the progressive steps of lava dam formation and removal in the western Grand Canyon. In two cases, far-traveled river sediments overtop the monomictic gravels implying that those lava dams were stable for longer time periods. Adapted from Crow et al. (2015).

References

Andrews, G.D.M., Russell, J.K., Brown, S.R., Enkin, R.J., 2012. Pleistocene reversal of the Fraser River, British Columbia. Geology 40, 111–114. https://doi.org/10.1130/G32488.1

Crow, R., Karlstrom, K.E., McIntosh, W., Peters, L., Dunbar, N., 2008. History of Quaternary volcanism and lava dams in western Grand Canyon based on lidar analysis, 40Ar/39Ar dating, and field studies: Implications for flow stratigraphy, timing of volcanic events, and lava dams. Geosphere 4, 183–206. https://doi.org/10.1130/GES00133.1

Crow, R.S., Karlstrom, K.E., McIntosh, W., Peters, L., Crossey, L., Eyster, A., 2015. A new model for Quaternary lava dams in Grand Canyon based on 40Ar/39Ar dating, basalt geochemistry, and field mapping. Geosphere 11, 1305–1342. https://doi.org/10.1130/GES01128.1

Dalrymple, G.B., Alexander, E.C., Lanphere, M.A., Kraker, G.P., 1981. Irradiation of samples for 40Ar/39Ar dating using the Geological Survey TRIGA reactor (USGS Numbered Series No. 1176), Professional Paper. U.S. G.P.O. : for sale by the Supt. of Docs., G.P.O.,.

Dalrymple, G.B., Hamblin, W.K., 1998. K-Ar ages of Pleistocene lava dams in the Grand Canyon in Arizona. Proc. Natl. Acad. Sci. U. S. A. 95, 9744–9749. https://doi.org/10.1073/pnas.95.17.9744

Darvill, C.M., 2013. Cosmogenic nuclide analysis. Geomorphol. Tech. 25.

Degraff, J.M., Long, P.E., Aydin, A., 1989. Use of joint-growth directions and rock textures to infer thermal regimes during solidification of basaltic lava flows. J. Volcanol. Geotherm. Res. 38, 309–324. https://doi.org/10.1016/0377-0273(89)90045-0

Fenton, C.R., Cerling, T.E., Nash, B.P., Webb, R.H., Poreda, R.J., 2002. Cosmogenic 3He ages and geochemical discrimination of lava-dam outburst-flood deposits in western Grand Canyon, Arizona. Anc. Floods Mod. Hazards Princ. Appl. Paleoflood Hydrol. 5, 191–215.

Fenton, C.R., Poreda, R.J., Nash, B.P., Webb, R.H., Cerling, T.E., 2004. Geochemical discrimination of five Pleistocene lava-dam outburst-flood deposits, western Grand Canyon, Arizona. J. Geol. 112, 91–110.

Fenton, C.R., Webb, R.H., Cerling, T.E., 2006. Peak discharge of a Pleistocene lava-dam outburst flood in Grand Canyon, Arizona, USA. Quat. Res. 65, 324–335.

Ferrari, R.L., 2008. 2001 Lake Mead Sedimentation Survey 212.

Hamblin, W.K., 1994. Late Cenozoic Lava Dams in the Western Grand Canyon. Geological Society of Amer, Boulder, Colo.

Huscroft, C.A., Ward, B.C., Barendregt, R.W., Jackson Jr., L.E., Opdyke, N.D., 2004. Pleistocene volcanic damming of Yukon River and the maximum age of the Reid Glaciation, west-central Yukon. Can. J. Earth Sci. 41, 151–164. https://doi.org/10.1139/e03-098

Malde, H.E., 1982. The Yahoo Clay: A Lacustrine Unit Impounded by the McKinney Basalt in the Snake River Canyon Near Bliss, Idaho. Ida. Bur. Mines Geol. Bull. 26, 617–628.

Marchetti, D.W., Harris, M.S., Bailey, C.M., Cerling, T.E., Bergman, S., 2011. Timing of glaciation and last glacial maximum paleoclimate estimates from the Fish Lake Plateau, Utah. Quat. Res. 75, 183–195. https://doi.org/10.1016/j.yqres.2010.09.009

Pederson, J.L., Anders, M.D., Rittenhour, T.M., Sharp, W.D., Gosse, J.C., Karlstrom, K.E., 2006. Using fill terraces to understand incision rates and evolution of the Colorado River

in eastern Grand Canyon, Arizona. J. Geophys. Res. Earth Surf. 111. https://doi.org/10.1029/2004JF000201
Roberts, M.C., Mccuaig, S.J., 2001. Geomorphic responses to the sudden blocking of a fluvial system: Aiyansh lava flow, northwest British Columbia. Can. Geogr. Géographe Can. 45, 319–323. https://doi.org/10.1111/j.1541-0064.2001.tb01492.x
Thordarson, T., Self, S., 1993. The Laki (Skaftár Fires) and Grímsvötn eruptions in 1783 1785. Bull. Volcanol. 55, 233–263. https://doi.org/10.1007/BF00624353